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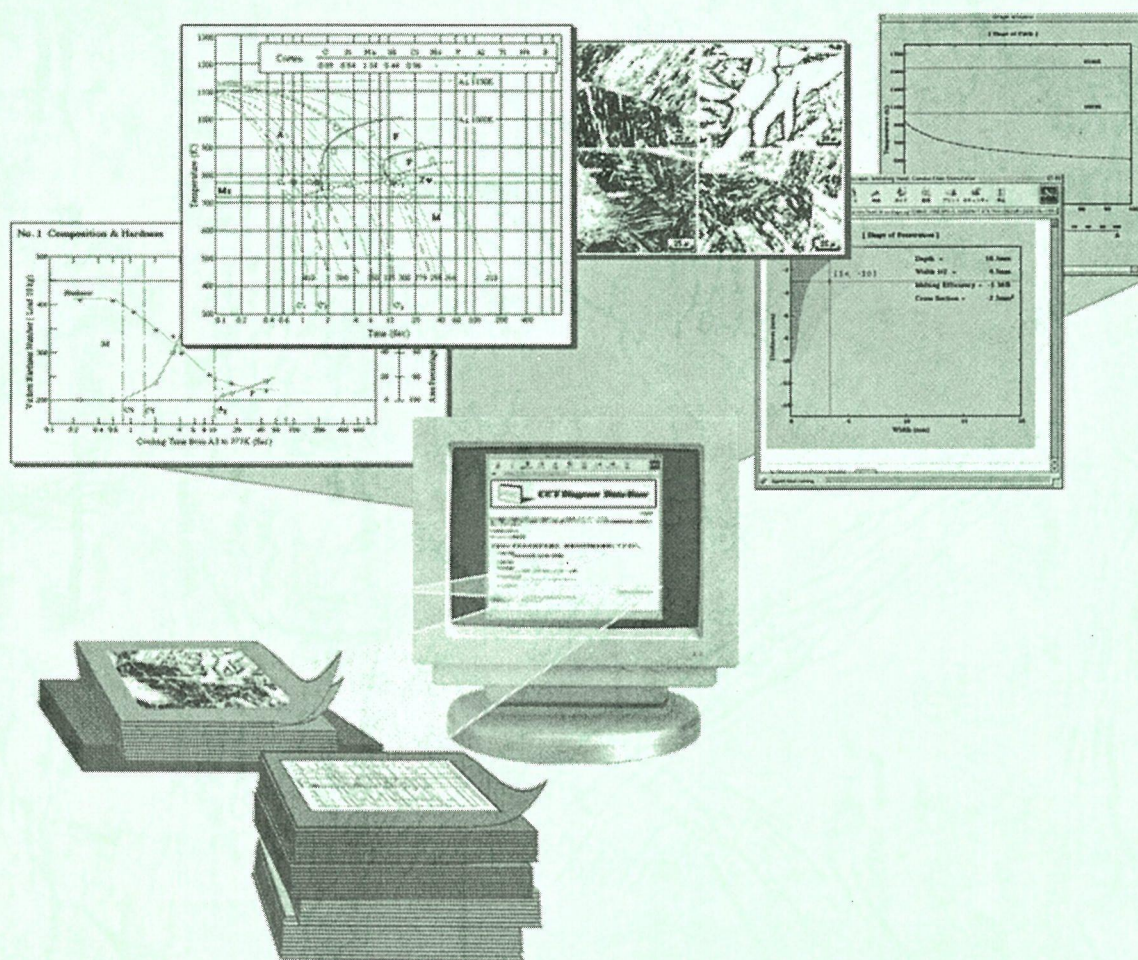
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Atlas of CCT Diagrams for Welding. (I)

Edited by

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Preface

The CCT diagrams for welding produced at the National Research Institute for Metals over a long period of time since the opening of the Institute were summarized. Most of them have been published in the Reports of the National Research Institute for Metals and Transactions of the National Research Institute for Metals. These diagrams, which represent about 200 kinds of steel, are produced under the same measurement conditions and the same conception, judging the continuous cooling transformation behavior of steel. Each of the CCT diagrams contains an image representing the dependence of the hardness and the ratio of transformation products consisting of a microstructure on the cooling time. The collection and edition of these diagrams, which were performed for the construction of a database accessible through the Internet, were part of a database construction project of the Japan Science and Technology Corporation (JST). The CCT database now in progress is accessible at WWW (<http://inaba.nrim.go.jp/Weld/>). Access to this database will allow a more effective utilization of these CCT diagrams.

Numerous colleagues contributed valuable suggestions that were incorporated in this report, and we are extremely grateful to them. We should particularly like to thank Dr. Satoru Ohno, Dr. Masahiro Uda, and Dr. Akira Okada for their extensive review and discussion of the manuscript. Finally, we should like to thank Ms. Misako Utsumi, Miss Kazuyo Miyamoto, and Ms. Hisayo Ando for their assistance during the writing and preparation of manuscript and our wives Yukiko Fujita and the late Noriko Kasugai for their patience and understanding.

Mitsutane FUJITA
Takayoshi KASUGAI

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Forward

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President of The Japan Welding Technology Center
Principal of The Japan Welding Structure College

It is my great pleasure to announce that the "CCT diagram of various kinds of steel products for welding" which is part of a database construction project of the Japan Science and Technology Corporation, is ready for publication on the Internet to be widely utilized. The production of CCT diagrams for welding for structural steel, high-strength steel, and low-temperature steel was commenced by Inagaki in the Welding/Fabrication Laboratory under the guidance of Prof. S. Haruji or Sekiguchi of Nagoya University under the auspices of a special research grant of the Ministry of Education in approximately 1955. At that time, a period of rapid economic growth was just starting in Japan, and a large number of steel products for welding were consumed in the shipbuilding, automobile, and construction industries. The welding technology was developed mainly in the welding of structural steel. The development of high-strength steel and low-temperature steel was also actively sought.

General-purpose CCT diagrams for heat treatment were produced by Dr. A. Rose et al. at the Max Plank Institute in Germany at that time. After receiving the specifications for an apparatus for the production of CCT diagrams for heat treatment from Dr. Rose, we started researching the development of an apparatus for the production of a CCT diagram for welding. We have developed the production method of a so-called CCT diagram for welding which reproduced stably the rapidly heating/cooling weld-heat cycle of a weld-heat affected zone similar to a fusion zone during welding on a small specimen. The most difficult points at that time were selecting the heat source and stably setting a maximum heating temperature of 1350 °C. A cylindrical resistance-heating furnace employed at Nagoya University for budgetary reasons gave insufficient heating velocity.

After being transferred to the National Research Institute for Metals, I developed and commercialized the Synthetic Weld Thermal Cycle Apparatus for Transformation Measurement by High-frequency Induction Heating for the first time in the world. This apparatus produced numbers of CCT diagrams for welding on various kinds of high-strength steel and low-temperature steel which were being developed by steel manufacturers in Japan at that time. Thus, the guidelines for development and the bases of weldability evaluation of these steel products have been established.

Concerning the production of CCT diagrams for welding, attention needs to be paid to how to determine the initiation and termination of the transformation of various kinds of microstructures. The transformation initiation point (1% initiation state) was determined from the heat-expansion curve, the thermal analysis curve, and microstructure observations after quenching the specimens taken out of different cooling states of the weld thermal cycle. The reason that the transformation initiation of a microstructure was defined as a 1% initiation state was that obtaining the strict point of transformation initiation with near-zero percent was too difficult.

I have presented a description of the characteristic of the weld thermal cycle and the CCT diagram for welding and its application at the 18th and 19th Nishiyama Memorial Technological Conferences (sponsored by the Japan Iron and Steel Association) "Change in Material Properties during Welding." The development and commercialization of the Synthetic Weld Thermal Cycle Apparatus for Transformation Measurement and

the Weld Thermal Restraint Simulator increased exports of the apparatus to China and many countries in Europe and America as well as sales in Japan. The apparatus and the simulator have been actively utilized. *

The "CCT Diagram of Structural Steel for Welding" was published in March 1997 by the Committee for the Technological Investigation of Basic Characteristics of Practically Used Structural Steel in the Production Technology Department of the Japan Iron and Steel Association. It is to be noticed that the CCT diagrams for welding summarized in this publication were not always based on the same reproduced weld-heat cycle, and the classification evaluation of mixed microstructures caused by continuous cooling is not always done under the same conception.

I hope that these results are utilized in the research project "STX-21* Structural Materials Xs for 21st Century," which is now advanced by the "Frontier Structural Materials Research Center" of the National Research Institute for Metals.

* M.Inagaki & H.Minematsu :“Application of Simulation Test Technology for Evaluating Weldability of Structural Steels”(June 1984).

CCT Diagram for Welding

Takayoshi KASUGAI

National Research Institute for Metals

1. Introduction

It is well known that the microstructural change of a steel at the equilibrium state can be investigated by a Fe-C equilibrium diagram. In practice, however, the thermal cycle of a steel during heat treatment or welding is heated and cooled faster than that at the equilibrium state. Therefore, it is necessary to know how the equilibrium or non-equilibrium microstructures appear in a heating and cooling process. The continuous cooling transformation diagram (CCT diagram) and the isothermal transformation diagram (TTT diagram or S curve) are the non-equilibrium diagrams which solve these problems. These non-equilibrium diagrams show how the transformation temperature shifts from the equilibrium state based on an A_3 temperature at which the ferrite transformation begins to take place or in what range of temperature and time the non-equilibrium microstructures appear when the cooling is done under non-equilibrium.

There are two types of CCT diagrams. One is for welding, and the other one is for heat treatment. The CCT diagram for welding is also divided into two, i.e., a SH-CCT diagram for a weld heat-affected zone (HAZ) and a SW-CCT diagram for weld metal. Most of the published SH-CCT diagrams for welding (hereinafter called CCT diagrams for welding) focus on the weld-heat affected zone near the fusion line, which is important for evaluating the weldability of the arc welding of the steels, such as weld-cold cracking and notch toughness. CCT diagrams with a maximum heating temperature of about 1120K~1470K (ca. 850~1200°C), corresponding to the HAZ far from the fusion line, have not been studied in depth. SH-CCT diagrams for welding of about 200 kinds for low-carbon and low-alloyed steels stored in this data book have been made by the National Research Institute for Metals of the Science and Technology Agency. Most of them have been made at the Institute by produced under the same measurement conditions and the same conception, judging the continuous cooling transformation behavior of steel. They are the CCT diagrams for welding corresponding to the HAZ near the fusion line with a maximum heating temperature of 1623K (1350°C).

2. CCT Diagram for Welding

The reference temperatures of the CCT diagram for welding, i.e., A_1 and A_3 temperatures, were measured in high vacuum with a heating and cooling velocity of 3 K/min. If the temperature differences between Ac_1 and Ar_1 or between Ac_3 and Ar_3 were below 50K, the average of Ac_1 and Ar_1 was defined as the A_1 temperature, and the average of Ac_3 and Ar_3 was defined as the A_3 temperature, respectively. If the difference was over 50K, both the Ac_1 temperature and the Ac_3 temperature were used. If Ar_1 and Ar_3 were extraordinarily lower than Ac_1 and Ac_3 , respectively, it was assumed that the equilibrium transformation did not proceed during cooling.

The specimen was rapidly heated up to 1623K (1350°C) and cooled down immediately without being held at that temperature, according to the synthetic weld-thermal cycle. The dimensions of the specimen were $\phi 4.5\text{mm} \times 15\text{mm}$ or $\phi 3\text{mm} \times 12\text{mm}$.

The production of earlier CCT diagrams was done using a tublar-Elema furnace.¹⁾ Later on, a program-controlled high-frequency induction heating furnace was used, as for the simulation of weld-thermal cycles.²⁾ Transformation temperatures during the cooling were measured by the thermal expansion method for slow cooling or by the thermal analysis method for fast cooling.

The classification of microstructures was done according to the classification method defined by the Welding Metallurgy Subcommittee of the Japan Welding Society.³⁾ The area percentage of microstructures was measured by the linear-analysis method. The hardness of specimens after cooling was measured using a Vicker's hardness meter (load 10 kgf) at three points to get the mean value. The CCT diagram for welding was

made by drawing the cooling curve for the temperatures below A_3 or Ac_3 temperatures of a simulated weld-thermal cycle. The ordinate of the diagram stands for temperature, and the abscissa stands for the logarithm of time. “A” in the CCT diagram is the austenite region, “F”, “P”, “Zw”, and “M” in the CCT diagram are the ferrite, pearlite, *zwischenstufen-gefüge* (intermediate structure), and martensite transformation region, respectively. The solid line in the transformation curves means that the transformation was clearly recognized, while the broken line means that the transformation did not clearly appear. In particular, the Zw transformation followed by the ferrite transformation progresses continuously from the ferrite transformation, preventing the appearance of a distinct knee on the thermal expansion curve. The majority of CCT diagrams for welding stored in this database indicate the transformation initiation lines but not the end of each transformation. The reason that the end of the transformation lines was not put on the CCT diagram is that it was difficult to obtain them from the thermal expansion curve and the thermal analysis curve.

In the low-carbon low-alloyed steel, the addition of alloying elements including carbon lowers the A_3 temperature. The microstructures in the HAZ of steels are roughly decided during the cooling time from 1073K(800°C) to 773K(500°C) in the weld-thermal cycle. Critical cooling times (SH-CCT characteristics) are shown in the CCT diagram for welding, and these values suggest the dependency of microstructures on the cooling time from A_3 or Ac_3 temperature to 773K(500°C). Among these characteristics, the C_z' is a critical cooling time for Zw precipitation, C_f' is a critical cooling time for ferrite precipitation, and C_p' is a critical cooling time for pearlite precipitation. C_e' is also a critical cooling time over which martensite transformation does not take place. All of these critical cooling times are expressed in the cooling time from A_3 or Ac_3 to 773K(500°C) and are closely related to the weldability of the HAZ described later.

3. Utilization of Diagram for Welding

The CCT diagram plays an important role in the prediction of microstructures of the HAZ near the fusion line. In particular, the CCT diagram for welding on the maximum heating temperature 1623K(1350°C) is closely related to the prediction of the weld-cold cracking sensitivity and the toughness among the weldability of the arc welding of steels. Weld-cold cracking is caused by the interaction between the microstructure, hydrogen, and restraint stress. Among these three factors causing weld-cold cracking, the microstructure can be predicted from the CCT diagram for welding, and it is thus possible to predict the weld-cold cracking of steels. The order of microstructure having higher sensitivity of the weld-cold cracking is martensite > bainite > pearlite > ferrite.⁴⁾ The prevention of weld-cold cracking from the viewpoint of the microstructure in the HAZ near the fusion line is suggested to be necessary to select the cooling time or welding condition so as to avoid martensite transformation and precipitate Zw and ferrite by the weld-thermal cycle. The microstructure affects the toughness to a great extent as well. The toughness of the steel comes from the microstructure of ferrite, pearlite, and martensite, but the toughness is also determined by the coexistence of various kinds of microstructures. The coexistence of different microstructures decreases the unit crack-pass against the fracture, improving the toughness.⁵⁾ In conclusion, weld-cold cracking and the toughness of the HAZ near the fusion line are highly dependent on the microstructure. The mixture of martensite, Zw, and ferrite seems to be the most suitable for the microstructure of the HAZ in the vicinity of the fusion line.⁶⁾⁷⁾

4. Application of CCT Diagram for Welding

When using a CCT diagram for welding, the following applications have to be avoided:

- (1) Application of a CCT diagram for welding to steel having different compositions.
- (2) Application of an SW-CCT diagram for welding to an SH-CCT diagram for welding and vice versa.
- (3) Application of a CCT diagram for welding of the HAZ near the fusion line to other parts of the HAZ and vice versa.

(4) Application of a CCT diagram for heat treatment to a CCT diagram for welding and vice versa.

- (1): It is well known that CCT diagrams with different compositions of steels are not the same. To what extent does the steel in question have to be similar to the reference steel in compositions so that it can be considered to be similar? For example, the CCT diagram for welding of a certain type of steel SM490 cannot be used for all of steel SM490 defined by the JIS standard as having a common CCT diagram for welding. The JIS standard does not define the microstructure of the weld heat-affected zone, but it defines the steel which satisfies a certain performance of its base metal and weld zone. Compositionally, the standard defines the upper limit of contents of C, Si, Mn, P, and S. No other alloying elements than these are defined by the JIS standard. Accordingly, there are various steels with different compositions in steel SM50. Some of them contain C, Si, Mn, P, and S at their maximum content near the upper limit, while others contain them in a much lower level. Some kinds of steel SM490 contain alloying elements other than C, Si, Mn, P, and S. The microstructures of the weld heat-affected zone are considerably different from one another. Very few papers have reported the limit of deviation of alloying elements from the given steel for adopting the CCT diagram for welding which comes from the given steel. The authors have already revealed the limit of alloying element deviation⁸⁾ for steel. Selecting the steel within this limit regardless of strength level enables the adoption of the proper CCT diagram.
- (2): There are two ways to prepare an SW-CCT diagram for welding. One way is to prepare a CCT diagram by applying a complete thermal cycle to specimens from melting/solidification to room temperature.⁹⁾ The other way is to prepare a CCT diagram from an SH-CCT diagram for welding using specimens taken out of weld metal.¹⁰⁾ In the weld metal in the arc welding, larger amounts of inclusions are dispersed than in the base metal. In particular, the dispersed inclusions in the weld metal with large weld-heat input welding are utilized as the ferrite precipitation nucleus in order to keep the notch toughness and tensile strength.¹¹⁾ Even if the composition of the weld metal is the same as that of the base metal, the transformation behavior during cooling is assumed to be considerably different from that of the HAZ.
- (3): Even in the same steel, there is a significant difference between the HAZ near the base metal and the HAZ near the fusion line in the grain size of austenite and the distribution of alloying elements including carbon. The difference certainly affects the transformation behavior during cooling. Mutual application, therefore, must be avoided.
- (4): The CCT diagram for heat treatment is different from the CCT diagram for welding in their utilization purpose. According to the CCT diagram for heat treatment, a specimen of a hypoeutectoid steel is kept at a temperature of $A_3 + 50K$ for a certain period of time and continuously cooled down. In the CCT diagram for welding, a specimen is rapidly heated to the maximum heating temperature and cooled down according to the synthetic weld-thermal cycle without being held at that maximum temperature. The two CCT diagrams have to be used differently, as mentioned in (3).

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Application of Simulation Test Technology for Evaluating Weldability of Structural Steels*

Michio INAGAKI** and Hiroyuki MINEMATSU***

Abstract

The authors have developed the Apparatus for Measuring Transformation in Synthetic Weld Thermal Cycles and Thermal Restraint Simulator. Using the former apparatus, a number of Continuous Cooling Transformation Diagrams in Synthetic Weld Heat-affected Zone (SH-CCT diagrams) for various structural steels were prepared, the transformation behaviour was analyzed and its relation with notch toughness, etc. was examined. Using the Thermal Restraint Simulator, quantitative analyses and evaluation of weld cold cracking and reheat cracking, etc. were made.

1. Introduction

For manufacture, heat treatment, processing and use of materials, test technologies of simulating thermal, dynamic and environmental conditions are very important for development of materials, improvement of procedures and analyses and evaluation of usage performance. Generally the welding phenomena include a number of factors and it is necessary to analyze these factors, evaluate weldability and select proper welding conditions. For these purposes the authors have developed the Apparatus for Measuring Transformation in Synthetic Weld Thermal Cycles in 1961 and Thermal Restraint Simulator in 1969. The scope of application of simulation test technologies offered by these equipments is very wide. Here, they give an account of the transformation behaviour of the synthetic weld heat-affected zone of structural steels and the relation between their microstructure and notch toughness, examined using these equipments. The present state in Japan of the analyses of these factors and the method of evaluating weld cold cracking and reheat cracking is also described.

2. Apparatus for Measuring Transformation in Synthetic Weld Thermal Cycles and Thermal Restraint Simulator

The authors have developed an apparatus to simulate weld thermal cycle in specimen by high frequency induction heating control and examine the transformation during the heating or cooling process. Using this apparatus, it is possible to measure the transformation in continuous cooling by simulating the weld thermal cycle near the weld bond and draw the continuous cooling transformation diagram of synthetic weld heat-affected zone (abbreviated as SH-CCT diagram).^{1),2)} The apparatus also enables making continuous heating transformation diagram and isothermal diagram. With some invent of this apparatus the continuous cooling transformation diagram of synthetic weld metals (abbreviated as SW-CCT diagram) in the cooling process after solidification of molten metal can also be prepared.³⁾

A block diagram of the apparatus for preparing the SH-CCT diagram is shown in Fig.1. In the programmable pattern generator of this diagram, the temperature and time program signals of weld thermal cycle are set digitally. These program signals are compared with the thermocouple signal from specimen, and the high

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frequency generator is controlled through the temperature controller; and in this manner the specimen is heated and cooled according to the preset conditions by the high frequency heating coil (inductor). Since the inductor is designed as a combination of inductor and gas-cooling nozzles, the specimen is cooled by injecting the cooling gas on it through the nozzles at the time of cooling. Transformation is detected by measuring the expansion or contraction of specimen by means of a differential transformer (L. V. D. T.) which is attached to the specimen through a ceramic jig . Especially in rapid cooling, transformation can be detected by the method of thermal analysis as well. The ceramic jig has been designed taking various factors, such as the thermocouple for measuring and controlling temperature, measurement of expansion and contraction and gas cooling effect of specimen, etc. into consideration and it is so constructed as to permit easy mounting and dismounting of specimen. To improve temperature control response, the high frequency generator employs the system of duty conversion by pulse modulation in order to follow quick control signals.

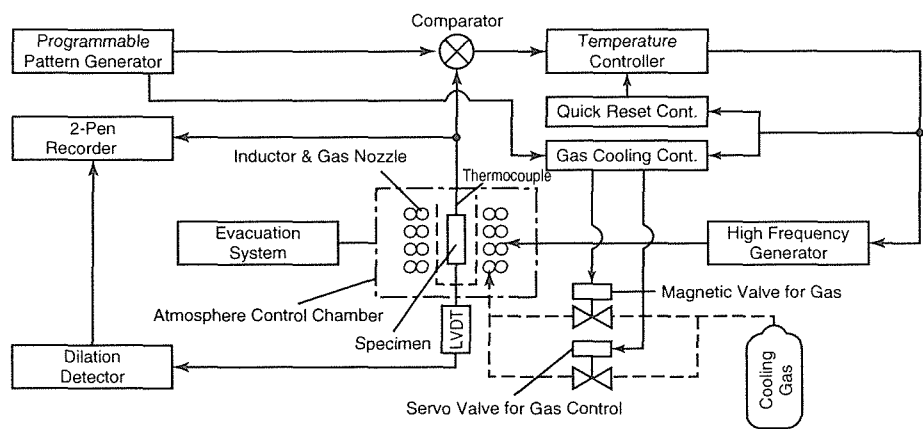


Fig.1 Block diagram of the apparatus for measuring transformation in synthetic weld thermal cycle.

The weld thermal restraint simulator is used for simulating the weld thermal cycle and the restraint stress or strain during this process and experimentally analyzing the welding phenomenon. The phenomena of thermal embrittlement, weld cracking, damage caused by diffusion of hydrogen and reheat cracking, etc. can be clarified with this apparatus.⁴⁾

As shown in the block diagram of Fig.2, this apparatus consists of a thermal system, a mechanical system and a control system for automatically controlling these systems.

Specimen is placed in a vacuum chamber or a chamber of adjustable atmosphere and is easily and accurately mounted in upper and lower grips by means of the cap nuts. The lower grip is directly connected to a hydraulic actuator. A digital electronic circuit incorporating a microprocessor is employed in the programmable pattern generator and the thermal system and mechanical system are controlled by closed loop control system (feedback control).

The thermal system is controlled by a combination of a high frequency induction heating method and a gas cooling method. The preset temperature program signal is compared with the signal received from the thermocouple welded to the specimen, the deviation signal produced after the comparison is fed to the high frequency generator through the temperature controller to control the high frequency output current fed to the heating coil. For cooling, a combined cooling control is used in which a cooling gas is injected on the specimen, when necessary, through the gas nozzles (built in the heating coil) together with the high frequency output.

The mechanical system is controlled by electric and hydraulic type control methods. The stress and strain applied to the specimen are detected by means of load cell directly connected to the upper grip and the

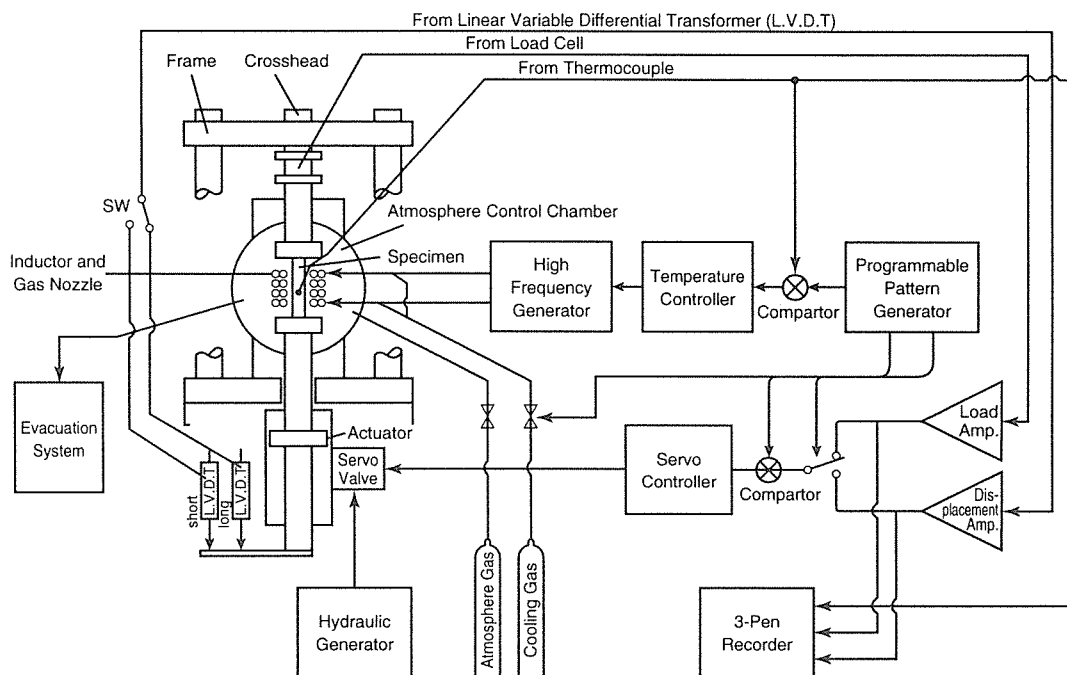


Fig.2 Block diagram of the weld thermal restraint simulator

differential transformer (L. V. D. T.) directly connected to the actuator of the lower side; these detected signals are compared with the preset stress and strain program signals and the deviation signal produced after the comparison is used to operate the servo valve through the servo controller. The servo valve controls the hydraulic pressure fed from the hydraulic generator, which drives the actuator.

In order to accurately simulate various welding phenomena, it is necessary to apply required stress and strain to the specimen during the thermal cycle. For this purpose, the apparatus is equipped with a zero-follow up memory circuit for exchanging the control configuration, which permits exchange of (strain control) $\Leftrightarrow$ (stress control) without time lag at any arbitrary point during the cycle. By using the zone melting process employing a heating coil of special shape, it is also possible to simulate the melting-solidification thermal cycle of a weld metal, conduct hot tensile test after solidification and evaluate hot cracking susceptibility of weld metal with this apparatus.⁵⁾

3. SH-CCT Diagram and Microstructures of Weld HAZ

To investigate the transformation behaviour of the weld HAZ by simulating the thermal cycle near weld bond, the SH-CCT diagram for welding is used. Fig.3 shows an example of the SH-CCT diagram for welding of a HT50 or HT60 class steel. This diagram was achieved by simulating a weld thermal cycle of maximum heating temperature of 1350°C in the specimen. Since the transformation microstructure is generally determined by the cooling time from A₃ (or 800°C) to 500°C, the cooling curve from A₃ is shown using logarithmic scale along the axis of abscissa. In the diagram, the regions A, F, P, B(Zw) and M represent the transformation areas of austenite, ferrite, pearlite, bainite or intermediate microstructure and martensite respectively. The number given under each transformation region shows the microstructure ratio and the number at the end of each cooling curve represents the Vickers' hardness (Hv10) of specimen after cooling. The cooling curves shown in broken line represent critical cooling curves at the boundary where specific

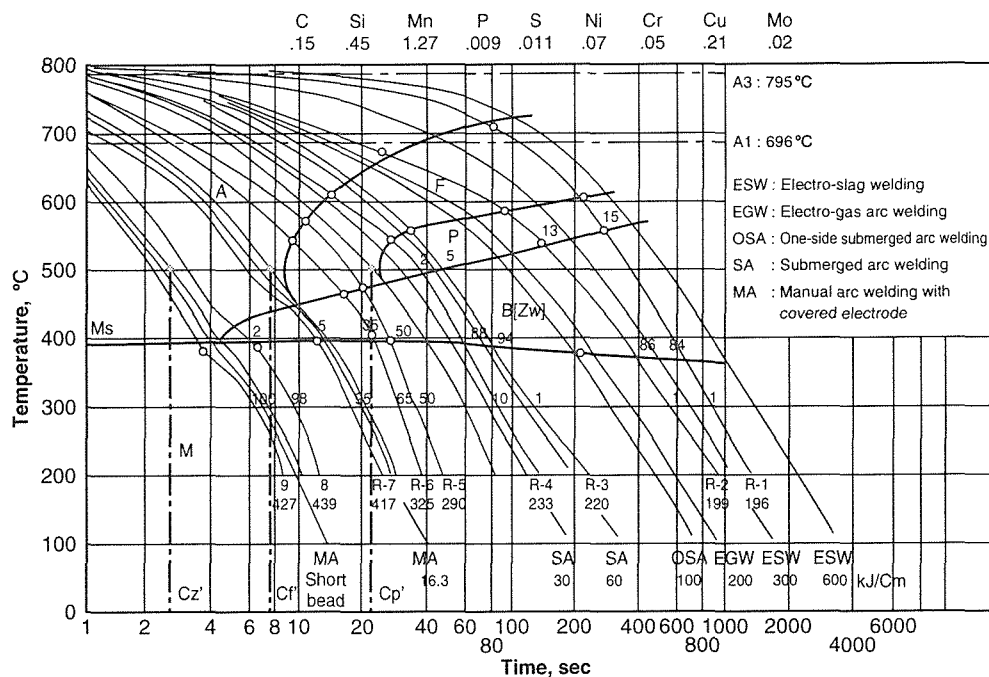


Fig.3 SH-CCT diagram for welding of a HT50 or HT60 class steel(Maximum heating temperature 1350°C

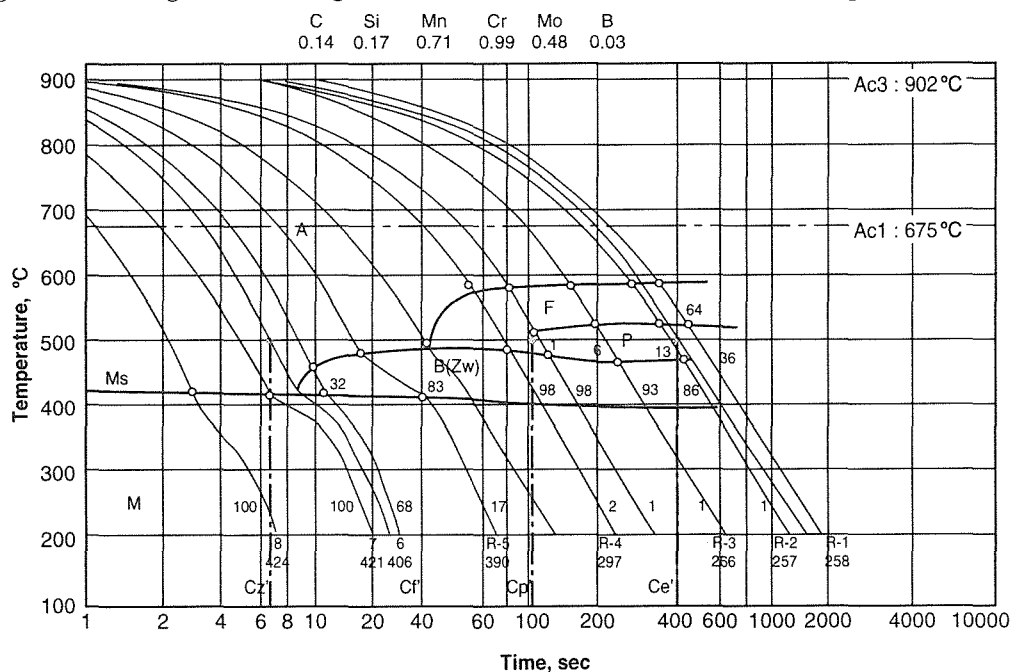


Fig.4 SH-CCT diagram for welding of a HT80 class steel (Maximum heating temperature 1350°C)

microstructure begins to appear. The A_3 500°C cooling time in these curves is called critical cooling time. If a cooling time occurs later than the critical cooling time Cz' , it means the appearance of bainite in martensite; and if a cooling time occurs later than the critical cooling time Cf' , ferrite appears. If a cooling time occurs later than Cp' , pearlite appears; and if a cooling time occurs later than Ce' , the microstructure consists of only two

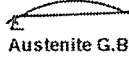
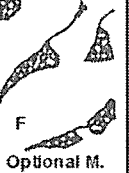
FERRITE	F-I, Ferrite Allotriomorph	F-II, Proeutectoid F. or Grainboundary Polygonal F.	F-III, F.Side plate or Bainitic F.	F-IV, Intragranular Rodlike F. or Acicular F.	F-V, Intragranular Fine Grained F.
	 Austenite G.B.	 Austenite G.B.	 Austenite G.B.		
PEARLITE	P-I, Lamellar Pearlite		P-II, Degenerate Pearlite		P-III, Fine Colony Pearlite
	 Optional M.	 Electron M.	 Optional M.	 Electron M.	 Optional M.
BAINITE	B-I, Upper Bainite		B-II, Lower Bainite		
	 Optical M.	 Electron M.	 Optical M.	 Electron M.	
MARTENSITE	M-I, Lath Martensite		M-II, M-A Constituent		
			 F M-A	 F M-A	

Fig.5 Classification of microstructure morphologies of weld HAZ for low C low alloyed steels and unification of their terminologies

microstructures (ferrite + pearlite). These critical cooling times Cz' , Cf' , Cp' , and Ce' are called a SHCCT characteristic value.⁶⁾ In the diagram, cooling curves for typical welding conditions in various welding processes are also shown.⁷⁾ Fig.4 shows the SH-CCT diagram prepared in the same manner for a HT80 class steel.⁶⁾

The microstructure of weld HAZ is largely affected by chemical composition of the steel and weld thermal cycle. The microstructure of HAZ is produced by the continuous cooling transformation and in many cases several microstructures exist in combinations in a HAZ . Moreover, the morphologies of the ferrite, pearlite, bainite and martensite thus produced change according to the temperature and time in the cooling process. No definite approach has yet been made for unification of classification of microstructure morphologies and their terminologies. The matter is under consideration by the IIW Commission IX, etc. and in Japan also a Working Group for investigating about unification of microstructure terminologies of weld has been established with the cooperation of the Welding Metallurgy Committee of the Japan Welding Society and Commission No. 9 of the Japan Institute of Welding (JIW). This working Group has proposed classification of microstructure morphologies and their terminologies for weld HAZ microstructure considering unification of their terminologies, which can be applied to various welding processes of low-carbon, low-alloyed steels. This

classification of microstructure morphologies was mainly based on optical microscope, but for fine structure the results obtained by using an electron microscope based on the replica method and the scanning type electron microscope, which is considered as an extension of the optical microscope, were also considered. Fig. 5 shows the classification of microstructure morphologies of weld HAZ for low-C low-alloyed steels and unification of their terminologies.^{8),9)}

Type F-I is ferrite allotriomorph which grows long in the form of a pancake precipitated along the austenite grainboundary, type F-II is proeutectoid ferrite or grainboundary polygonal ferrite which grows into a massive form assuming roundness, and type F-III is a ferrite sideplate which grows in the form of spearhead from austenite grainboundary into the grains and tends to become bainitic ferrite when many elements are included in comparatively large quantities. Type F-IV is intragranular rodlike or acicular ferrite which precipitates in rodlike or acicular form in austenite grains. Type F-V is intragranular fine "rained ferrite which precipitates in small massive form in austenite grains.

According to the results obtained by using electron microscope, ferrite side plate and bainitic ferrite can be distinguished; but it seems from the results obtained by using an optical microscope in the case of a continuous cooling transformation, such as in a weld HAZ, that the distinction is difficult. For this reason the bainitic ferrite has been included in the ferrite in the classification of microstructure morphologies mainly based on optical microscope presented in this paper.

Regarding the morphologies of pearlite, type P-I is the lamellar pearlite in which the ferrite and cementite take lamellar form in rather good order, and it is easy to precipitate when the cooling time is long. It precipitates among various types of comparatively coarse ferrite morphologies. Type P-II is the degenerate pearlite in which the cementite in pearlite gets cut into small pieces or becomes granular. This cementite becomes smaller as the the cooling time decreases and is easy to precipitate in weld HAZ of steels having comparatively less quantities of alloying elements like mild steel. In some cases, degenerate pearlite precipitates in quantities considerably larger than those estimated from the C content of the steel, and the C content of this pearlite shifts from eutectoid composition (0.80% C) to low C side. Type P-III is very fine pearlite colonies which precipitate between the narrow ferrite sideplate and narrow intragranular rodlike or acicular ferrite and is called fine colony pearlite. The cementite in this pearlite has a morphology like round threads. The fine colony pearlite is easy to precipitate in a cooling time shorter than the cooling times for the lamellar pearlite or degenerate pearlite.

Regarding the morphologies of bainite, type B-I is the upper bainite in which the cementite precipitates between the ferrite laths. Type B-II is the lower bainite in which the cementite precipitates at the ferrite lath boundaries and in the laths. In a weld HAZ, the upper bainite is easier to precipitate on the higher temperature and longer time side compared to the lower bainite but it is difficult to clearly distinguish them on the SH-CCT diagram for welding. However, in low-carbon low-alloyed steels, the limit of formation temperature regions of upper bainite and lower bainite tends to be about 450°C.

Regarding morphologies of martensite, type M-I is the lath martensite which is formed when the cooling time is short. Type M-II is an insular martensite which forms between the bainitic ferrite and intragranular rodlike ferrite or acicular ferrite; and as it is a high C martensite mixed with retained austenite, it is called M-A constituent.

In normal welding conditions of various arc welding processes for low-carbon low-alloyed steels, in the continuous cooling process of the weld thermal cycle, the ferrites of various morphologies precipitate at first and especially from type F-III ferrite to upper bainite, lower bainite and M-A constituent are easier to precipitate. In a cooling process of a middle rate, when type F-III ferrite grows, carbon is discharged to untransformed γ and C concentration of γ increases. The distribution of C concentration at this time shows a peak on the γ side of the α/γ boundary of type F-III ferrite and is said to reach a C content of about 0.6%. Upper bainite mostly appears in the intermediate temperature region of 500 to 450°C and in this transformation the ferrite amount further increases, C concentration of the untransformed γ of α/γ boundary also further increases and cementite partly precipitates. On the other hand, carbon gradually diffuses into γ . Next, the lower bainite

appears on the lower temperature side near about 450°C to Ms point; and because the diffusion of carbon is slow although the driving force of transformation increases and the transformation rate becomes large, carbon accumulates on the γ side of the tip of ferrite lath growth in the lower bainite transformation. Finally, the untransformed γ reaches below the Ms point and M-A constituent is formed.

For formation of M-A constituent, temperature and time conditions are necessary under which alloys of some kinds and quantities be added and the bainite transformation start temperature Bs should drop below about 500°C and untransformed γ should exist in stable state below the Ms point. Therefore, the M-A constituent is mostly formed when many alloying elements are contained in comparatively large quantities and the type F-III ferrite and upper bainite exist in large quantity in the middle cooling time of the weld thermal cycle. In a detailed example of 170 sec cooling time in synthetic weld thermal cycle for a HT80 class steel, the amount of formation of M-A constituent was approximately 15%, of which the amount of γ was approximately 8%.¹⁰⁾

4. Notch Toughness of Weld HAZ

The weld bond in an arc welded joint is the boundary where the base metal undergoes fusion and solidification, but there is not definite boundary line in the bond. Generally, in the weld metal side, the base metal melts but does not mix with the deposited metal of welding material, that is, an unmixed zone exists and in the base metal side the grain size increases and a partial melt zone exists at the grain boundaries. In the beginning of solidification of molten weld metal, there is a trend of columnar grain growth along the same crystal axis as the coarsened grains in the base metal side or under the solidification surface, that is, there is a trend of epitaxial growth. It has been found from the results of investigation of microstructure near weld bond of various kinds of materials that in each case epitaxial growth occurs from the coarsened grain of weld HAZ, unmelted in a base metal, in widths similar to those of coarsened grains. So there is a transition region of the order of 20 to 100 μm , in which the chemical composition and microstructures change abruptly in a weld bond.

The factors of material quality for notch toughness near weld bond are (1) chemical composition and microstructures, (2) grain size and facet unit, (3) dissolved atoms and precipitates, nonmetallic inclusions, dislocations, etc. and (4) effect of weld metal. Moreover, from the viewpoint of welding procedure conditions, single layer weld or multilayer weld as well as the weld heat input and the effects of preheating and postheating, etc. can be considered.

The notch toughness of HAZ near the bond of a welded joint is said to decrease due to the upper bainite microstructure and coarseness of austenite grains. As a measure to improve the material quality, a mixed microstructure of (ferrite+pearlite) should be made by decreasing the hardenability in structural steels of HT60 or lower class; and for steels of HT70 or higher class, on the contrary, the composition design and the control of weld thermal cycle should be made by increasing the hardenability to obtain a mixed microstructure of (low-carbon martensite+lower bainite).

The brittle fracture of a welded joint tends to initiate near the bond without regard to the class of steel. However, for steels of HT60 or lower class, even if brittle fracture initiates near the bond, the crack deviates to the unaffected zone side of base metal due to the effect of residual stress field; but in the case of HT80 class steel, etc., the crack tends to propagate along the bond embrittled due to large heat input welding. For this reason the notch toughness of HAZ near weld bond of higher strength steels is important.

Since the bond in a welded joint has microstructural transition region as described above, the toughness considerably varies according to the position of notch in a notch-toughness test specimen and is affected by the quality of weld metal, etc. with regard to crack initiation and propagation courses. This happens when a brittle upper bainite microstructure appears in the transition region of the bond. To investigate this by simplifying the relation between notch toughness and microstructure of HAZ near a weld bond, the material of uniform quality subjected to synthetic weld thermal cycle is mostly used. This simulation test is conducted by applying a single

weld thermal cycle corresponding to single layer weld or by applying multiple weld thermal cycles at a certain position in the case of multilayer welding. Moreover, restraint conditions during a weld thermal cycle can also be simulated. For example, a synthetic weld thermal (heating and cooling) cycle was applied to the round bar specimen of a HT50 class steel keeping its both ends restrained, a half size Charpy test specimen was cut off from its middle part and the test was performed. In this case the effect of restraint on the toughness almost could not be recognized in a wide range of cooling time $S_8/5$ of 60 to 600 sec.¹¹⁾

Main composition of mild steels and HT50 class non-QT steels are C, Mn and Si; and also P, S, O and N are included as impurities. To improve notch toughness of a weld HAZ, generally it is desirable that contents of these elements shall be kept low and the impurities be decreased. In the upper bainite region in a SH-CCT diagram for welding, high-C M-A constituent (insular martensite) is formed and facet unit increases, which gives rise to brittleness. This M-A constituent is the insular part containing high-C martensite and retained austenite surrounded by lath shaped ferrite. The limit of formation temperature regions of upper bainite and lower bainite is not clear, but in low-C type steels it is about 400°C and the concentration of carbon in the untransformed γ surrounded by lath shaped ferrite seems to occur in the region from the bainite transformation start temperature to near this 400°C. It is said that in order to diminish this M-A constituent, decreases in C, N and Si contents are effective. Lower carbon content makes martensite tough. Low N content and a decrease in dissolved N due to TiN and BN accelerates fine ferrite transformation, makes strain ageing decrease and ensures toughness, and such steels are being used for large heat input applications. A lower Si content accelerates precipitation of cementite and makes the lath width of ferrite narrow and the toughness high. Moreover, it is said that REM also accelerates fine ferrite transformation through formation of oxysulphide. TiN and BN are more difficult to dissolve at high temperature compared to AlN and VN; and in HT50 class steels for large heat input containing TiN or REM-B, fine nitrides precipitate in the process of cooling of weld HAZ, which serve as ferrite generating nucleous and, together with the low-N effect, suppress the formation of M-A constituent and ensure high toughness.¹¹⁾

Regarding HT50 class steels for large heat input containing TiN (as rolled, 30mmt), the notch toughness was evaluated by single-V-groove butt welded joint, which was performed with a heat input of 150 kJ/cm (cooling time from 800°C to 500°C : $S_8/5 = 180S$) for one-side single-layer submerged arc welding process, taking 2mm V notch Charpy test specimens from the middle of the plate thickness of welded joint, making a notch including HAZ and weld metal (50% each) in the direction of plate thickness with the bond as the center and determining the absorbed energy (vE_0) at 0°C. On the other hand, in the case of an actual welded joint, since it is difficult to quantitatively investigate the precipitation state of TiN in HAZ, observation of TiN particles and quantitative analysis of insoluble Ti with electrolytic extraction were carried out by applying a synthetic weld thermal cycle (maximum heating temperature 1350°C x 5S, $S_8/5 = 180S$). From the results of this investigation it was found that the optimum content of Ti is approximately 0.015% and that of N approximately 0.0050% to obtain correct distribution of TiN for securing notch toughness of HAZ.¹²⁾

Regarding aluminum killed steels for low temperature use, coarsening of γ grains has been prevented by decreasing N and performing TiN fine dispersion treatment as well as extremely decreasing S and performing Ca treatment for dispersion of stable CaO particles in the high temperature region. Regarding butt welded joints of aluminum killed steel plate (20 to 40 mm) for low temperature use, 4-pass 4-layer welding was performed with about 60 kJ/cm heat input without preheating and standard Charpy test specimens of 2mm V notch were taken from the middle of plate thickness. On the other hand, regarding specimens subjected to synthetic single weld thermal cycle (heating time from room temperature to the maximum heating temperature 1350 to 1450°C : 10S, $S_8/5 = 32S$) corresponding to the welding condition, similar Charpy test specimens were taken, and the relations among the notch toughness ($vTrs$, $vE-60$), dispersion of TiN & CaO and microstructures were investigated. As a result of the investigation it was found that the notch toughness of HAZ near weld bond was optimum when $Ti/N \approx 2$ in the case that the content of N is below 80 ppm, and even more stable high toughness was obtained by further extremely decreasing S and performing Ca treatment. This depends on fineness of γ

grains and acceleration of fine ferrite transformation due to dispersion of TiN particles and stability of CaO particles near the weld bond.

In HT60 class steels, quenched and tempered (QT) steels are the main type, but because of such limitations as hot forming or postweld heat treatment (PWHT), etc., the non-QT steels are also used. Generally the strength of HT50 class steels is increased by adding Nb, V, Cr, Ni, Cu, etc., but in this case suitable procedure control (preheating, heat input control) is necessary because of the tendency of lowering notch toughness of HAZ. The HT60 class steels for large heat input welding are low-C low-N and TiN-treated HT50 class steel for large heat input welding levelled up by quenching and tempering. The M-A constituent is decreased by suppressing the formation of upper bainite in HAZ near weld bond of such steels and the microstructure changes to (F+P) by accelerating the ferrite transformation.¹³⁾

Recently, controlled rolling (abbreviated as CR) technology is developing at an alarming rate. In controlled rolling, recrystallization behavior of γ grains during hot rolling is most important factor; and superior base metal characteristics (strength, toughness) are achieved by adjusting the rolling temperature and the ratio of rolling and using the recrystallization delay effect. That is, when rolling is done in unrecrystallized region, the γ grains are elongated, deformation bands occur, formation of ferrite nuclei in Ar_3 transformation are accelerated and the grains become fine. By further relating the Ar_3 and Ar_1 transformations based on this fineness of grains, various technologies are being developed according to desired purpose, such as 2-phase region rolling, controlled Cooling, retransformation hot rolling and tempering or the combination of their processes, etc.

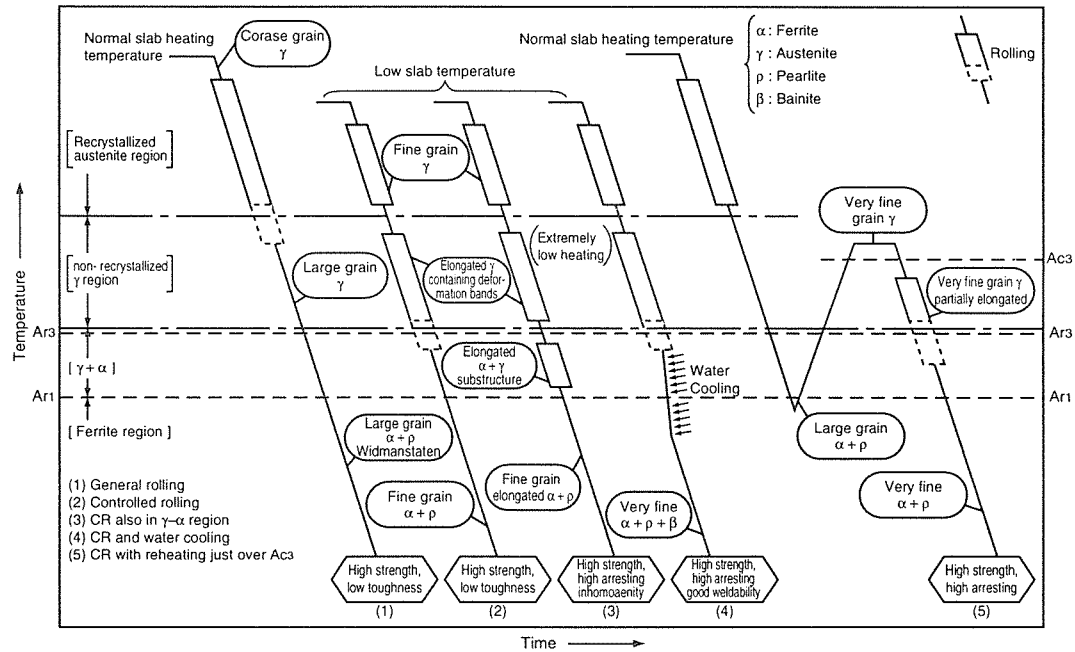


Fig.6 Comparison of various types of Thermo-Mechanical Control Process (TMCP) for steels containing Nb

Fig. 6 shows an outline of the various thermo-mechanical control processes. (1) represents conventional rolling, (2) controlled rolling in unrecrystallized region and (3) shows 2-phase ($\alpha + \gamma$) region rolling by which steels strong in brittle fracture propagation can be achieved from the mixed microstructure of ferrite containing substructure and fine elongated γ grains. (4) represents a type of process in which accelerated cooling is added to the particular temperature range after normal controlled rolling of the above (2) and the strength is increased without degrading the weldability by means of fine grains and rapid cooling microstructure. In this process,

water cooling stop temperature carries important meaning. (5) represents the process in which reheating and rerolling are performed up to above the Ac_3 point after once cooling down to below the Ar_1 point. By this process, tempering effect and formation of uniform fine grains are accelerated. In this process, the notch toughness of steel is considerably affected by the ratio of rolling. By combining alloying elements characteristics of materials can be further changed and the characteristics such as toughness of base metal and HAZ, resistance against weld cracking, high yield strength and other characteristics for large heat input welding purpose can be expected.

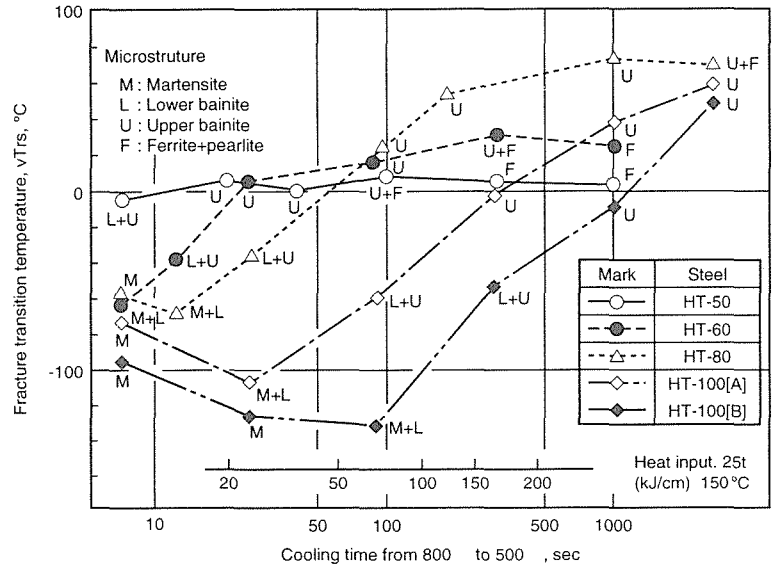


Fig.7 Relation between cooling time and notch toughness in the synthetic weld HAZ near bond for various high strength steels

The HT80 class steels are QT type whose hardenability has been increased by adding small contents of Cu, Ni, Cr, Mo, V, B, etc.; the weld HAZ microstructure near bond is mainly the lower bainite and such composition is adopted as to suppress the formation of upper bainite. In HT80 class steels there is a type to which Ni is not added because of resistance to sulphide cracking, etc., but this is slightly inferior in notch toughness compared to the type to which Ni has been added.¹⁴⁾ For ordinary HT80 class steels, the weld heat input is limited to 45 kJ/cm maximum (plate thickness ≤ 25 mm) to prevent embrittlement in weld bond. To improve the toughness of HT80, low-N, high alloying, low-Si or addition of large content of Ni, etc. can be considered. Boron is added to HT80 class steels as an element for increasing the hardenability, but the boron effective for hardenability is the soluble boron which segregates at the γ grain boundaries before quenching and optimum content of this soluble boron is said to be 3 to 5 ppm. Therefore, the hardening effect of boron is suppressed by AlN, BN and boron carbide Fe₂₃(B.C)₆, etc., and low N is effective for ensuring notch toughness of weld HAZ near bond. With regard to weld bond toughness for large heat input, the effect of adding Ti to a HT80 class steel is not so prominent as in the case of HT50 or HT60 class steels; addition of large contents of Ti, Zr, Nb, etc. rather degrades the toughness. Ni is the only element which improves toughness of ferrite matrix. Moreover, it affects the bainite transformation behaviour; and by adding more than 2% Ni content, the bainite transformation start temperature is lowered to change to lower bainite and the facet unit is also decreased by fine cementite precipitation, which is effective for increasing the toughness. Like low_C, low_Si also tends to decrease hardenability, but on large heat input side it suppresses the formation of insular M-A constituent in upper bainite by changing the microstructure to (F+P), and is effective for improving notch toughness.

The relation between notch toughness and cooling time S8/5 from 800 to 500°C of synthetic weld HAZ near bond for various types of high-strength steels has been investigated. 2mm V notch Charpy impact test was

performed on half sized (5x10x50mm) specimens after subjecting them to syntheti weld thermal cycle with 1350°C maximum heating temperature and 5 seconds holding time, and fracture transition temperature $vTrs$ was determined. The results are shown in Fig.7. It has been found that the optimum cooling time for notch toughness of HAZ shifts to the longer time side as the strength and contents of alloying elements increase; and as compared to HT50 and HT60 class steels, the weld bond toughness of HT80 and HT100 class steels depends more on the cooling time and they become very brittle on the large heat input side. This is because on the large heat input side of any steel the upper bainite becomes the main microstructure and more M-A constituent is formed as contents of alloying elements increase. The HT100 class steel contains about 4% Ni and is superior in notch toughness under the practical welding conditions.¹⁵⁾

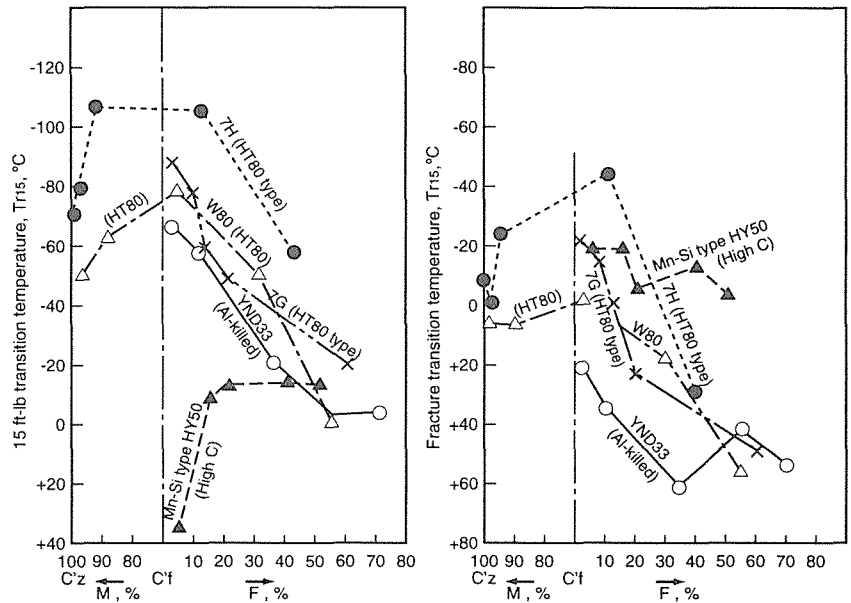


Fig.8 Relation between microstructure and notch toughness (Tr15,Trs) in the synthetic weld HAZ near bond for high strength steels

Fig.8 shows the relation between synthetic weld HAZ toughness (transition temperature with standard 2mm V notch Charpy impact test) and microstructures near bond. The optimum microstructure with regard to toughness is generally the one in which 10 to 30% lower bainite is included in martensite. As the cooling time becomes longer and the quantities of ferrite and upper bainite increase, the toughness tends to decrease. However, this trend does not hold good for the high- carbon type HT50 class steel (0.22% C) because in this type the toughness of martensite is low.¹⁶⁾ For this, the limiting carbon content is said to be about 0.18%.¹⁷⁾

Facet unit or effective crystal grain diameter of brittle fracture is closely related to microstructures. This is said to be the finest in mixed microstructure of (martensite M + lower bainite LB). In the upper bainite UB, this facet unit becomes coarse and it becomes extremely brittle due to the formation of M-A constituent. In (ferrite F + pearlite P) microstructure, $vTrs$ is proportional to the ferrite grain diameter $d^{-1/2}$.

Fig.9 shows the relation between $vTrs$ of synthetic weld HAZ near bond and the facet unit.^{18),19),20)} In this figure, in the case of HT80 class steel, as the microstructure changes from the mixed microstructure (M+LB) to (F+UB), $vTrs$ shifts to considerably higher temperature side, so embrittlement due to change in microstructure is recognized. This can be considered as the M-A constituent effect of in UB; and embrittlement remarkably increases when the microstructure changes from UB 0% to UB 100% as the contents of alloying elements increase.

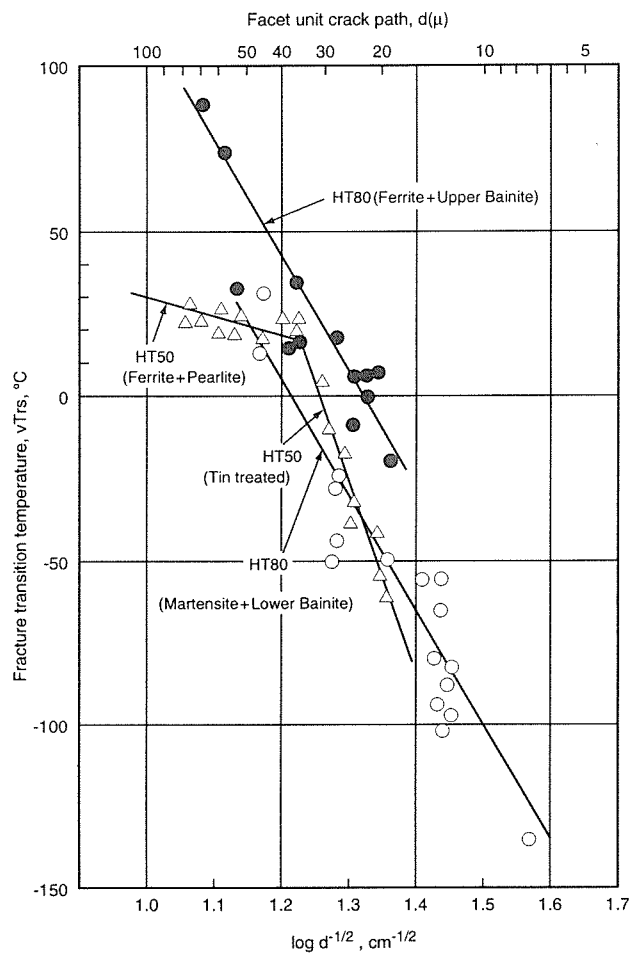


Fig.9 Relation between notch toughness and facet unit in the synthetic weld HAZ near bond for HT50 and HT80 class steels

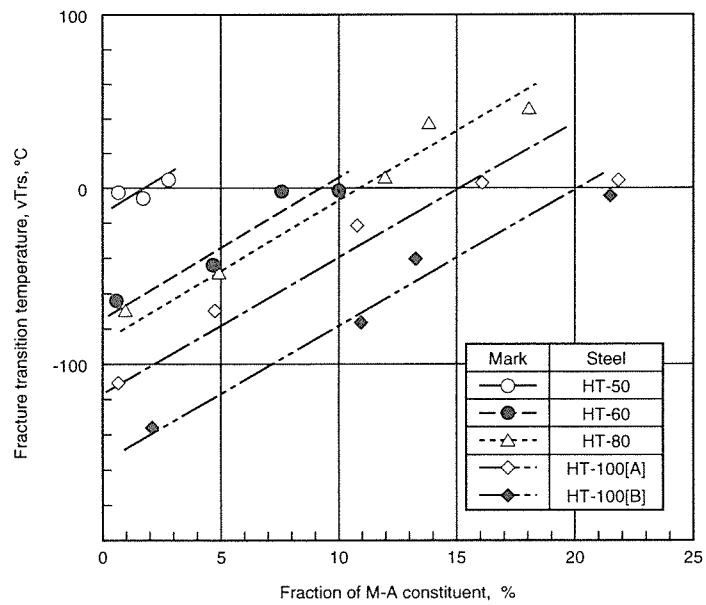


Fig.10 Influence of martensite-austenite constituent, % synthetic weld HAZ toughness

Fig. 10 shows the relation between $vTrs$ of synthetic weld HAZ for various types of steels and the fraction of M-A constituent. Without regard to the type of steel, their straight line gradients are almost the same, $8^{\circ}\text{C}/\%$ M-A constituent. In this figure, the contribution of the facet unit on the $vTrs$ has been removed as $-13^{\circ}\text{C}/d^{1/2}$. Moreover it can be seen in this figure that as the strength increases, the values of $vTrs$ shift to the lower temperature side. This is because of the toughness improvement effect of matrix due to Ni. Moreover, by means of very low C content, the amount of M-A constituent decreases, the morphology also becomes round and the toughness of HAZ improves, which is very effective for large heat input welding purposes.¹⁵⁾

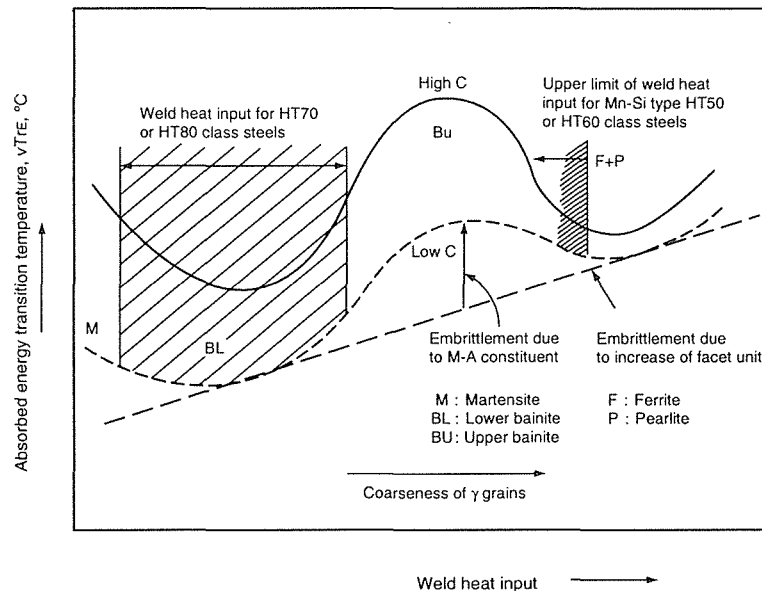


Fig.11 Schematic diagram of effect of weld heat input on notch toughness and microstructures in the weld HAZ near bond for various high strength steels

Eventually, the trend of the relation between notch toughness of weld HAZ near bond and weld heat input or cooling time is as shown in Fig.11.⁷⁾

For multilayer welding, the microstructures and notch toughness of the heat-affected zone (HAZ) change by being subjected to multiple thermal cycles. The factors which affect this notch toughness can be considered to be (1) fineness of crystal grains, (2) tempering effect of quenched microstructure, (3) embrittlement due to heating above A_{c1} point, (4) tempered embrittlement around 600°C and (5) hot strain aging embrittlement at 200 to 350°C , etc.. Of these, factors (1) and (2) tend to improve the toughness whereas factors (3) to (5) tend to decrease the toughness.

γ grains, which coarsen in weld single thermal cycle near bond, become fine in weld double thermal cycle in the temperature range from 800 to 1000°C , but the fineness of γ grains is not as effective as in the case of single thermal cycle and the γ grains become mixed size. In the case of steels below the Mn-Si type HT60 class steel, in most cases the toughness gets improved by multiple weld thermal cycles, but if Nb, V and Cu, etc are contained in large quantities, the weld HAZ near bond tends to become brittle and the embrittlement accelerates when stress or strain is added. In the case of HT70 to HT100 class steels, the weld HAZ near bond becomes more brittle than in the case of weld single cycle near bond when reheated to 750 to 1200°C , which differs with the case of steels below the HT60 class.

Especially in the case of steels to which boron has been added, formation of BN in multiple thermal cycle zone is prevented due to low-N, quenching effect increases and the toughness is improved. For embrittlement above A_{c1} point, the main cause is considered to be the M-A constituent; effective soluble boron is assured due to low-N and the formation of upper bainite including the M-A constituent is prevented.²¹⁾

5. Weld Cold Cracking

Basically, the main factors for weld cold cracking of structural steels are (1) hardened microstructures, (2) diffusible hydrogen and (3) restraint conditions.

These three factors are quantitatively analyzed by using weld thermal restraint simulator, and weld cold cracking is evaluated.

For investigating cold cracking of the weld HAZ near bond, that is, delayed cracking due to hydrogen, as shown in Fig.12, hydrogen is charged in high _strength steel specimens (outer dia. 7mm, notch depth 1mm, radius of notch tip 0.25mm) by changing the atmosphere from argon to hydrogen gas at 950°C during cooling of a synthetic weld thermal cycle and the restraint distance (displacement) is kept constant or the load is controlled at a constant value at a certain point during the cooling.

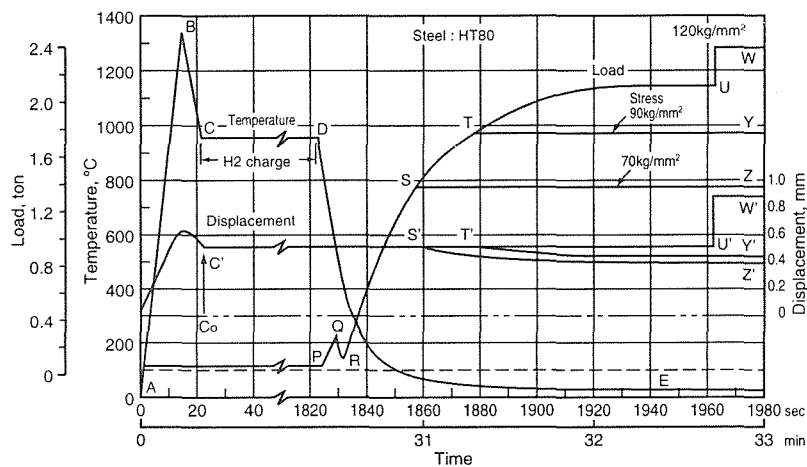


Fig.12 Each cycle of thermal, strain, stress and hydrogen charge for investigating the delayed cracking phenomenon due to hydrogen in the synthetic weld HAZ near bond

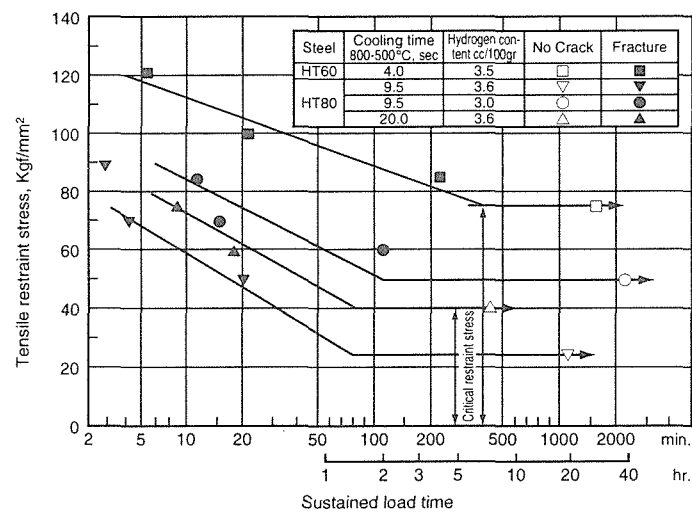


Fig.13 Evaluation of cold cracking sensitivity in the synthetic weld HAZ of HT60 and HT80 class steels

Fig. 12 shows each cycle of temperature, displacement and load in such cases. Examples of the results are shown in Fig. 13. From this figure the relation among the cooling time, the hydrogen content for HT60 and HT80 class steels and the critical restraint stress at which the delayed cracking occurs can be known. The figure

shows that the critical restraint stress of HT60 class steel is higher than that of HT80 class, and hence cold cracking is difficult to occur in HT60 class. Moreover, for HT80 class steel, the critical restraint stress becomes higher in the case of longer cooling time and it further increases as the hydrogen content decreases.

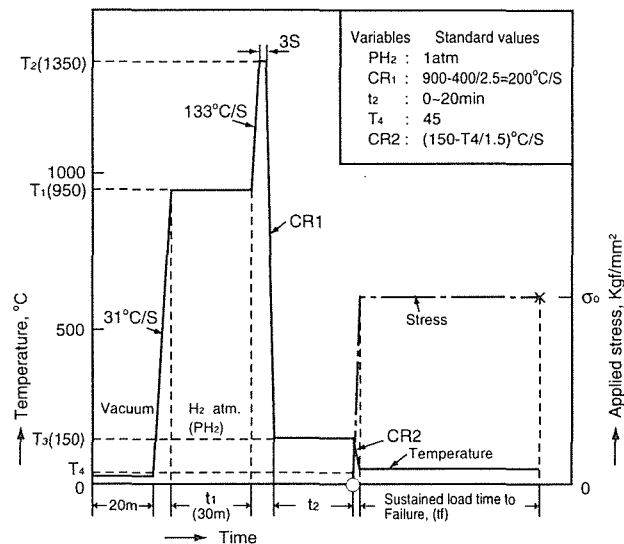


Fig.14 Testing program of simulation test for hydrogen delayed cracking in the synthetic weld HAZ near bond

In the same manner, the inhomogeneity of delayed cracking phenomenon for rolled steels can also be investigated. According to the results of such investigation, the critical stress for weld cracking of through-thickness specimen is very small compared to that along the direction of rolling and in the transverse direction. This can be also used for analyzing lamellar tear.⁴⁾

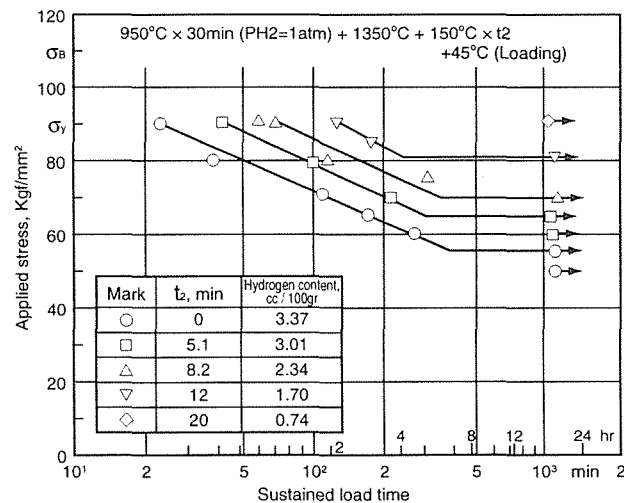


Fig.15 Result of delayed cracking test of smooth specimen for a 2 1/4Cr-1Mo steels

Weld cold cracking occurs due to hydrogen embrittlement of hardened microstructures when hydrogen diffuses at the parts where the restraint stress or strain of welded joints concentrates. The temperature at which this cracking occurs ranges from 100°C to a normal temperature, and especially the concentration of residual hydrogen at the points where the cracking occurs becomes a problem. The diffusible hydrogen of weld

continues being discharged to outside atmosphere until the temperature reaches the normal temperature during the cooling process of the weld thermal cycle, but it is necessary to investigate the critical value for crackpreventing of residual hydrogen content of weld near 100°C at which the cold cracking occurs. For this purpose, a hydrogen delayed cracking test was conducted according to the program shown in Fig.14 on smooth round factor weld bar specimens and notched round bar specimens (notch depth 1mm and tip radius 0.4mm, stress concentration $K_t=2.5$) using the weld thermal simulator. Fig.15 shows an example of the results of testing with smooth round bar specimens for a 2 1/4Cr1Mo steel.

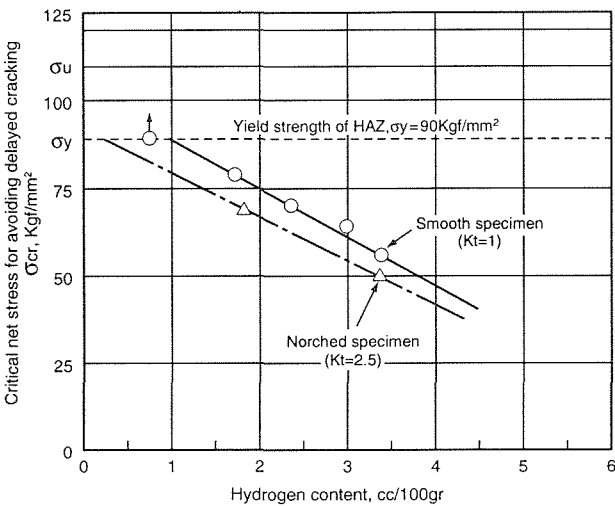


Fig.16 Relation between hydrogen content and critical stress for avoiding delayed cracking in the synthetic weld HAZ of a 2 1/4Cr-1Mo steel

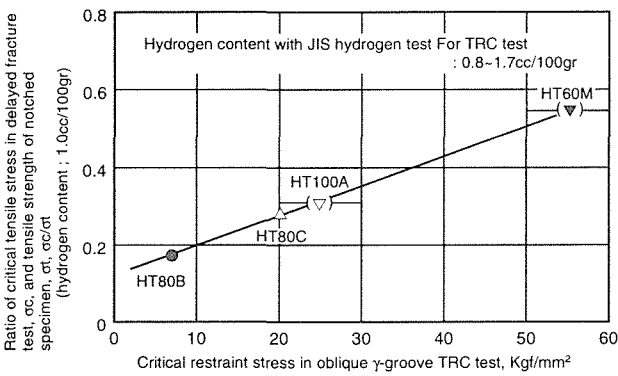


Fig.17 Relation between the σ_c/σ_t value in delayed fracture test and critical restraint stress in TRC test

Fig.16 shows the delayed cracking critical stress σ_{cr} obtained from these test results and the calculated hydrogen content in the middle part of notched round bar specimen. The σ_{cr} value decreases as using the restraint hydrogen content increases, and the σ_{cr} value of notched round bar specimens is lower than that of smooth specimens. In oblique γ -groove weld cracking test, since the restraint stress is considered to be of the order of the yield strength σ_y of HAZ, the critical hydrogen content for preventing delayed cracking at $\sigma_y=90\text{kgf/mm}^2$ is about 1.0 cc/100gr for the smooth specimen and about 0.3cc/100gr for the notched one.²²⁾

The test for delayed cracking due to hydrogen for various kinds of structural steel is also possible by preparing specimens subjected to synthetic weld thermal cycle, adding hydrogen to them by cathodic electrolysis method and then, if necessary, plating them with cadmium for suppressing discharge of hydrogen, and performing constant-load tensile test on them at a room temperature; which enables evaluation of cold

cracking sensitivity of weld HAZ near bond. In this manner, an almost linear relationship was achieved between critical restraint stress for weld cracking obtained from oblique y-groove TRC (tensile restraint cracking) test and the ratio (σ_c/σ_t) of critical tensile stress obtained from simulation test for delayed cracking due to hydrogen, σ_c and notched tensile strength, σ_t , as shown in Fig.17.

As regards evaluation of lamella tear susceptibility, for detecting the time of tear in the laminated nonmetallic inclusions due to the contraction strain during welding, it is possible by simulating the weld thermal cycles in the middle of the parallel part of a through-thickness tensile test specimen keeping its both ends restrained and mounting the AE sensor in the grip of weld thermal restraint simulator. According to the results of this test, generation of acoustic emission (AE) was confirmed from the stress levels lower than the yield strength of HAZ in the cooling process of weld thermal cycle and it was found that the tear is easy to occur near about 300 °C without regard to the kind of nonmetallic inclusions.²⁴⁾ Moreover, it was also clarified in constant load tensile test of through-thickness specimens in which hydrogen was by cathodic electrolysis, that the roles of microstructures and hydrogen are large for the propagation of lamella tear from nonmetallic inclusions.²⁵⁾

6. Reheat Cracking

Reheat cracking tends to occur along grain boundaries of coarse “rained HAZ near weld bond at the time of postweld heat treatment of HT80 class steels or Cr-Mo-V type steels, etc. As for the cause of this cracking, there are two lines of thinking. According to one, at the time of postweld heat treatment the intragranular region gets strengthened by fine precipitates of precipitation hardening elements and slip occurs preferentially at grain boundaries which leads to cracking; and according to the other, the intergranular segregation of impurities, similar to temper embrittlement, occurs and the intergranular strength decreases which leads to the cracking. Practically, reheat cracking is considered to occur due to the result of combination of both of these factors.

Using the weld thermal restraint simulator, there is circular notched loading test method during heating process, to evaluate quantitatively the susceptibility of reheat cracking. Reheat cracking occurs when the strain applied to material at the time of postweld heat treatment becomes larger than the strain capacity of the material. So it is necessary to evaluate the continuous stress relaxation and amount of strain during the heating process and holding process of postweld heat treatment.²⁶⁾ For this, thermal cycle near weld bond was simulated in a circular notched specimen (for example, specimen of outer dia.10mm, notch depth 1mm, notch tip radius 0.25mm, stress concentration factor $K_t \approx 3.4$), the specimen was heated at a constant rate (150 to 200°C/hr) up to a specified temperature (600 to 720°C) after applying initial stress load at a room temperature, and then kept for a fixed period of time (1 to 2 hours) and investigated for cracking. The critical displacement or critical stress for producing cracking was determined and these values were taken as an index of reheat cracking susceptibility.

Fig.18 shows an example of thermal stress cycles used in the reheat cracking simulation test. In this figure, zero load control and free expansion and contraction are adopted during the synthetic weld thermal cycle. In reheat treatment, temperature is raised up to specified temperature at a constant rate after applying initial stress of 5 to 50 kgf/mm², and the load is kept constant at that temperature. An example of relation between the displacement and temperature on heating of reheating process for a 2 1/4Cr-1Mo steel achieved in this manner is shown in Fig.19. The cracking shifts to the high temperature side as the initial load stress decreases, but the critical displacement becomes minimum near 600°C and shows a concave curve. Evaluation can be made with the critical initial stress where reheat cracking occurs at 600°C on heating, which is more convenient, simple and practical.²⁷⁾ The results of loading test during reheating of circular notched specimens for various kinds of Cr-Mo steel show that addition of V (0.05 to 0.25%) or Mo increases reheat cracking susceptibility by intragranular precipitation hardening, which is highest when Cr content is about 1%, but cracking is rather difficult to occur when Cr content is about 3%.²⁸⁾

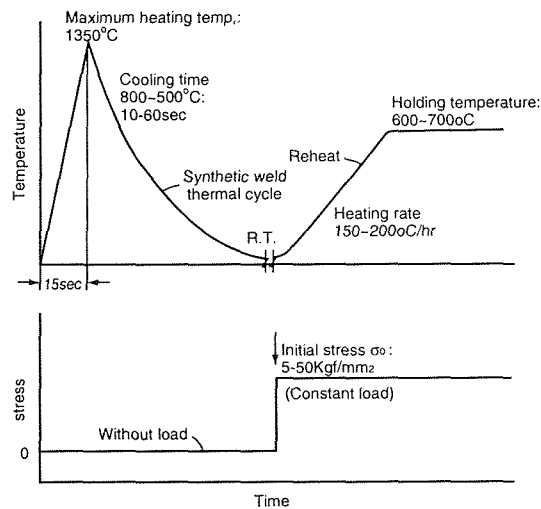


Fig.18 Schematic diagram of synthetic thermal and stress cycles in reheat cracking test

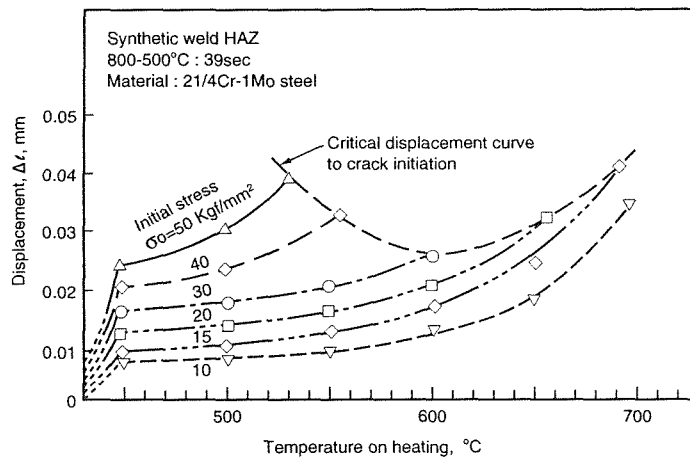


Fig.19 Relation between temperature on heating and displacement in the synthetic weld HAZ for evaluation of reheat cracking susceptibility of a 21/4Cr-Mo steel

To investigate stress relaxation characteristic at postweld heat treatment, initial strain is applied to a round bar specimen at a room temperature, the specimen is heated up to a specified temperature at a constant heating rate while keeping the initial strain along a predetermined thermal expansion curve, and held at that temperature for a certain period of time, and the stress relaxation state is measured during this process. In this case, in order to achieve a wide uniform heat zone, a high frequency heating coil of about 5 turns is used, a single bevel notch or projection for measuring displacement is applied to the specimen, and a quartz knife edge (GL about 17mm) and differential transformer are mounted. To investigate intergranular fracture strength of synthetic weld HAZ, synthetic weld thermal cycle near bond is applied to a notched round bar specimen, the specimen is heated up to a specified temperature at a constant heating rate under constant load condition and is kept at that temperature until it fractures. Fracture initiation and propagation was observed by means of a high temperature microscope, and the relation between the time or temperature when intergranular fracture occurs and the intergranular fracture stress was determined. A combination of the curves of stress relaxation characteristic and intergranular fracture strength is shown in Fig.20. The figure reveals that in a HT100 class steel, when initial stress is larger than about 22 kgf/mm², the two curves intersect, fracture occurs during the reheating process and the reheat cracking susceptibility is very high. On the other hand, in the case of a HT60 class steel, two curves do not intersect and the reheat cracking susceptibility is low.²⁹⁾

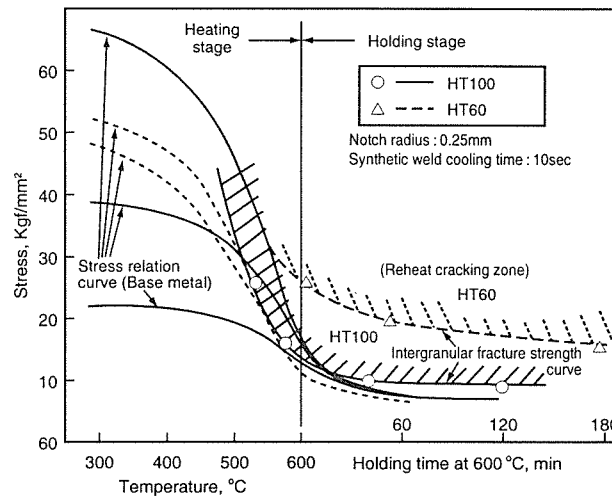


Fig.20 Evaluation of susceptibility to reheat cracking for HT60 and HT80 class steels

As for practical industrial test for investigating reheat cracking through actual welding and postweld heat treatment, there are oblique y-groove reheat cracking test and H type restraint reheat cracking test, but analysis of the reheat cracking phenomenon is difficult.

7. Final Comments

In this paper, the application of simulation test technology has been described only for the behaviour of weld HAZ near bond for structural steels, but the technology can also be used for evaluating the behaviour including fusion and solidification of weld metals and for evaluating the performance of welded joints under various environmental loading conditions.

Moreover, with suitable invents it can also be applied to alloying design in steel production and analysis of continuous casting, controlled rolling and heat treatment, and is already being used to some extent for these purposes. The equipments described here are already in regular use in main Japanese steel manufacturers, welding procedure companies and engineering companies. Further new applications of these equipments are under investigation.

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Materials Information System on the Internet

(Prediction of the Properties of Weld Heat-Affected Zones, <http://inaba.nrim.go.jp/Weld/>)

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Akira OKADA and Takayoshi KASUGAI

1. Introduction

In recent years, rapid advance has been made in the field of information processing technology using networks and computers. This progress has enabled everyone to transmit valuable information through the Internet and thus play an active role in his field.

The previous sentence is very unclear and convoluted. In the technical field of welding, the systematic organization of theories and past experiences into a database system and the availability of such a system to the public on the Internet can undoubtedly promote continuous transfer and development of welding technology. However, breakthroughs concerning how to store and retrieve data and express results are necessary for the realization of this useful system.

National Research Institute for Metals (NRIM) has been constructing a new system to predict the microstructures and mechanical properties of weld heat-affected zones (HAZ) which combines a database system of continuous cooling transformation diagrams for welding (CCT diagrams) and an expert system for computing weld thermal histories. In addition, this system employs a technique which was invented while developing another distributed database system named “Data-Free-Way” (DFW) for advanced nuclear materials [1] and others obtained through some programs of welding research at NRIM in the past [2].

This paper describes the present state of our new system for predicting the properties of weld HAZ's, which is now available through the Internet. Some problems with the database in such a system are also presented.

2. General Concept of an Information System for a Welding Procedure

Generally speaking, any welding procedure needs the following information: the material to be welded (base metal), the geometry of the joint (how to prepare its edge), the welding process, welding consumables, and procedural parameters such as weld heat input and conditions of pre/post-weld heat treatment.

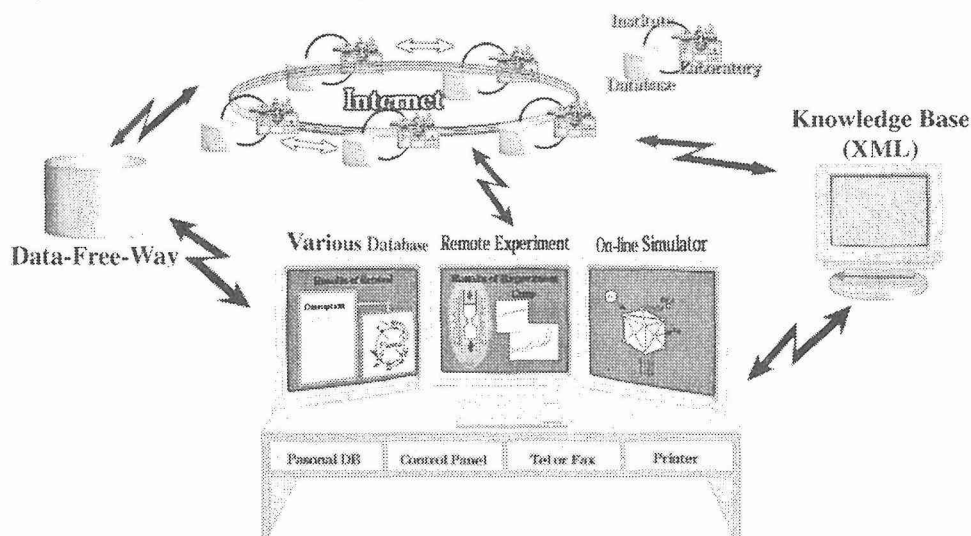


Fig. 1 Schematic representation of a materials information system.

Besides, especially in order to make sound welds, the following problems must be solved as well: yes-or-no of weld cracks caused by hydrogen, residual stresses and martensitic structures, and needless to say, service performance including the mechanical properties of the joint must be predicted in advance.

Due to these special requirements of the welding procedure, any designed system should be able to answer as many of these questions as fast and accurately as possible. Such a system may be a combination of some sub-systems, i.e., a database for the procedural data of welding, a knowledge base for past empirical data, an expert system for calculating heat flows, and thermal experiences during welding.

Last, but not least, attention should be focused on the fact that, even though a great advance in the field of database technology is surely expected in the near future, only a very limited amount of empirical information can be stored and retrieved. Thus, if possible, it is desirable to prepare a function for conducting some remote operations as is referred to elsewhere.

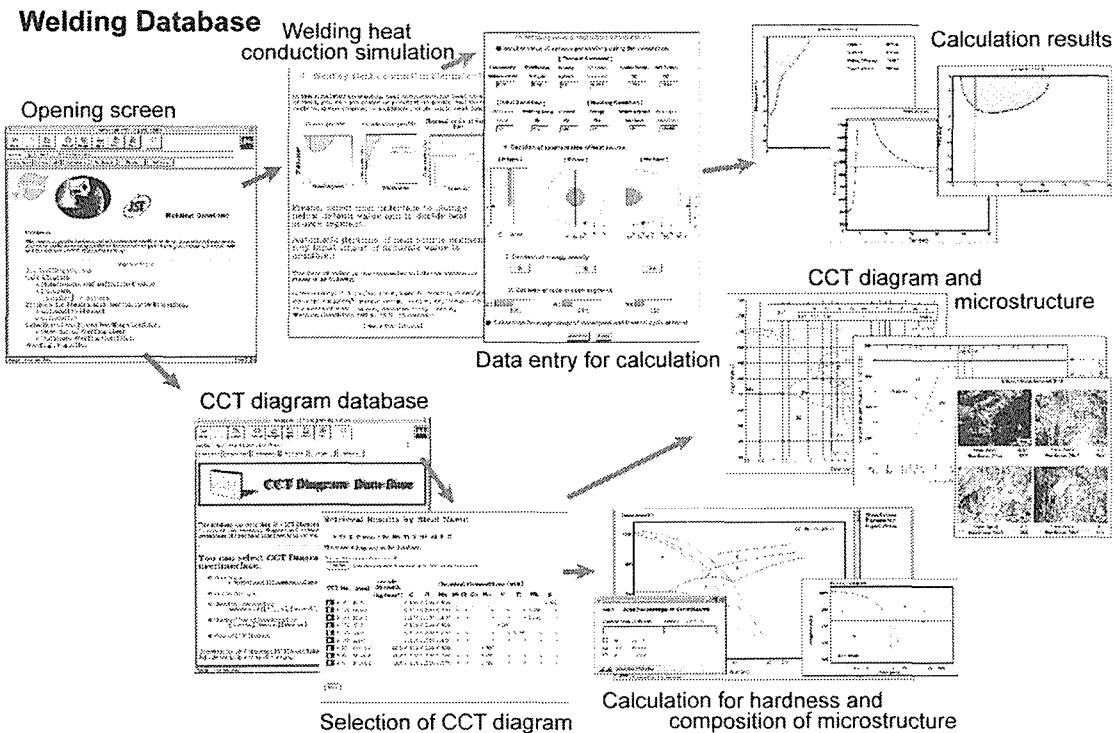


Fig. 2 Outline of the heat-conduction simulation for the properties of welded HAZ.

3. System for Predicting the Properties of Welded HAZ

3.1 Outline

The schematic representation of our distributed database system DFW for materials information on the Internet is shown in Fig. 1. A new sub-system for predicting weld HAZ properties was put in this old DFW system.

The new system is substantially an updated version of the prototype by Okada *et al.* [2], which is operated only on a personal computer and consists of mainly two parts.

One is a database, the major part of which is filled with factual information obtained at NRIM in the past, while the rest contains bibliographic information collected from various places around the world. The database stores the information not only in numerical data or letters but also in a certain form of diagrams or photographs. Users can retrieve this information in printed form, which differs little from that displayed on monitors at

present. Nevertheless, because of the difficulties entailed in expressing all the practices of the welding procedure in a still photograph, it may be necessary to store them in motion pictures with voice and sound in future. Such a sub-system, as well as the hardware for it, is currently being prepared by our group. Most of the stored information are CCT diagrams in welding steels, which show transformation temperatures and metallographic changes of weld HAZ's during cooling from some 1623 K (just below the melting temperatures of steels) under different rates of cooling as well as the resulting constitution of micro-structures and hardness. The database stores all curves of transformation starting temperatures in numerical values as well. Storing data in numerical values is most advantageous for their most efficient use and expression throughout the system. In the present system, however, data are not yet linked directly between this CCT diagram database and the Weld thermal history simulator presented later. Further consideration may be necessary for finding the best way to store data.

The other is an expert system for simulating the temperature distributions around the part being welded. Hereafter, this system is referred to as "Weld thermal history simulator".

Users who have to make a final decision for each of the procedural parameters often need more detailed and concrete information than the very things retrieved from the database. To meet such a need, in the present system, some functions for making remote experiments or remote maintenance are prepared in advance.

The whole system can be used anywhere in the world where an Internet Browser (Netscape, Explorer, etc.) is available. Figure 2 illustrates the outline of this system and gives a guide map to access the CCT diagram database, the Weld thermal history simulator, or an animated program for beginners on how to utilize them.

3.2 CCT Diagram Database

3.2.1 Outline

For utilizing CCT diagrams through the Internet, data are managed by using the Oracle, which is connected with the Oracle Web. They are retrieved by accessing the Web through an Internet browser. This operation is made by clicking the mouse or hitting digit keys. Instructions on the screen make the operation easy.

The database is featured by the ability to connect the stored data with image files or some programs outside the database such as the Weld thermal history simulator.

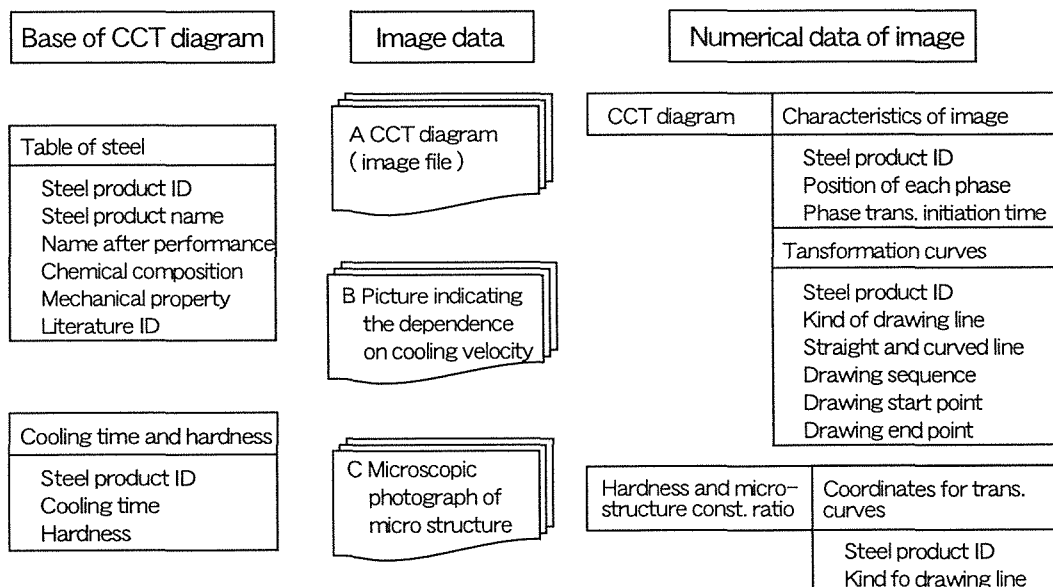


Fig. 3 Data structure of a CCT diagram database.

3.2.2 Stored Data and their Structure

The stored data include the chemical composition and mechanical properties of the said steel, its CCT diagram, the graph attached to the diagram, which shows the change in HAZ hardness, and also that in micro-structural constitutions with cooling time, the photo-micrographs of HAZ, the data in numerical values and letters directly connected with any CCT behavior of the steel, and data somehow associated with it.

Figure 3 explains their structures. The table for the product forms of steels consists of the product ID, its proper, popular, or technical name, another name after some processing, its chemical composition, and its mechanical properties, while that for cooling time and HAZ hardness contains its product ID and the critical (shortest) values of cooling time necessary for making phase transformations of the steel. The database stores CCT diagrams and the attached graphs showing the change in HAZ hardness and microstructure with cooling time in two data forms, i.e., image and numerical data. As mentioned before, experts in welding should be relatively familiar with these images. On the other hand, needless to say, numerical data are essentially suitable for making experimental formulas of the HAZ hardness or ratio of micro-structural constitutions vs. cooling time. Thus, quantitative information of HAZ properties can readily be obtained in advance to the welding procedure by substituting the predicted time of cooling into these formulas.

3.2.3 Expression For retrieval

For retrieving CCT diagrams, such items, measures, and parameters may be thought of as the name of the steel to be retrieved, its properties, application, chemical composition, micro-structure, and, in some cases, the morphology of the phase transformation and its rate. Moreover, as a preliminary step of retrieval in the present CCT diagram database, several of the CCT diagrams, which are presumed to meet the user's requirements, are listed by inputting some of these items, measures, and parameters. Here, the morphology of the transformation and its above-mentioned rate are substituted briefly by the type (shape) of the CCT diagram and the critical cooling time at which the transformations start. Then, the user finally selects the most appropriate one to be displayed from those retrieved firstly.

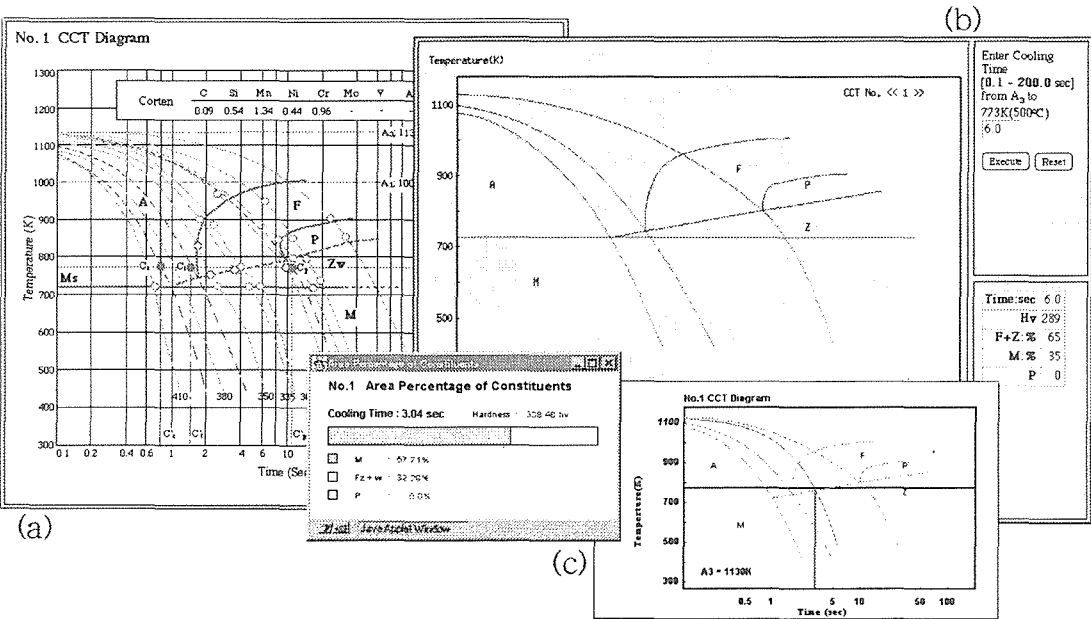


Fig. 4 Original CCT diagram expressed by image data (a), that recomposed by numerical data (b), and another expression for retrieval of numerical data (c).

(b) is recomposed of the numerical data stored in the database. In order to express the CCT diagram more simply, only its essence is given here. Since such re-composition needs only a limited number of numerical data, it results in a shortened time of retrieval as well as a reduced load on the network. In addition, several CCT diagrams can be compared at the same time.

Another attempt for expressing the retrieval of numerical data was made by adopting the JAVA language. An example of such retrieval is shown in (c). This makes it possible to express simultaneously any numerical data such as HAZ hardness and micro-structural constitutions for a specified rate of cooling.

For HAZ micro-structures, users can exhibit their photographs on a display either one by one or as a set.

3.3 Weld Thermal History Simulator

3.3.1 Inputting Data

Computations of heat flows require thermal properties such as the thermal conductivity and specific heat of materials. The melting temperatures and Ac1 transformation temperatures of steels are also necessary for computing the locations of molten pools and weld HAZ's, respectively. In addition, computations require such procedural parameters of welding as the arc current, arc voltage, welding speed preheat temperature, and dimensions of the work to be welded. Figure 5 shows the screen for inputting these data in the present simulator. Most of the data are input by hitting keys. In addition, by operating his mouse, the user can select other information related to the heat source such as its shape and energy density. On the screen, boxes for setting conditions and patterns representing features of heat sources are laid out for inputting data with ease. Complete inputting, however, requires that the user of the system have some degree of expertise of welding.

<< Welding Heat Conduction Simulator >>

● Input of value of various parameters using the calculation.

[Thermal Constant]					
Conductivity (cal/sec.cm.K)	Specific Heat (cal/g.K)	Density (g/cm ³)	Diffusivity (cm ² /sec)	Fusion Temp. (K)	Ac1 Temp. (K)
0.05	0.12	7.8	0.053	1773	1023

[Initial Condition]			[Welding Condition]		
Thickness (mm)	Ambient Temp (K)	Current (A)	Voltage (V)	Welding Speed (cm/min)	Heat Input (J/mm ²)
10	293	200	15	15	12000

1. Decision of segment size of heat source.

[D-type]

D: 10mm

[R-type]

R: 5mm

[He-type]

Ex: 10mm Ey: 5mm

2. Decision of energy density.

☐ D

☐ R

☐ He

3. Decision of ratio of each segment.

D:

R:

He:

● Calculation for morphology of molten pool and thermal cycle at bond

R - Type

D - Type

Screen for setting of energy density of heat source.

Fig. 5 Data input screen of the thermal properties of materials for thermal cycle prediction using the heat-conduction simulator.

With a view to making a more usable database, especially for non-experts of welding, we are now collecting additional data of heat sources applicable for different welding processes and welding conditions.

3.3.2 Method of Computations

Numerical computations, which are necessary for simulating transient or quasi-stationary distributions of temperatures around the part being welded, start by inputting the data stated above, pushing the button that reads "start computation", and then, using a program sent from the Web server. The program is written in the JAVA language. Thus, the computations run without a platform. They are executed by taking the most suitable measure, or in some cases, by combining suitable ones from empirical equations reported in the past, analytical solutions, or an iterative finite difference method.

3.3.3 Expression of Computed results

The results of computations are expressed as shown in Figs. 6 and 7. Figure 6 shows the contour line of the melting temperature and that of the A_{c1} temperature on the transversal (perpendicular to the weld centerline) cross-section of a weld, which give the profile of a molten pool and HAZ, respectively. In Fig. 7, the weld thermal history at + point in Fig. 6 and that at the crossing point of two fine lines in the same figure are drawn in two curves. Inputting the coordinates of such points is achieved by only pointing and clicking with the mouse. A slight but not negligible difference between the two is seen, especially around their peaks.

Needless to say, the HAZ hardness and micro-structures of a steel result from its thermal history during welding and its chemical composition. In practice, they correspond to the time of cooling from A₃ transformation temperature to 773 K (500 °C). As a matter of course, every computed curve makes it possible to predict HAZ hardness and micro-structures for each specified steel. In brief, the CCT diagram database and Weld thermal history simulator make it possible to predict the HAZ hardness distribution for a steel.

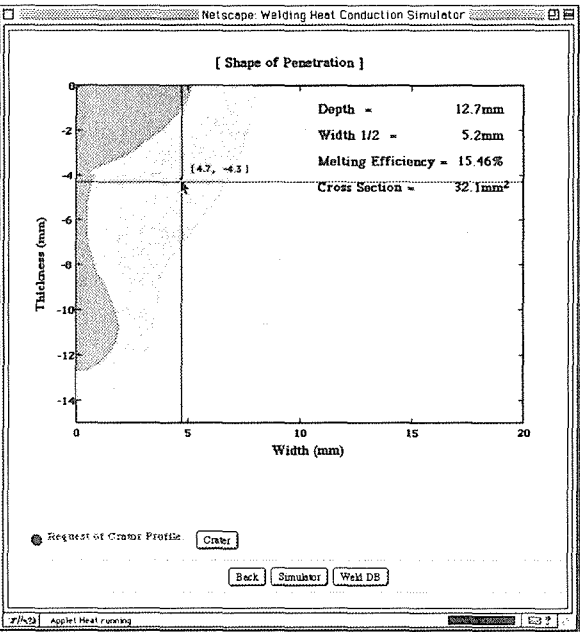


Fig. 6 Shape of molten pool and HAZ.

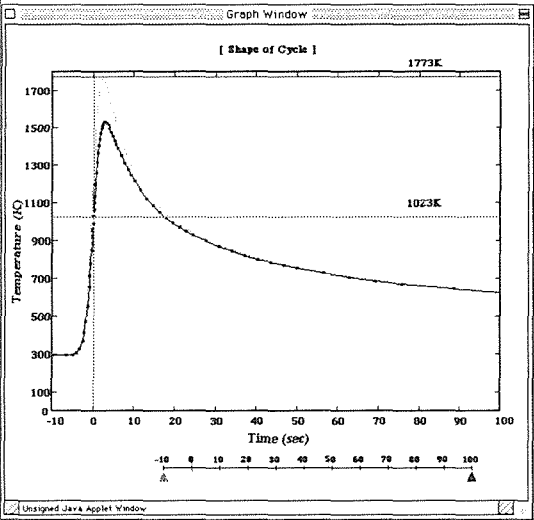


Fig. 7 Thermal history curve at + point and cross lines shown in Fig. 6.

3.4 Prediction of Weld HAZ Properties

3.4.1 Flow of Prediction

The present system has a database subsystem in the computer to memorize data temporarily, according to the flow of calculation, as shown in Fig. 8.

First of all, we select a steel, the chemical composition of which is the closest to that of the steel to be predicted. Then, we retrieve the CCT diagram of the selected steel. The retrieved CCT diagram and all the data concerned with it are sent into that subsystem automatically. In these data, we find a graph which shows the change in Vickers' hardness (load: 9.8 kN) and that in the ratio of micro-structural constitutions (area %) with cooling time from Ac3 transformation temperature to 773 K (500 °C). Figure 9 shows a typical example of such graphs. Experimental formulas of HAZ hardness and ratio of micro-structural constitutions as a function of cooling time are also stored temporarily in that subsystem.

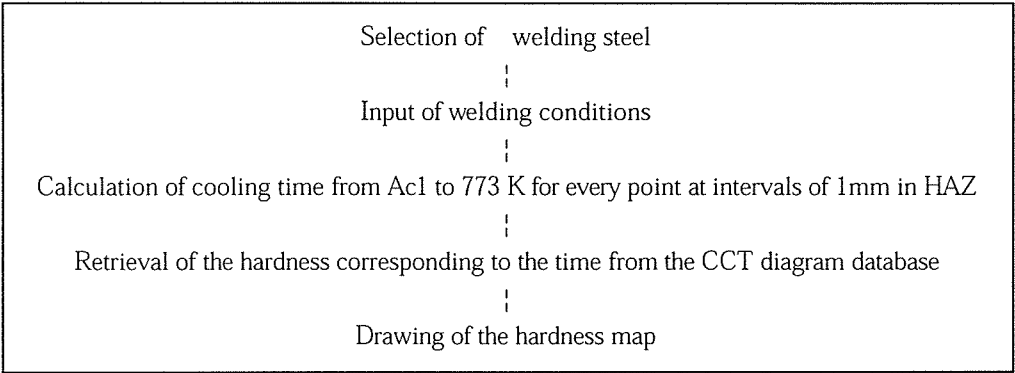


Fig. 8 Flow-chart for the prediction of weld HAZ properties.

Second, thermal properties of the selected steel and procedural parameters of welding are input into the Weld thermal history simulator. Computations of cooling time were executed over the whole HAZ. Finally, we get the contour lines of HAZ hardness by referring the computed cooling time at each point to the formula of HAZ hardness.

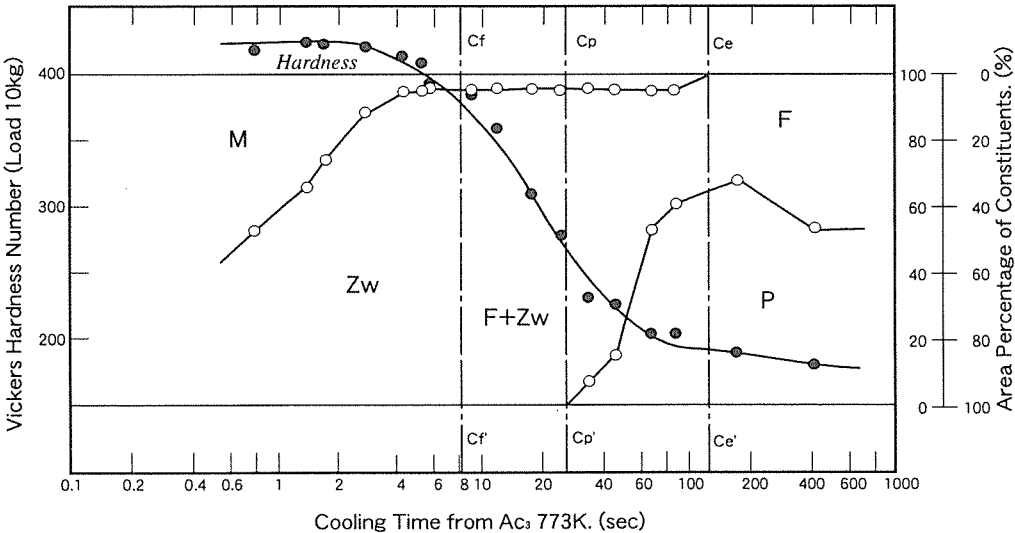


Fig. 9 Change in Vickers' hardness and ratio of micro-structural constitutions with cooling time from Ac3 transformation temperature to 773 K.

3.4.2 Hardness Distribution Map

Figure 10 shows an example of hardness contour lines on the transversal cross-section of a bead weld. In the figure, the white-washed and semi-elliptical zone is that of weld metal, and its outside is the HAZ. Hardness, which is the highest just adjacent to the bond line, gradually lowers towards its base metal zone. The reason for this is the nature of heat conduction, in which the shorter distance from the heat source causes a higher peak temperature and faster cooling.

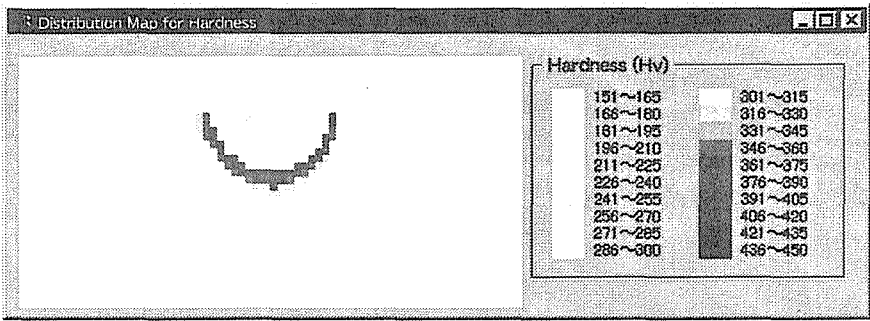


Fig.10 Hardness contour lines on a cross-section of weld.

Thus, all the data retrieved here converge into a hardness distribution map. Usually, it takes a long time and much effort to get such a map by processing measured data only. The present system of prediction, however, achieves the same purpose quickly and with ease. In Fig. 10, the map is ruled into 1-mm squares. Finer squares, which are available, allow for more detailed and delicate information for predicting the geometry and properties of HAZ's; this is helpful to check any overlooks and to make welded joints of higher quality.

This subsystem for making HAZ hardness distribution maps is a combination of the subsystem of the CCT diagram database and that of the Weld thermal history simulator. It is currently being rearranged for more diversified kinds of steel products and more extended ranges of procedural parameters of welding. Before long, this third subsystem will be available to the public on the Internet. It is believed that the release of this system will contribute to the circulation of technical information of higher levels. Another subsystem for making HAZ micro-structural constituent distribution maps will also be available in the future.

4. Future Problems

Our next target of development is a system for rapid exhibitions of images, maps, and photographs. After realizing it, the system is to be improved for three-dimensional computations and exhibitions.

Further acquisition of data is most essential. Few CCT diagrams of advanced materials have been input in the recent past. Our database will be completed by supplying such lack, helping us to understand the historical process of materials technology and predict future materials. A database for welding consumables such as welding rods and wires may be necessary, especially for matching the properties of weld metal to those of base metal. Databases for service performances and case studies on accidental fractures of welded joints components and structures are also future problems.

5. Concluding Remarks

To achieve state-of-the-art welding, it is desirable to increase the mutual utilization of information between the fields of materials and welding. The new system presented in this paper represents such an effort. It combines a database system of continuous cooling transformation diagrams for welding and an expert system for computing weld thermal histories, both of which have been accumulated and developed at the National

Research Institute for Metals over several years.

The work was conducted as part of the "Research Information Database Service Project" sponsored by the Japan Science and Technology Corporation.

References

- [1] FUJITA, M., KURIHARA, Y., SHINDO, M., YOKOYAMA, N., TACHI, Y., and IWATA, S.: "A Distributed Database System for Mutual Usage of Material Information (Data-Free-Way)", ASTM STP1311, 1977. pp.249-260.
- [2] See for example, OKADA, A., KASUGAI, T., and HIRAOKA, K.: "Heat-Source Model in Arc Welding and Evaluation of Weld Heat-Affected Zone", Trans. ISIJ, Vol. 28, 1988, pp.876-882.

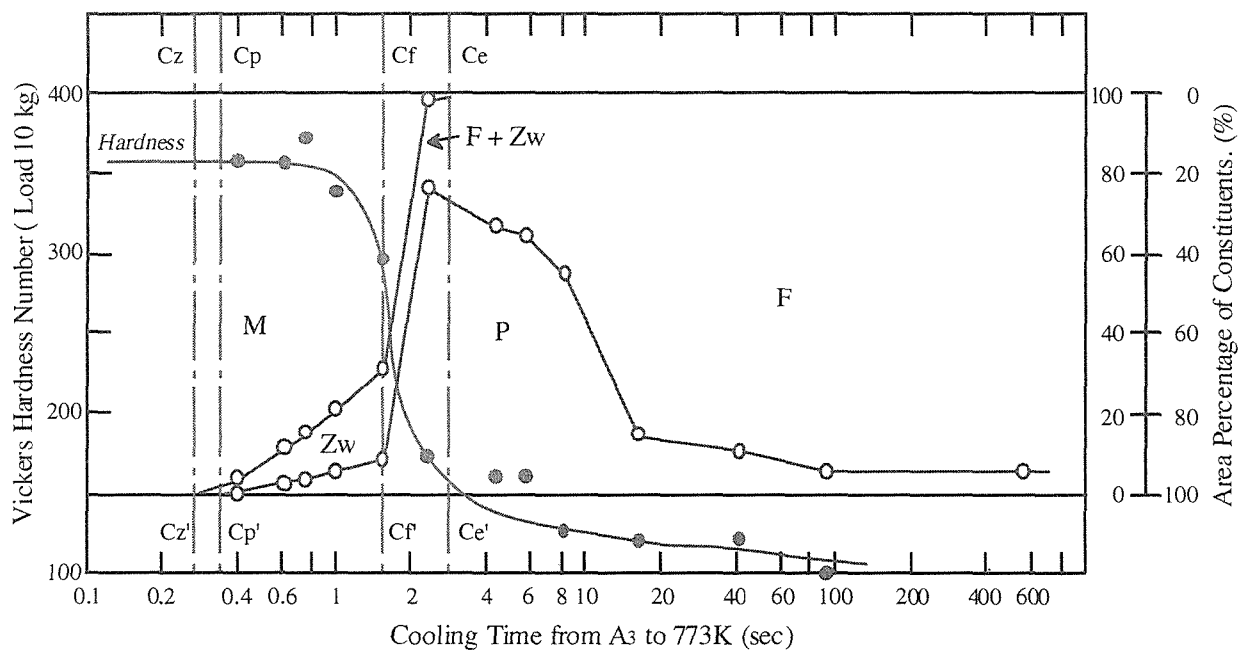
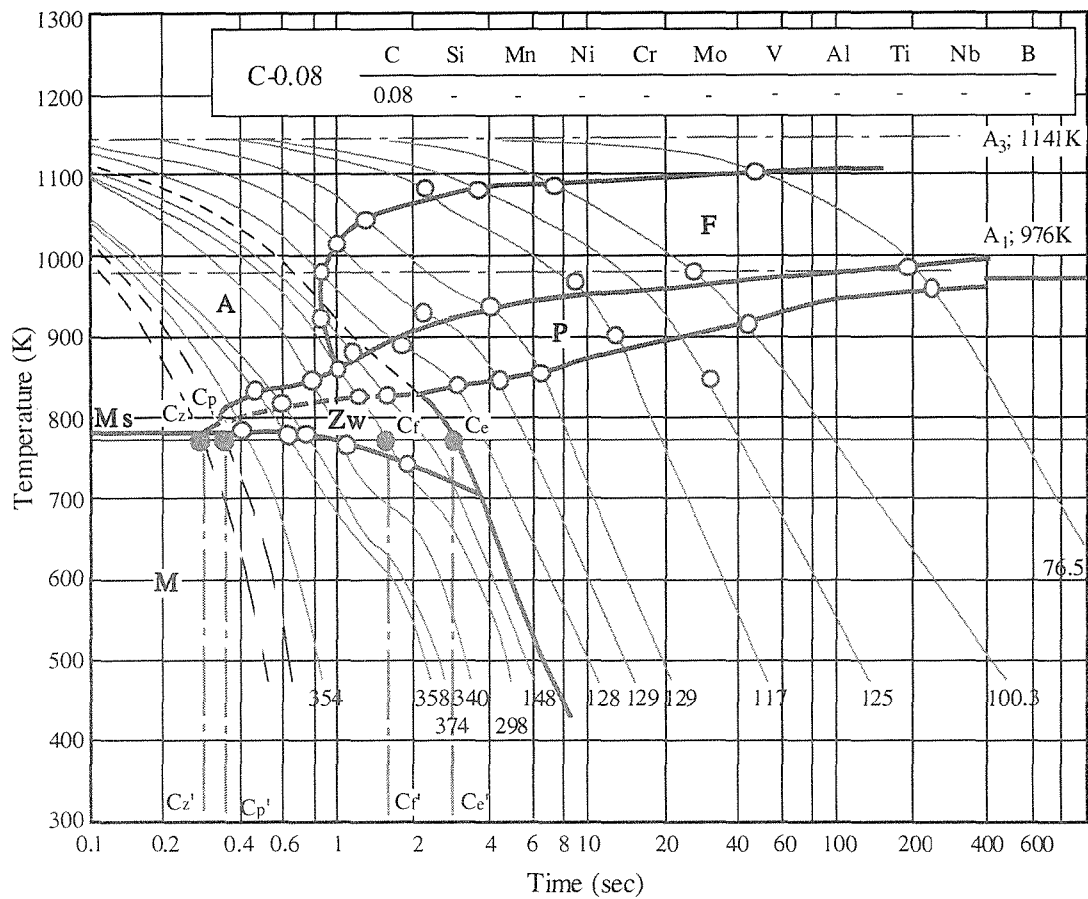
Note for Symbols used in CCT diagrams

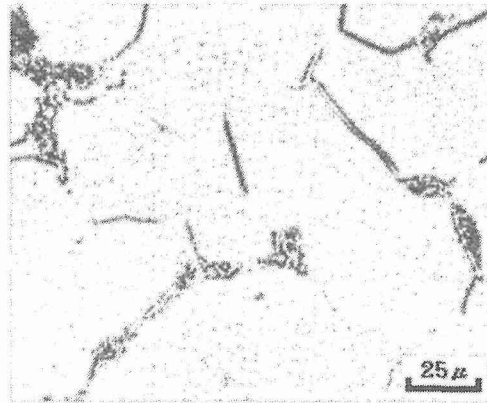
A	Austenite
F	Ferrite
F+Zw	Ferrite + Bainite
P	Pearlite
Zw	Bainite
M	Martensite
Cz—Cz'	Starting time of bainite transformation on cooling from A ₃ or Ac ₃ to 773K
Cf—Cf'	Starting time of ferrite transformation on cooling from A ₃ or Ac ₃ to 773K
Cp—Cp'	Starting time of pearlite transformation on cooling from A ₃ or Ac ₃ to 773K
Ce—Ce'	Ending time of all transformations

CCT Diagram for Welding

Simple Fe-C-X Alloy
Fe-C Alloy

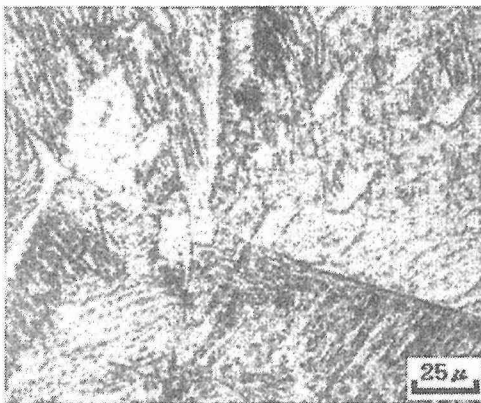
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	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
C-0.08	0.08	-	-	-	-	-	-	-	-	-	-	-	-	-	2	1
C-0.15	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	4	1
C-0.3	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-	6	1
C-0.38	0.38	-	-	-	-	-	-	-	-	-	-	-	-	-	8	1
C-0.53	0.53	-	-	-	-	-	-	-	-	-	-	-	-	-	10	1
C-0.94	0.94	-	-	-	-	-	-	-	-	-	-	-	-	-	12	1
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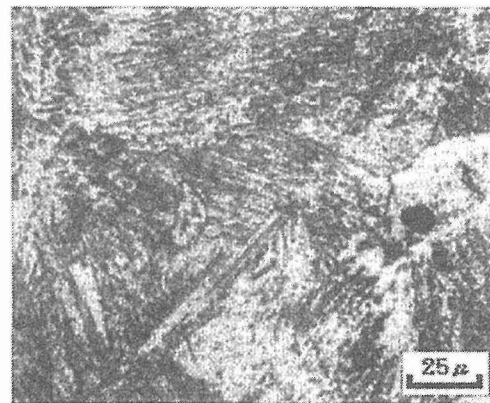


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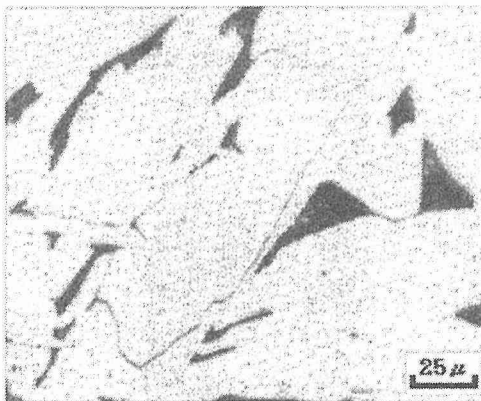
Hv 67.6



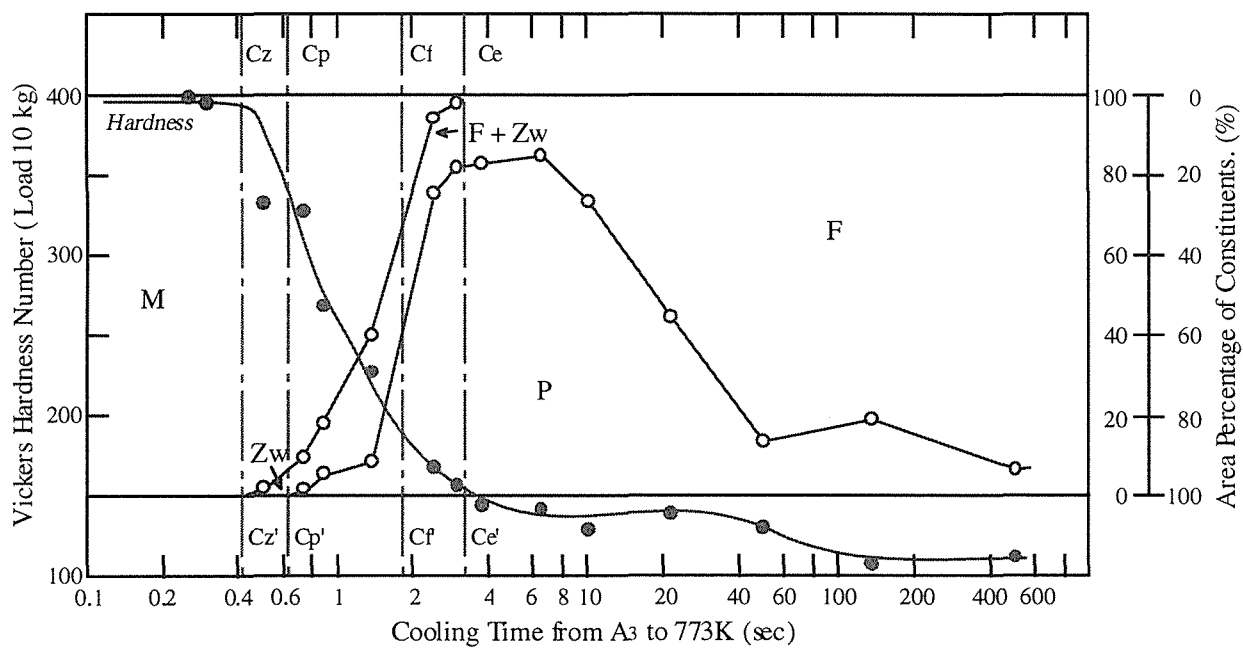
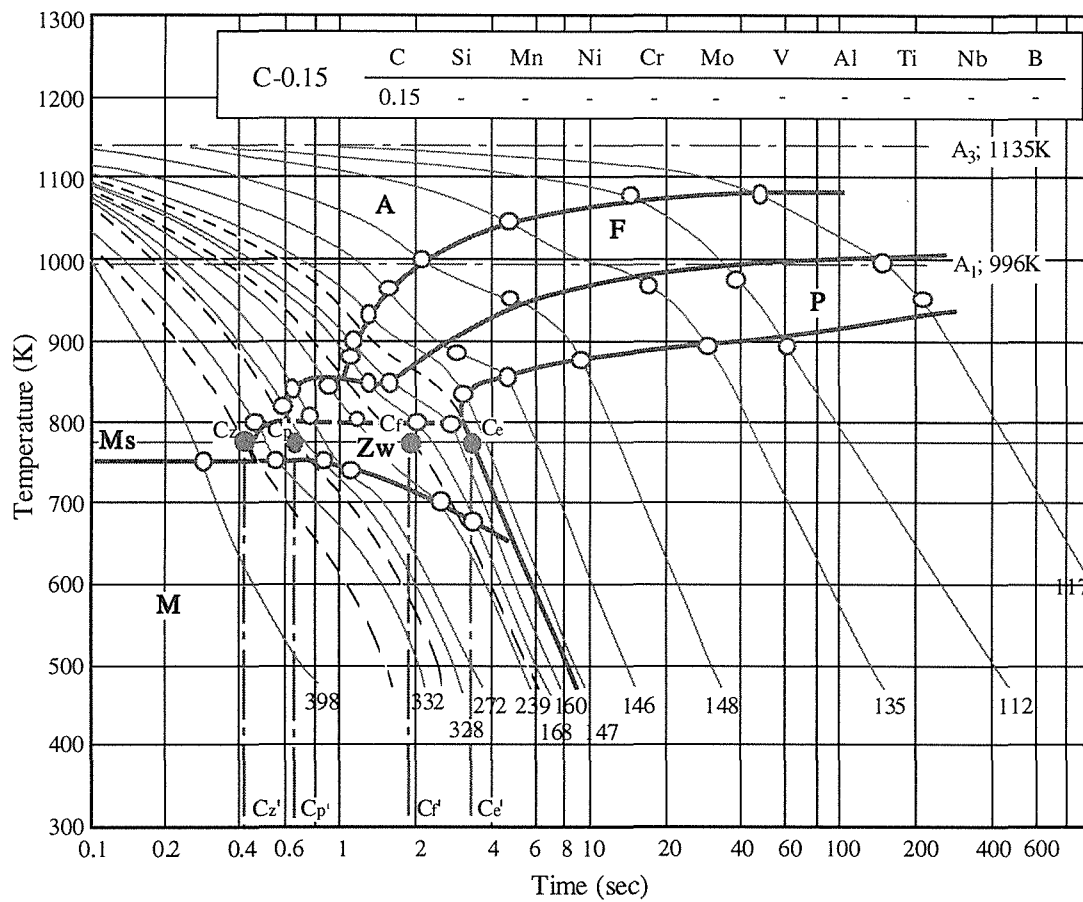
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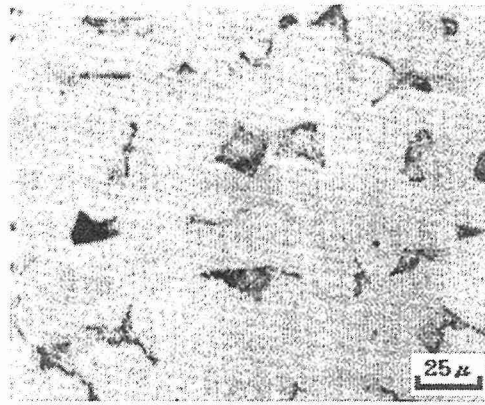


Time 1.66sec Hv 298



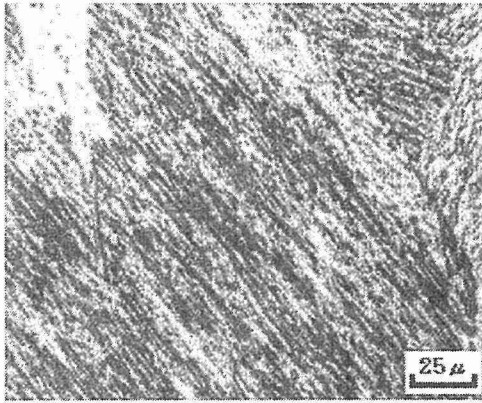
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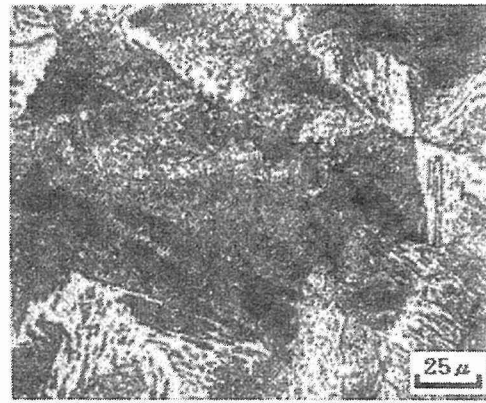


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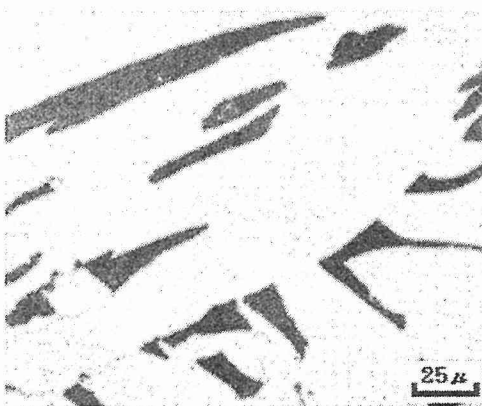
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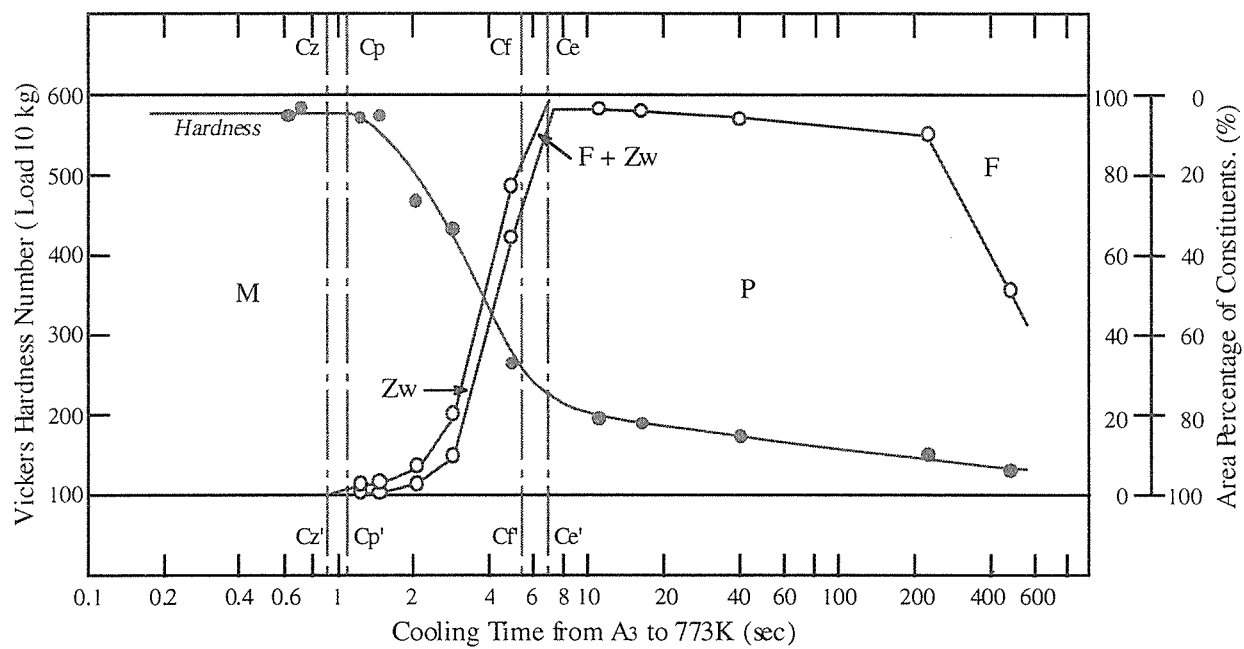
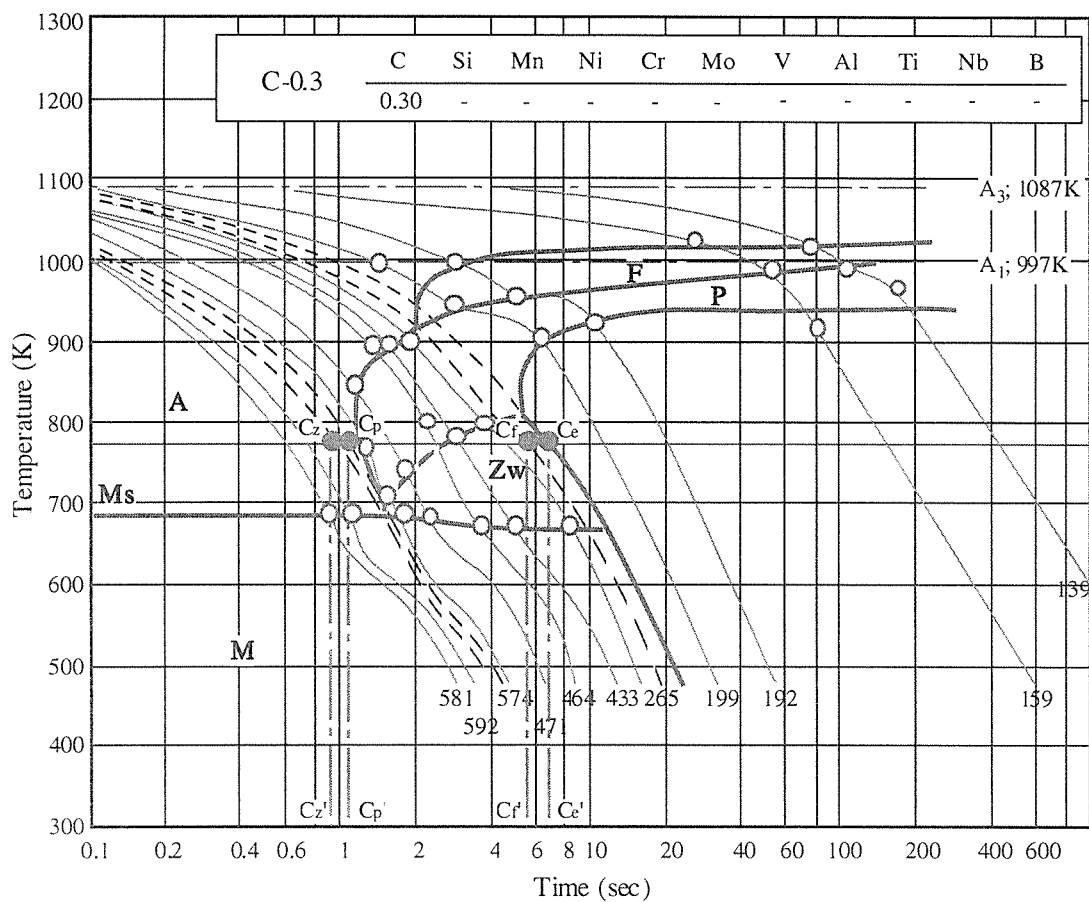
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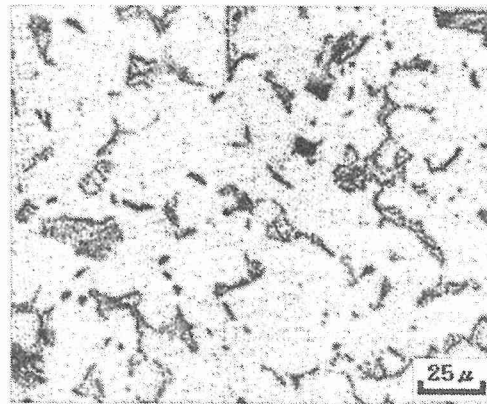


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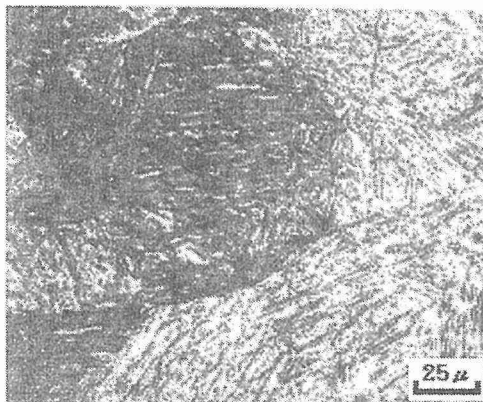
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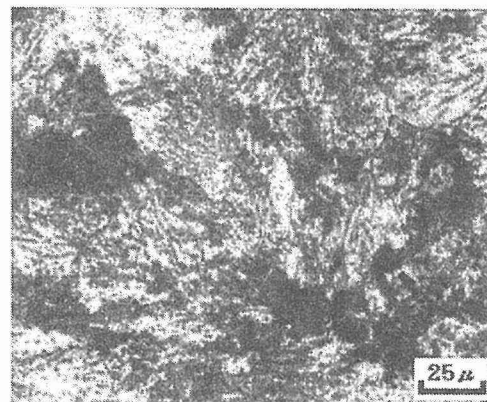
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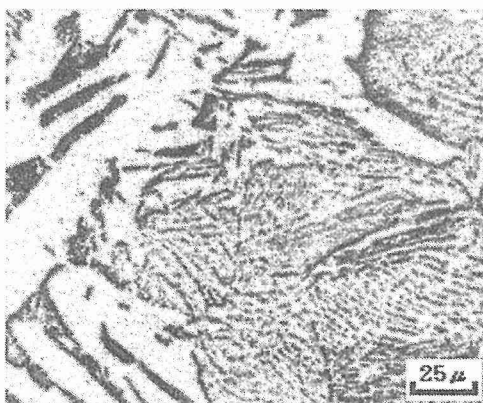
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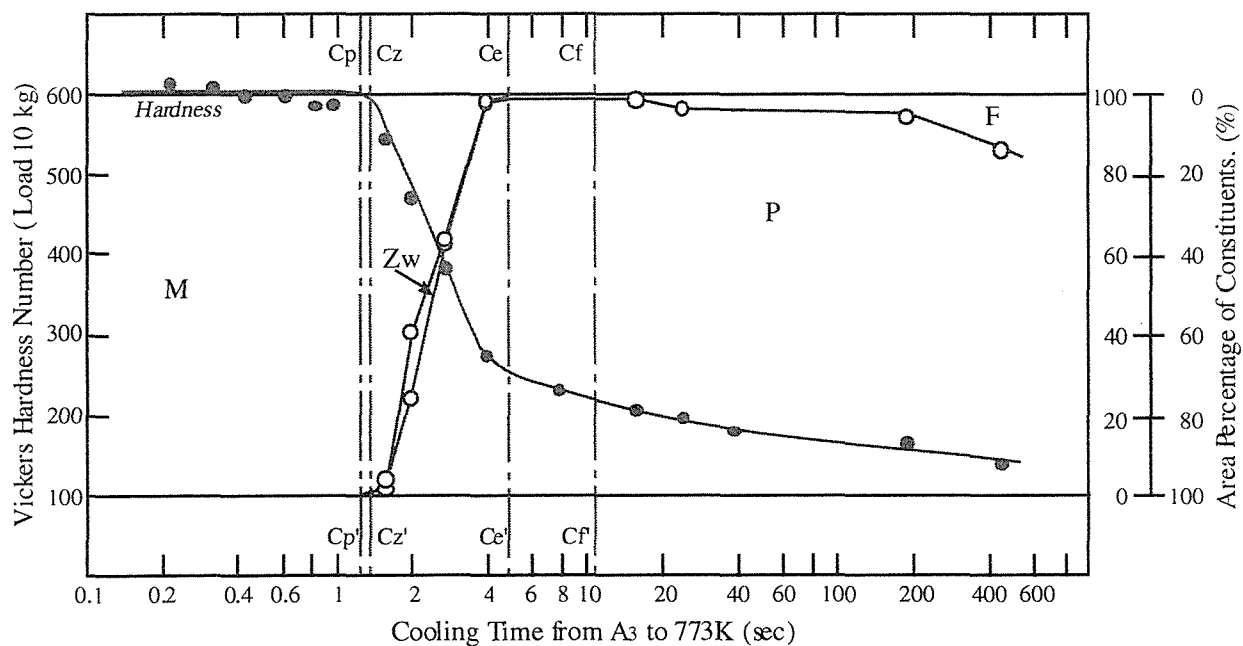
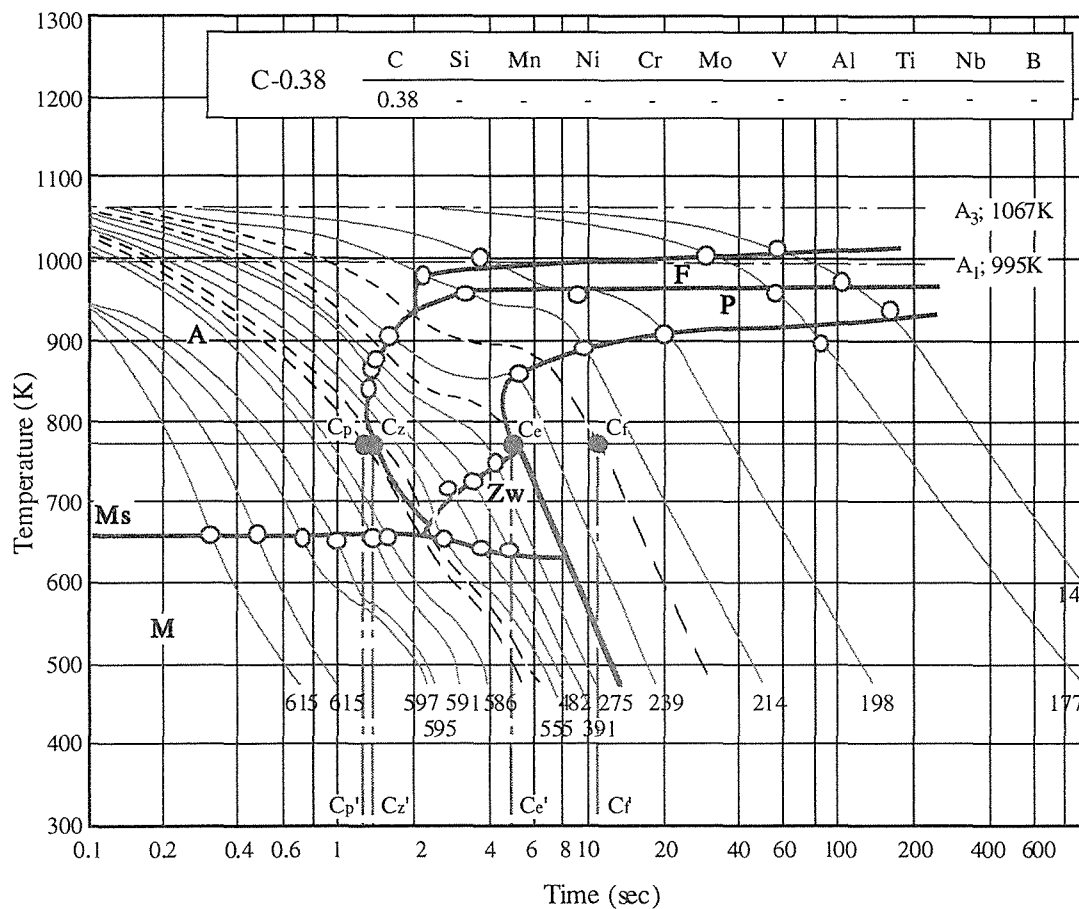
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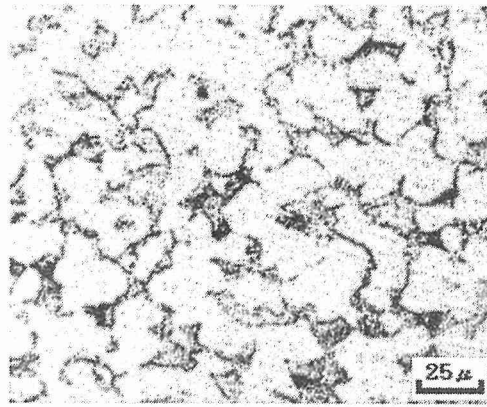
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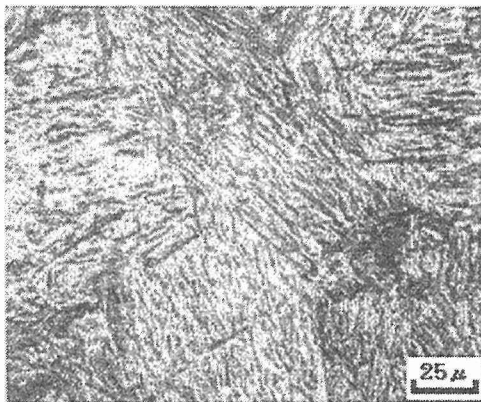
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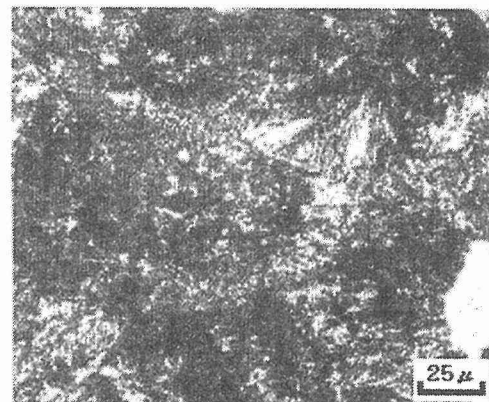
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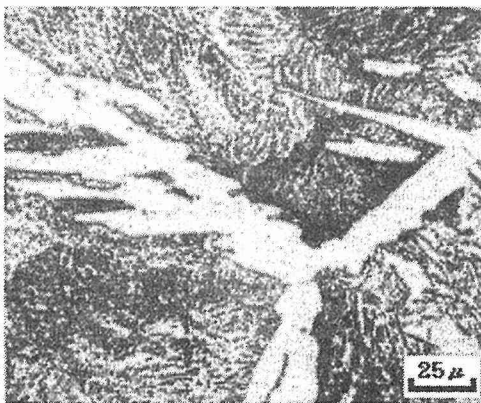
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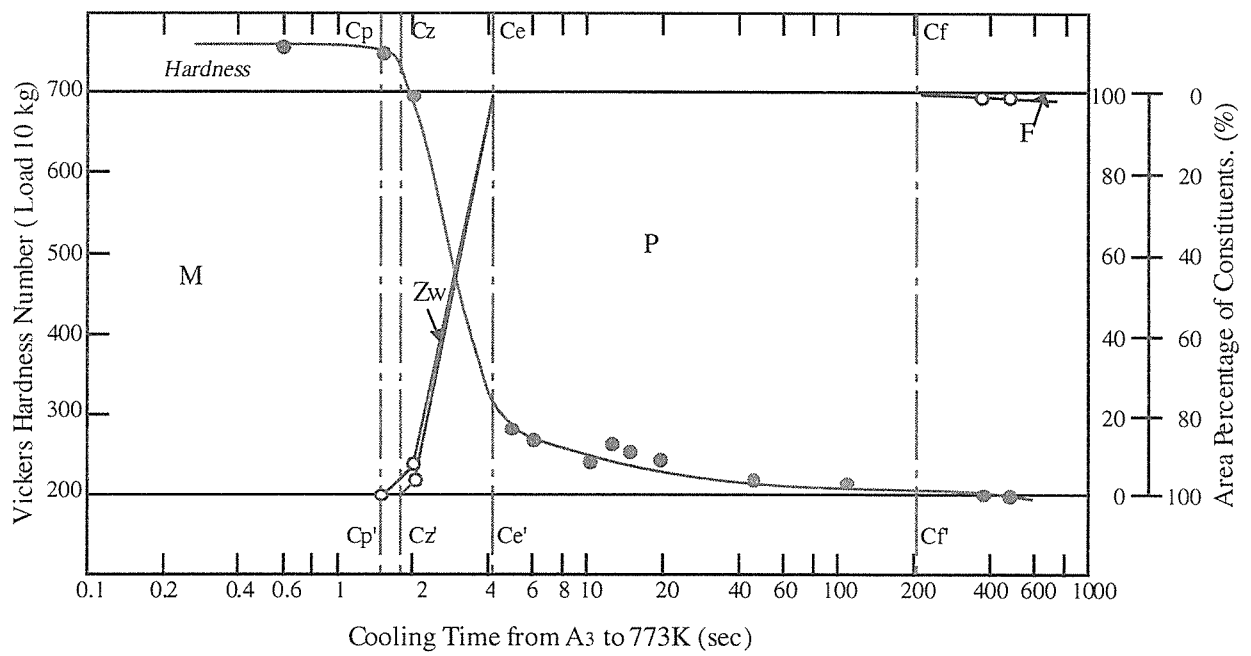
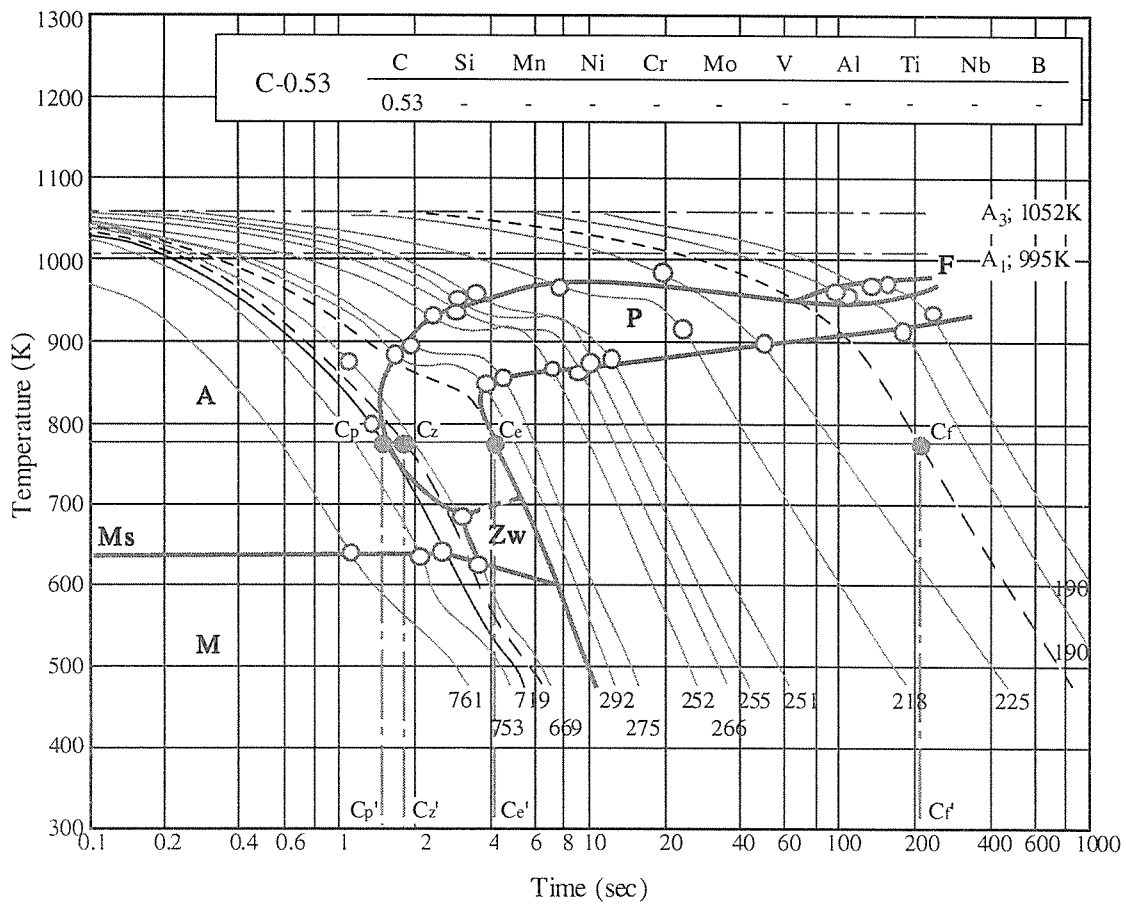
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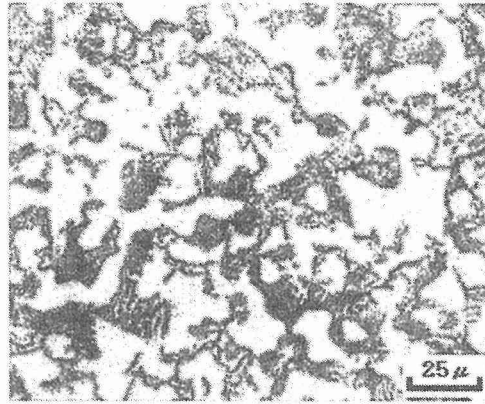
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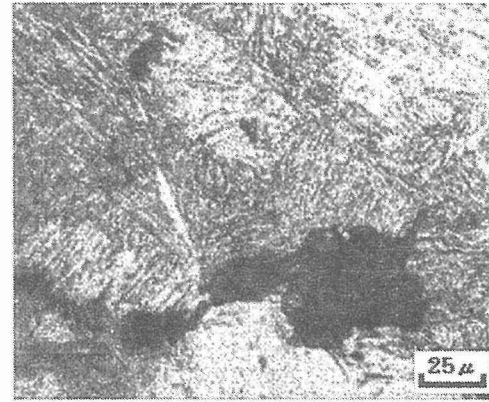
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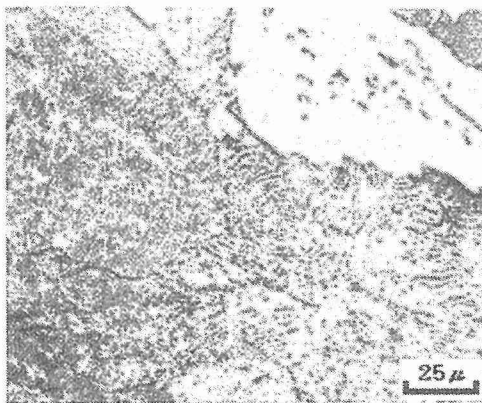
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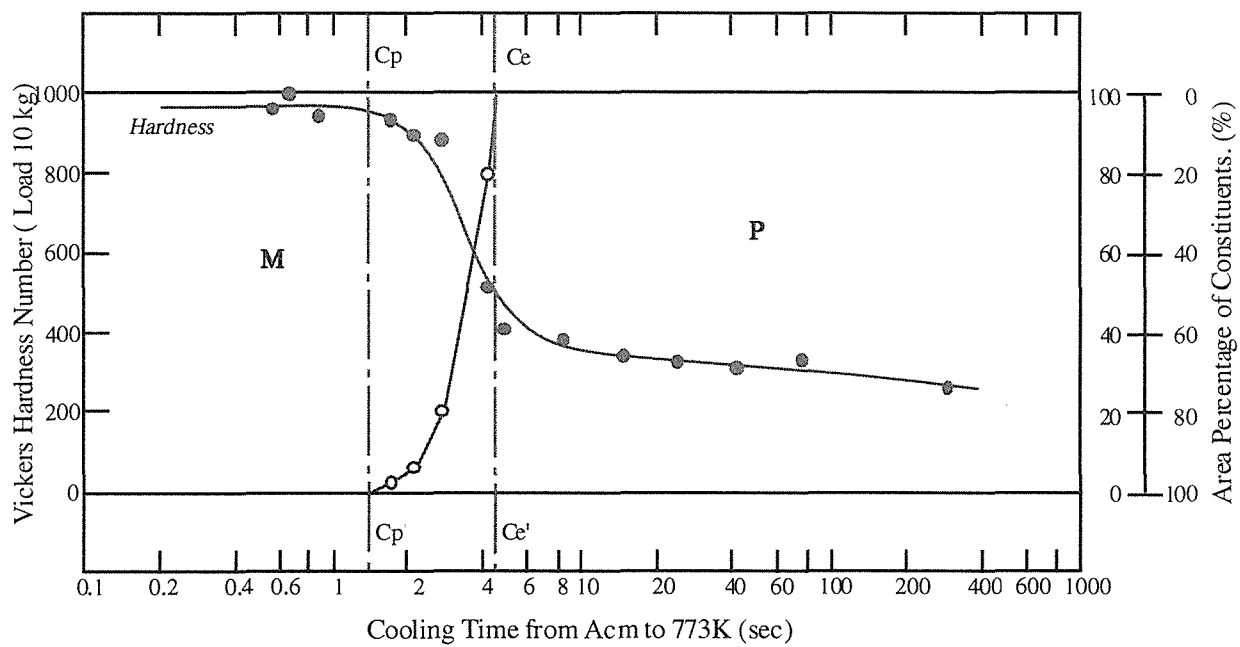
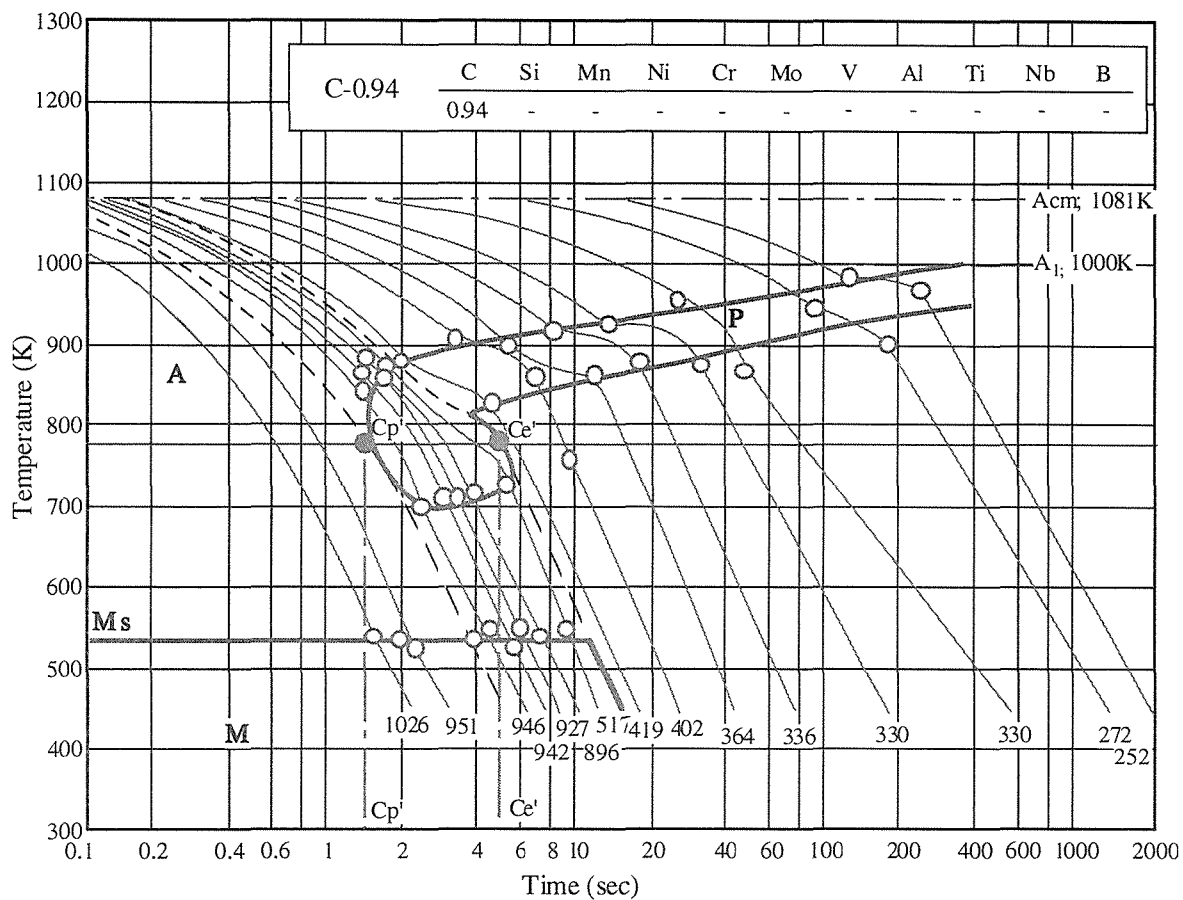
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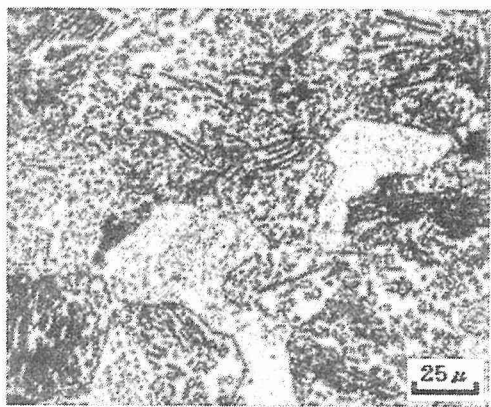
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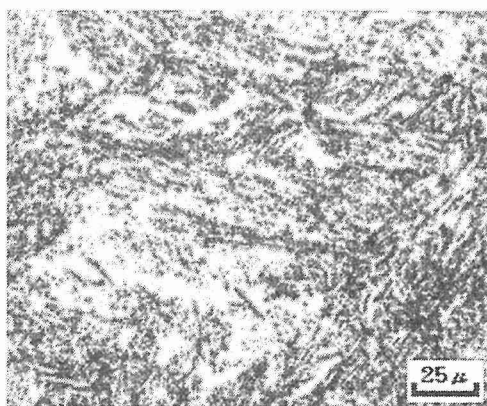
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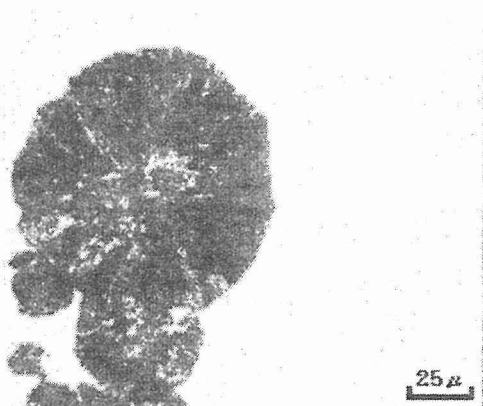
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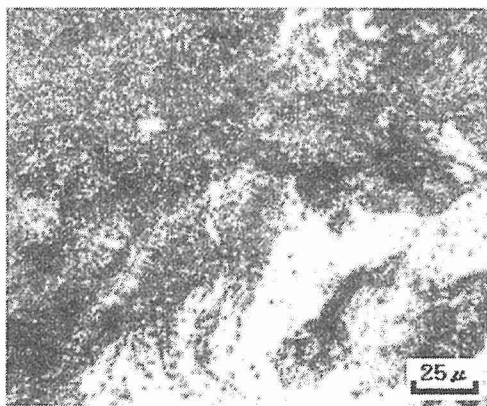
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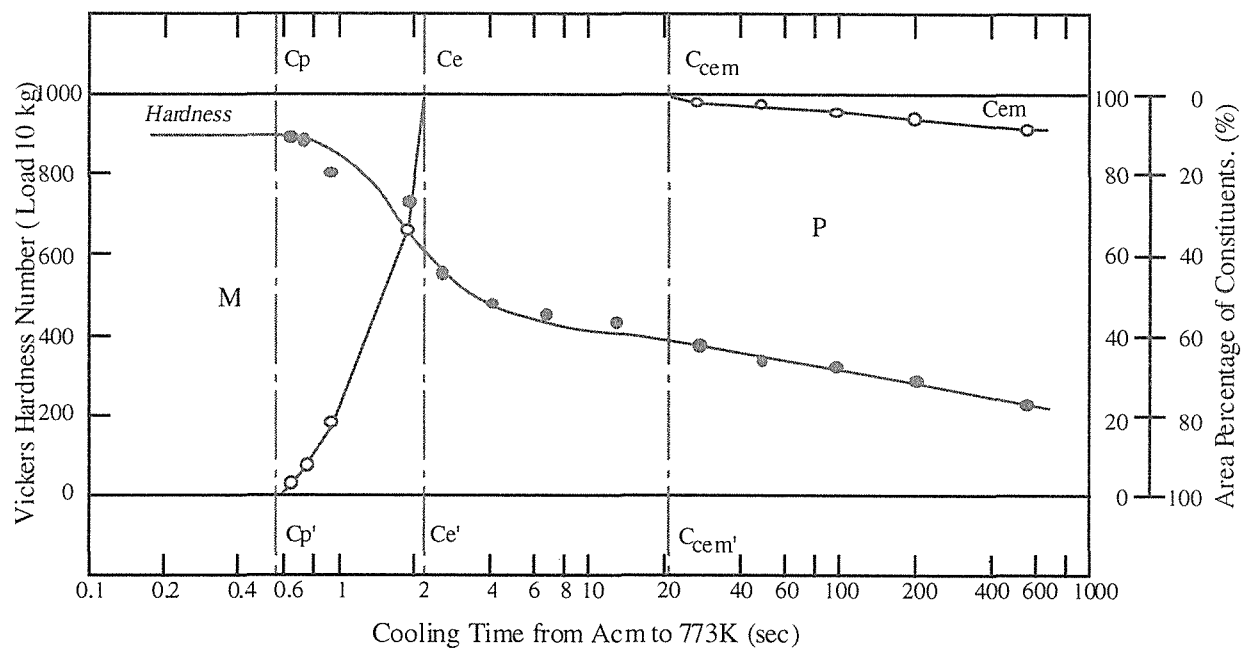
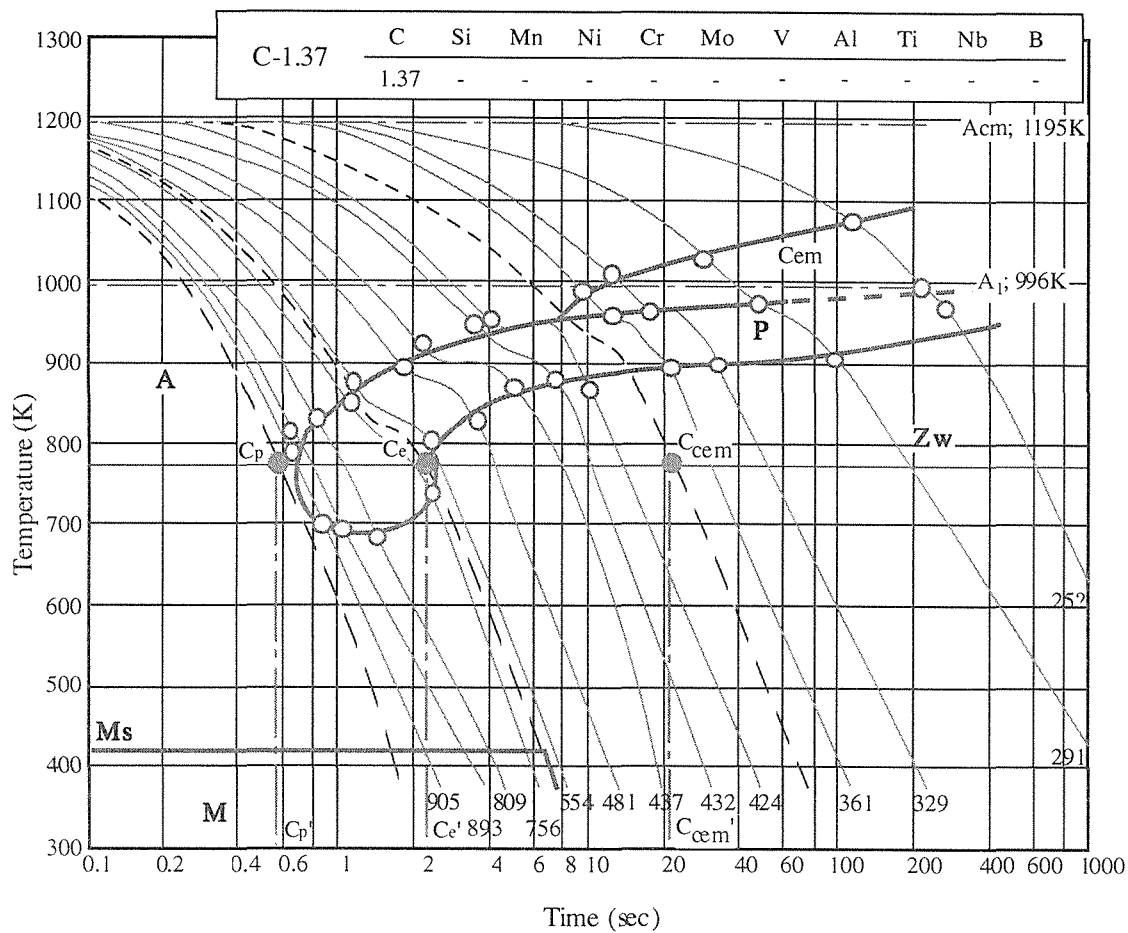
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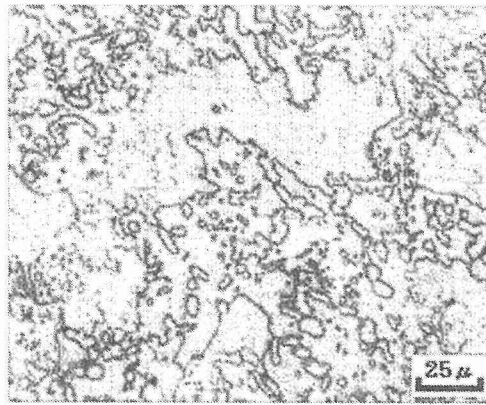
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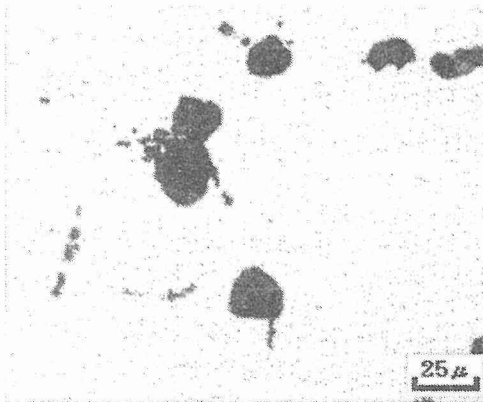
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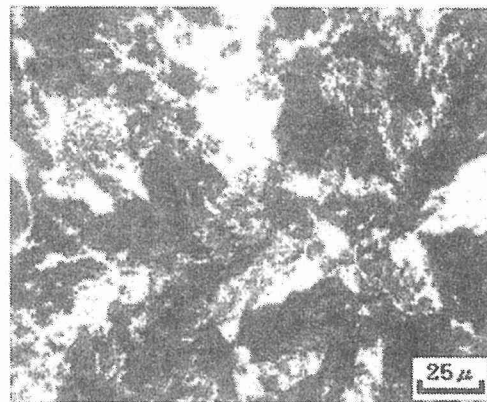
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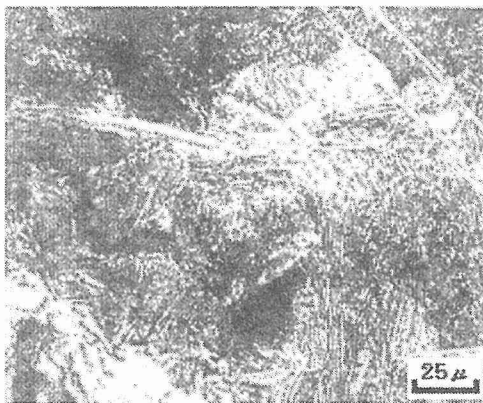
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Time 4.3sec

Hv 481

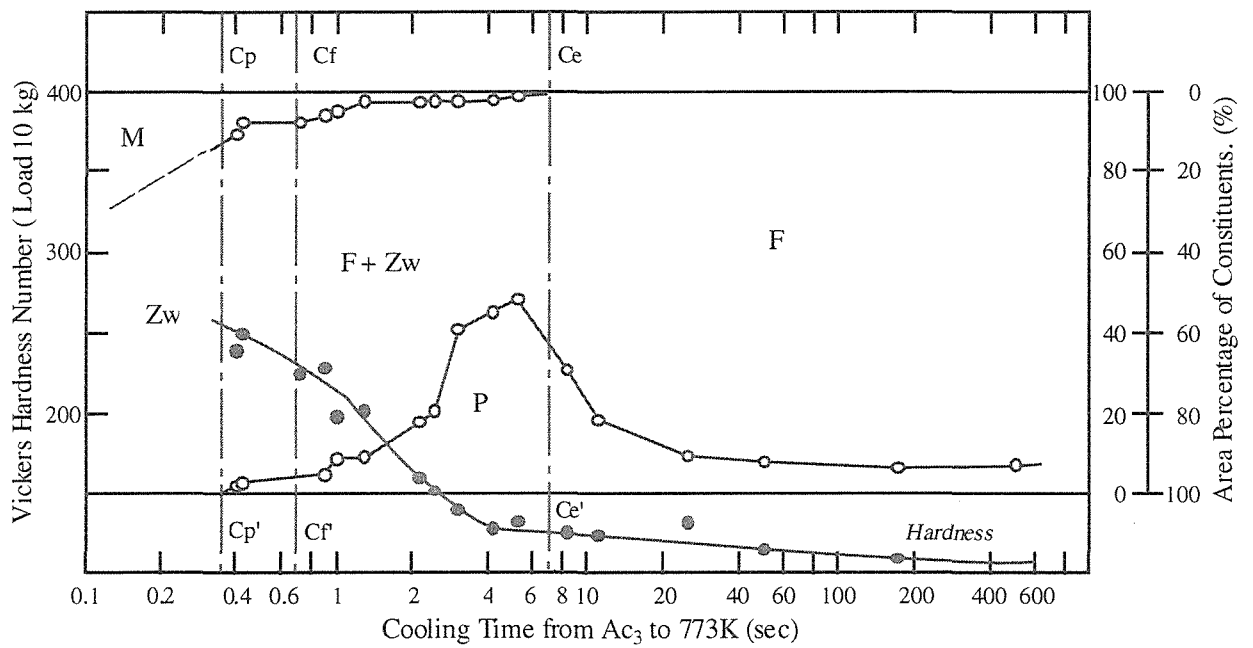
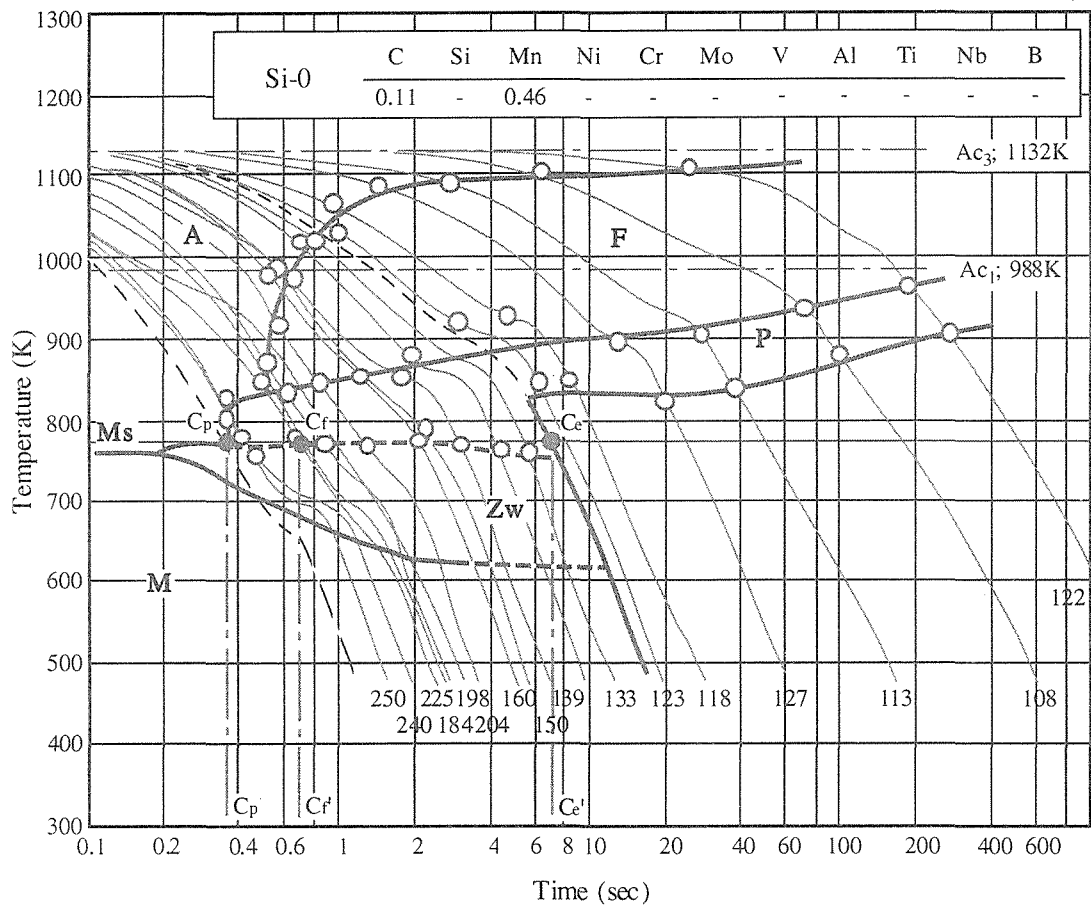


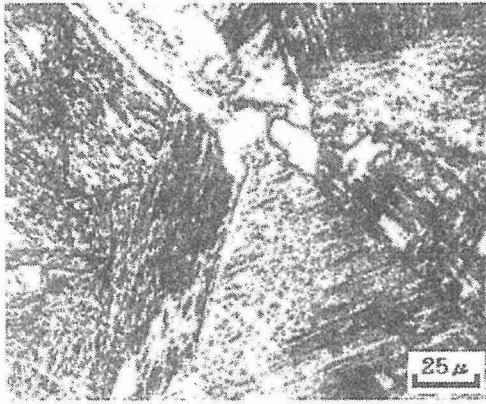
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Hv 252

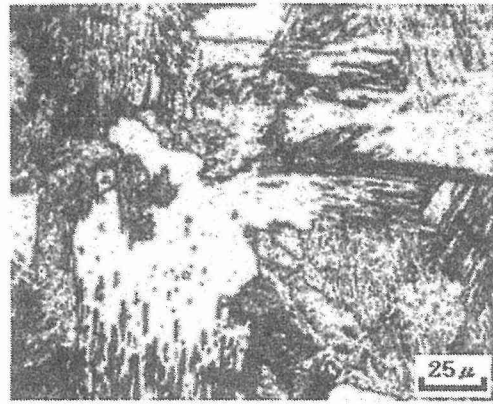
Fe-C-Si-Mn Alloy

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	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Si-0	0.11		0.46	-	-	-	-	-	-	-	-	-	-	-	18	2
Si-0.2	0.11	0.22	0.46	-	-	-	-	-	-	-	-	-	-	-	20	2
Si-0.5	0.11	0.56	0.47	-	-	-	-	-	-	-	-	-	-	-	22	2
Si-1.0	0.12	1.1	0.43	-	-	-	-	-	-	-	-	-	-	-	24	2
Si-1.6	0.12	1.64	0.4	-	-	-	-	-	-	-	-	-	-	-	26	2
Mn-0	0.11	0.21	-	-	-	-	-	-	-	-	-	-	-	-	28	3
Mn-1.0	0.11	0.21	1.06	-	-	-	-	-	-	-	-	-	-	-	30	3
Mn-2.0	0.12	0.21	2.05	-	-	-	-	-	-	-	-	-	-	-	32	3

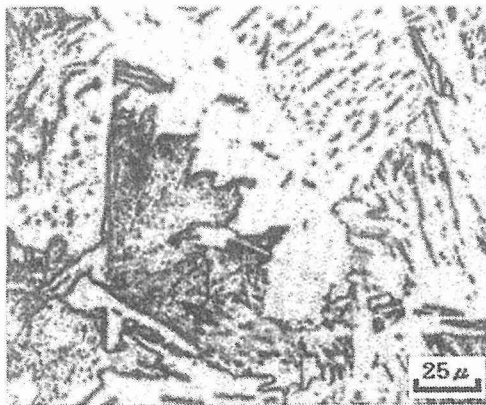




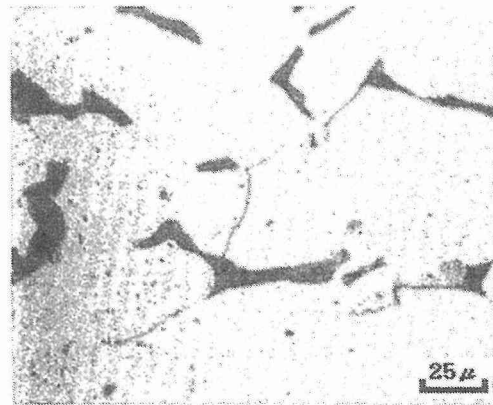
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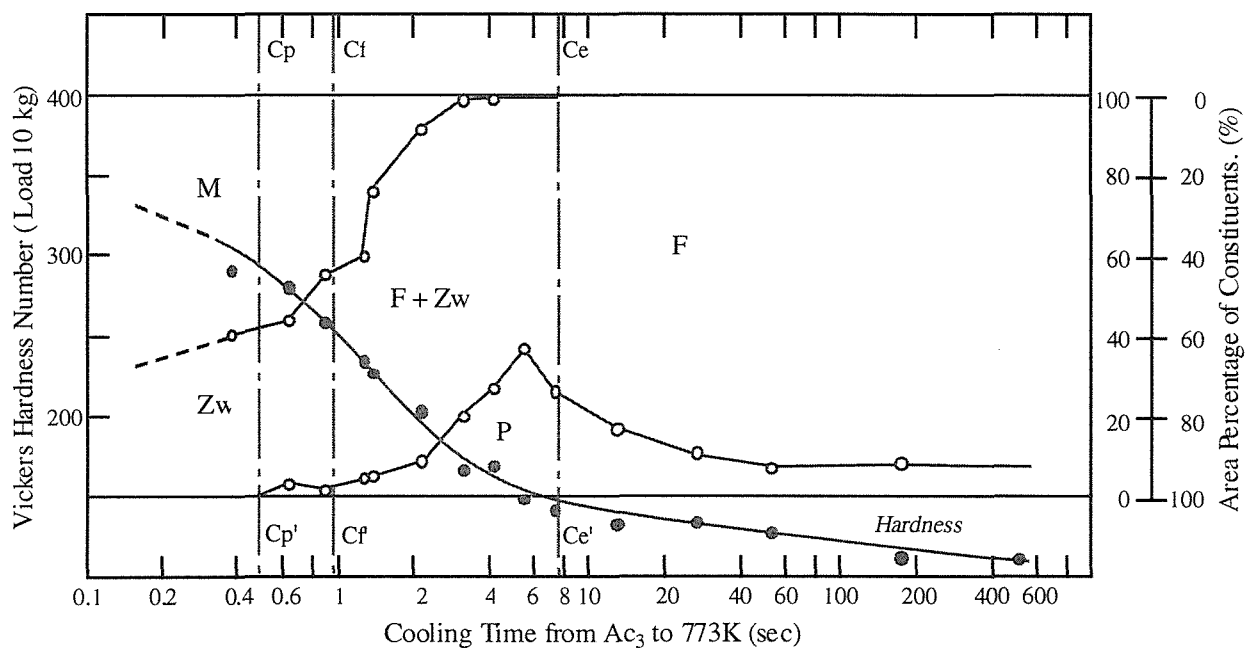
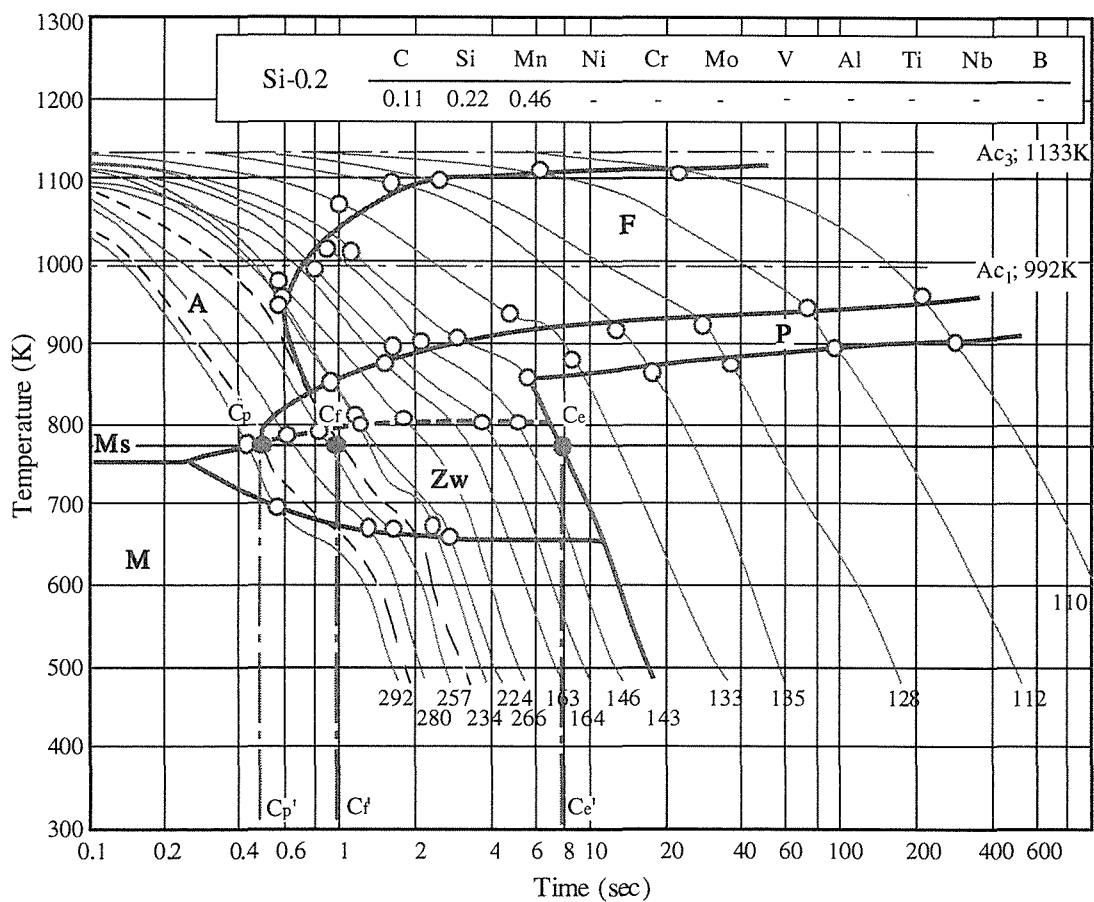
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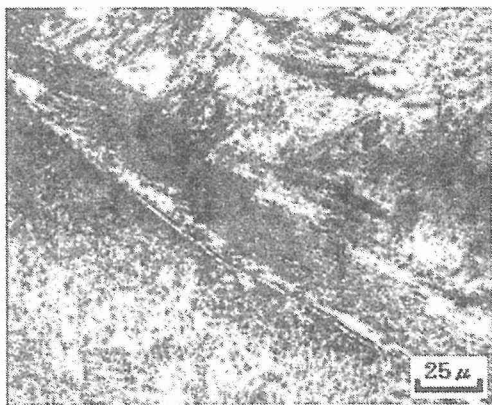


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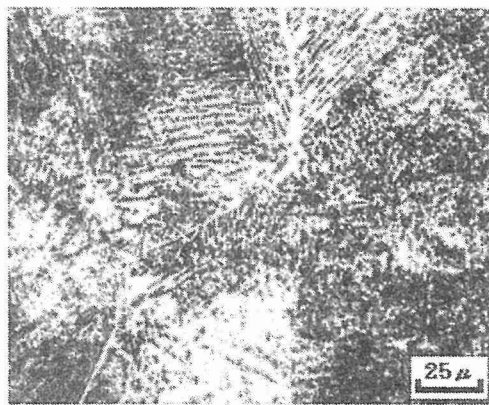


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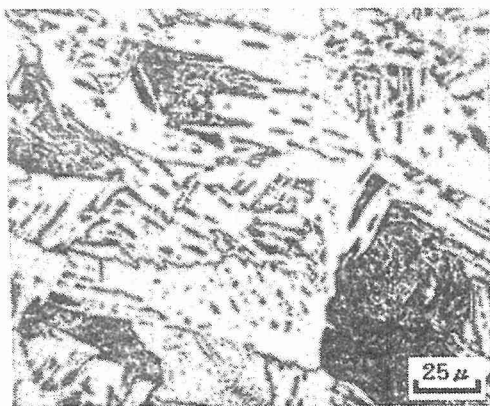




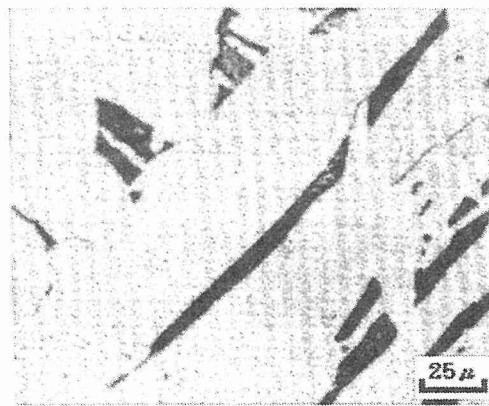
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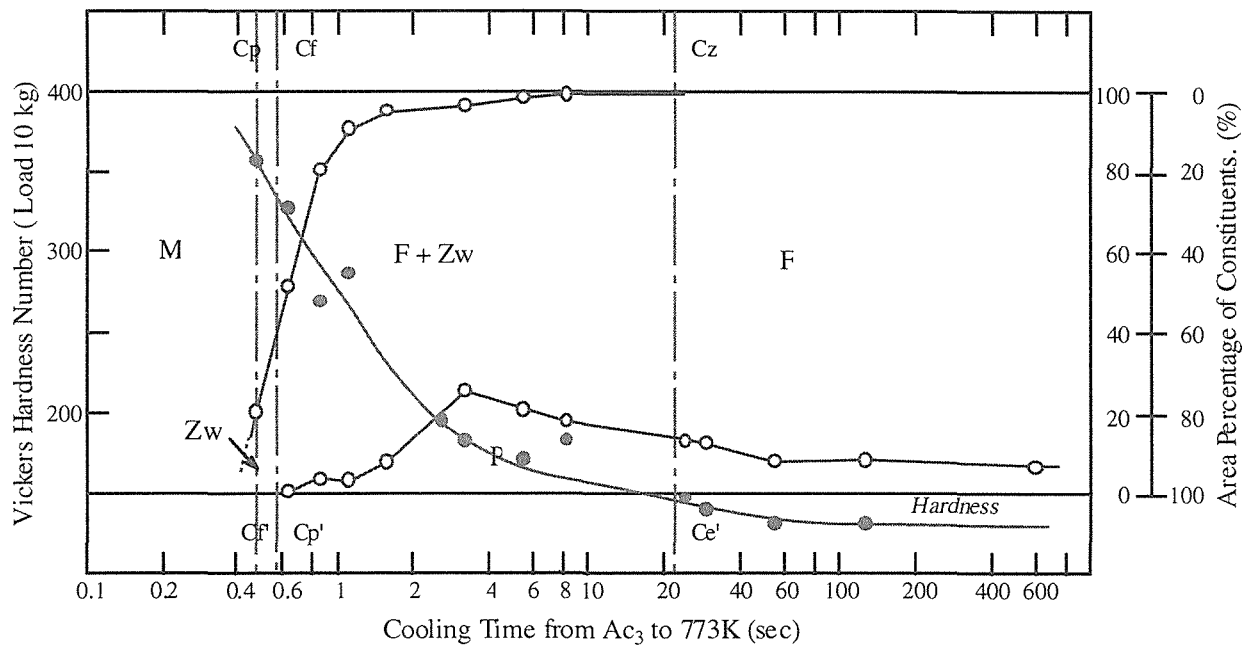
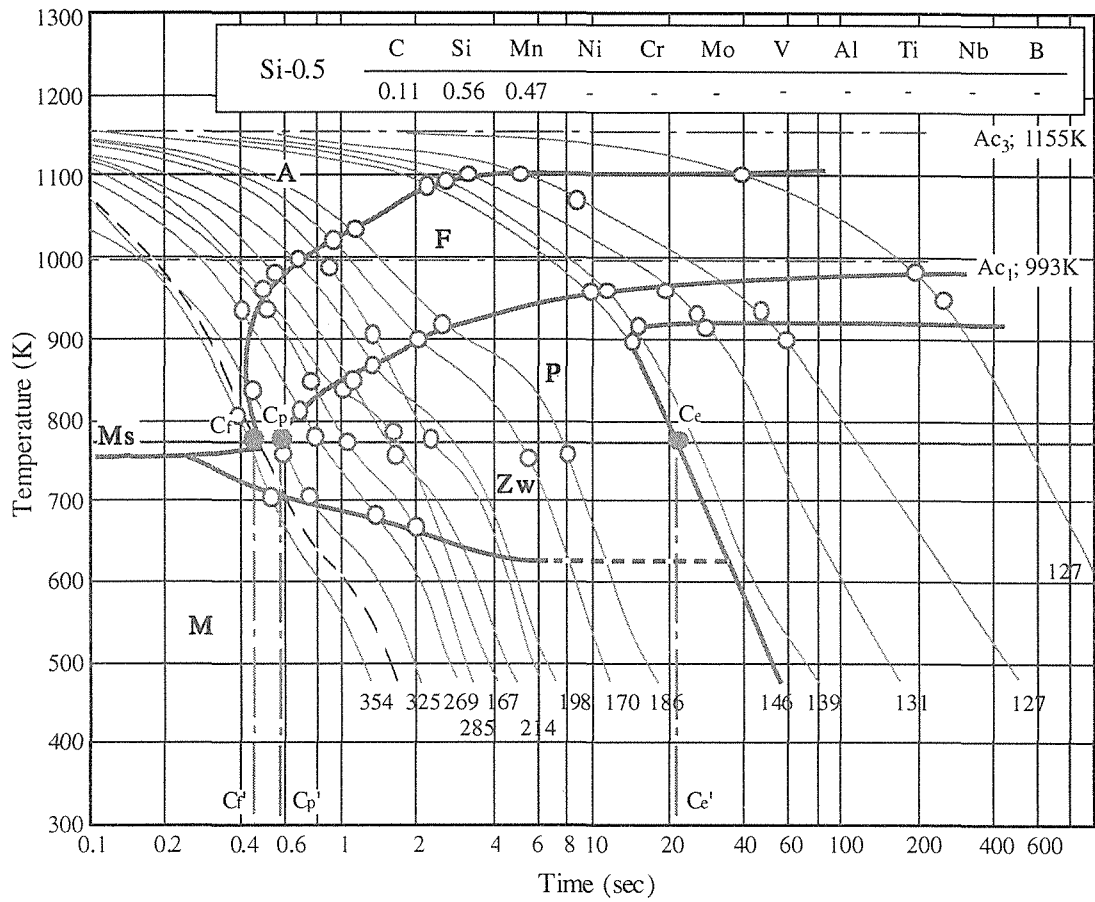
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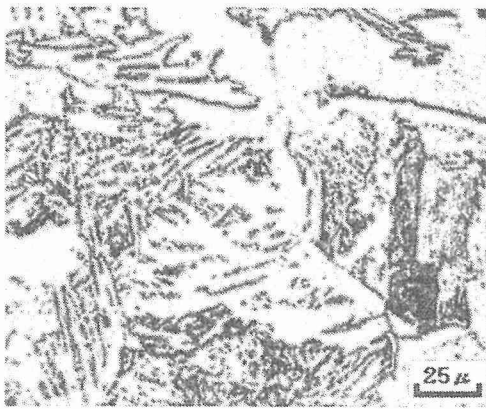


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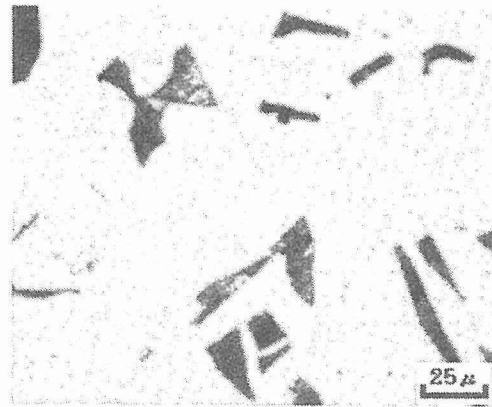


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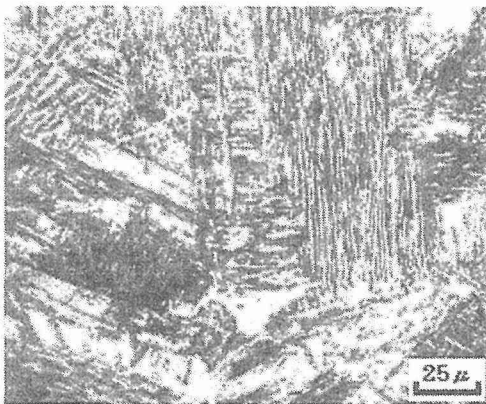




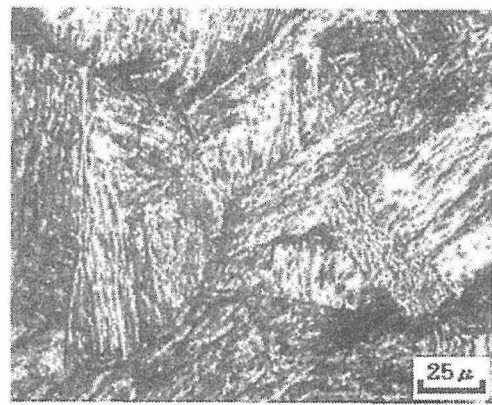
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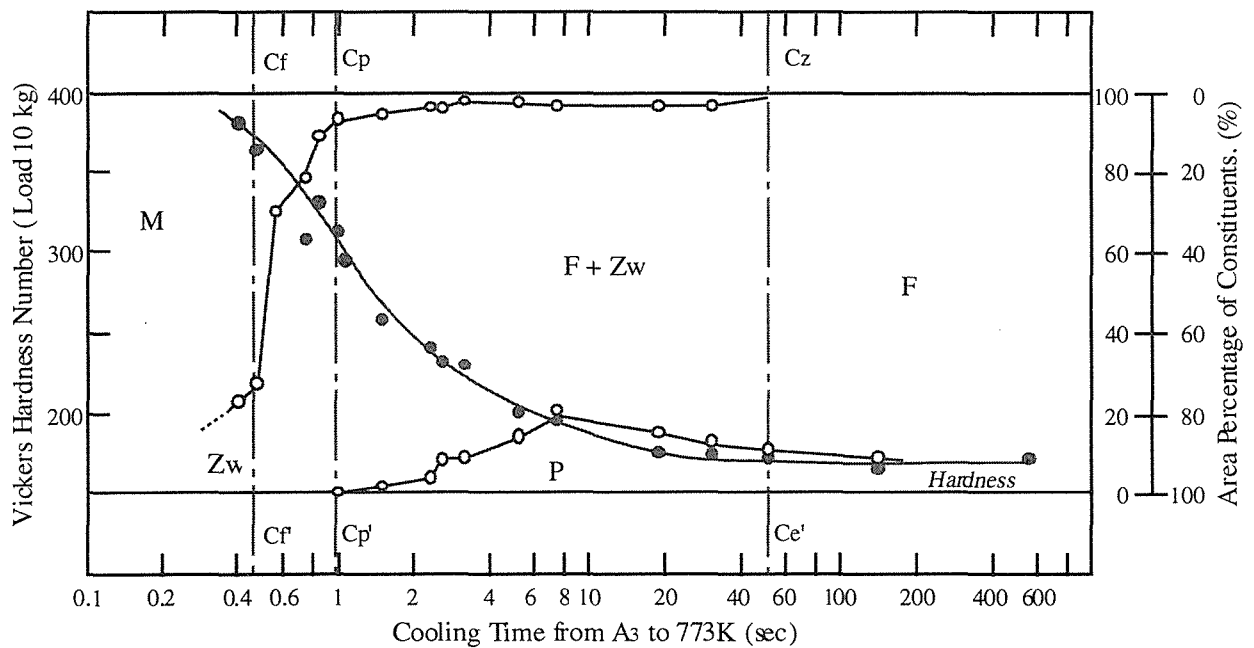
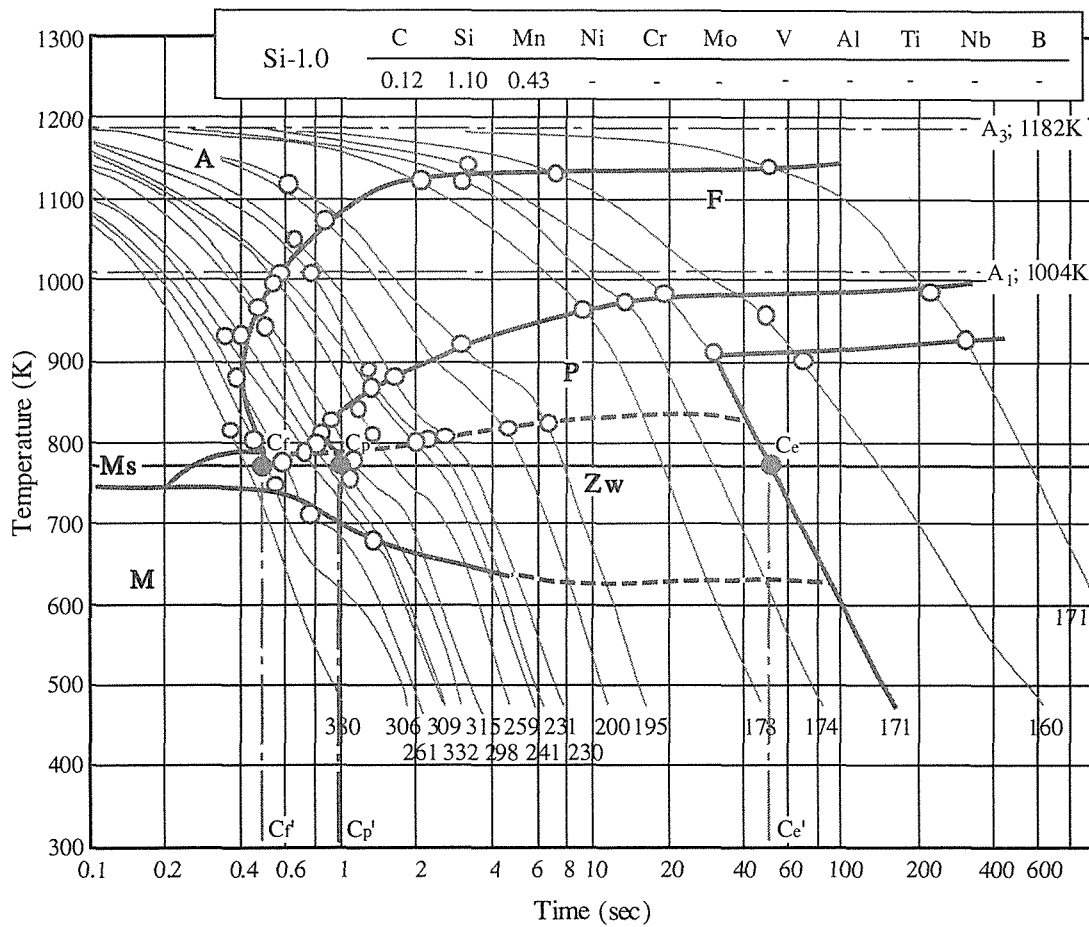
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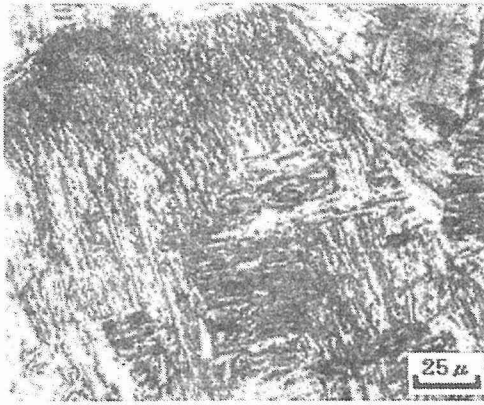


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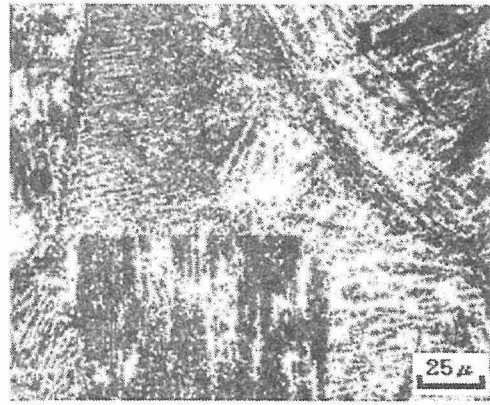


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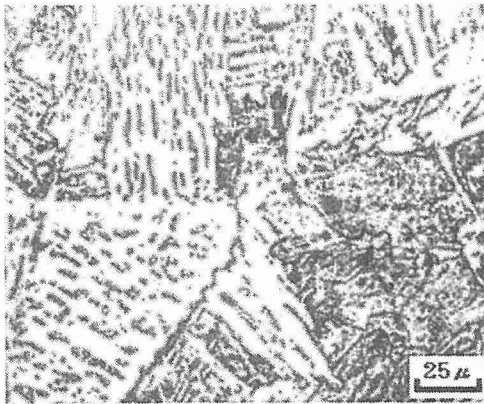




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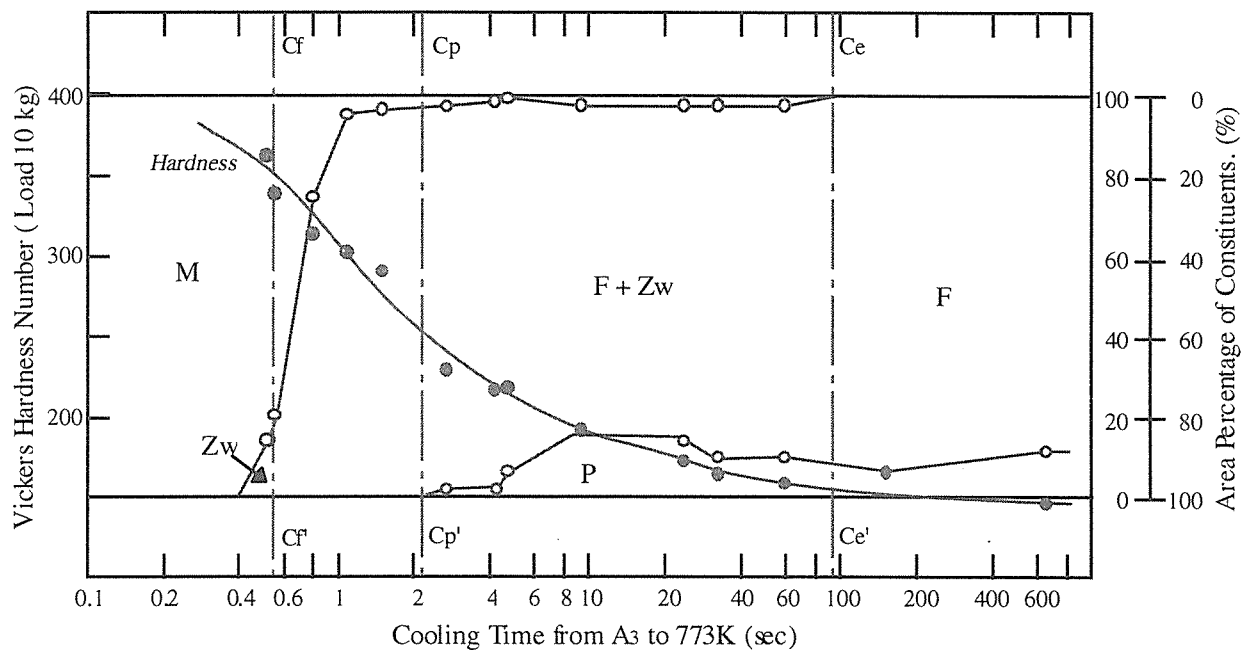
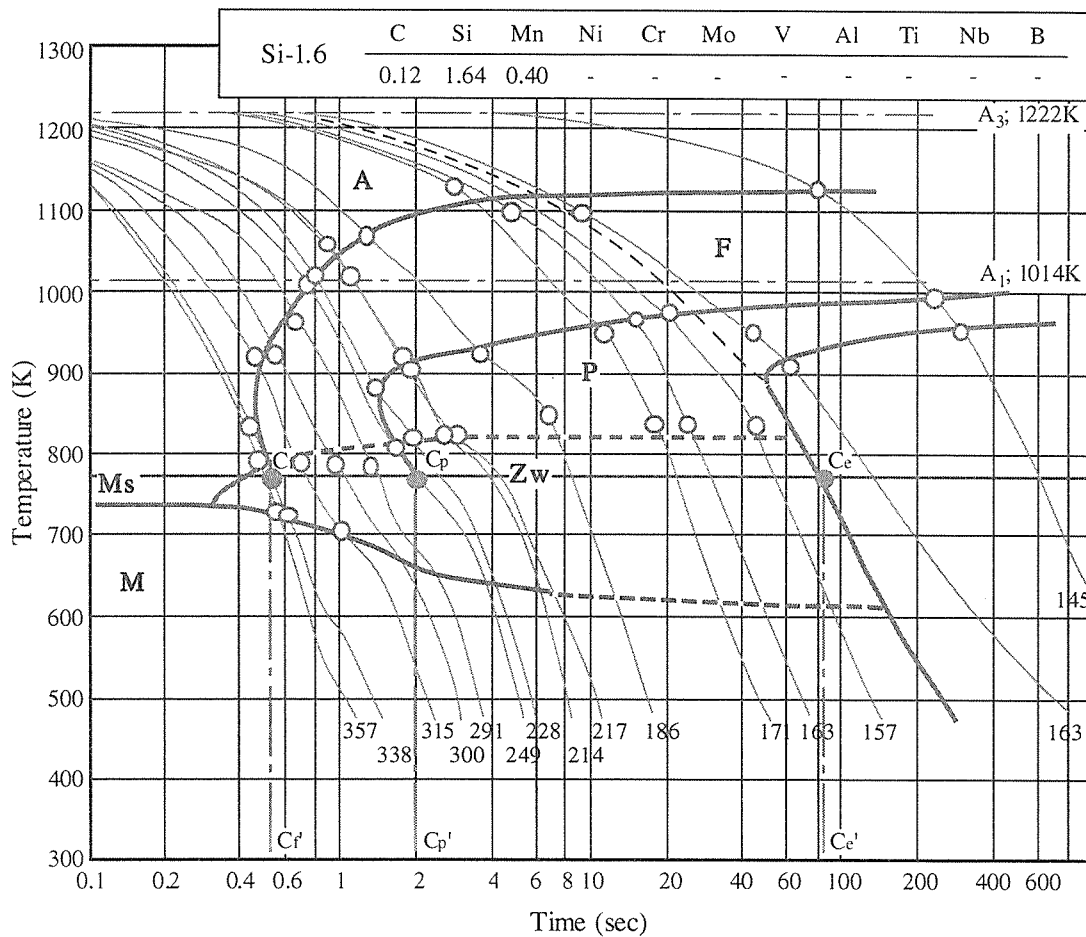
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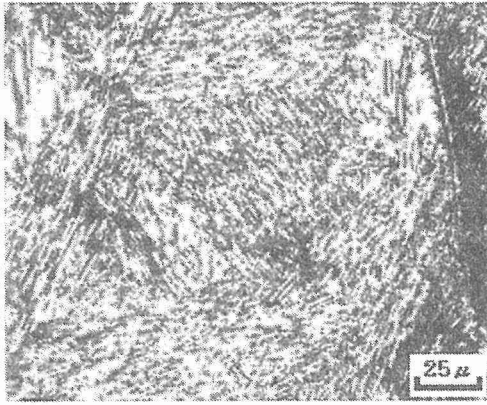


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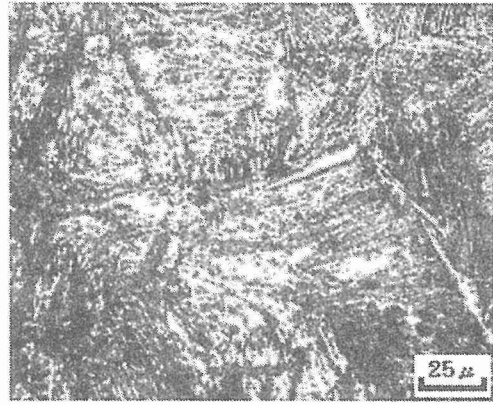


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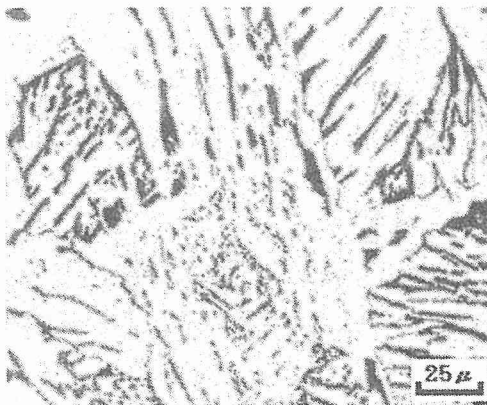




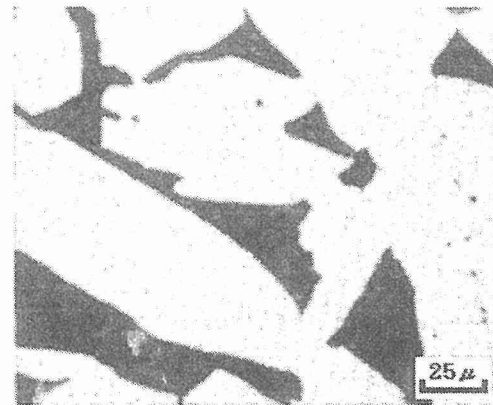
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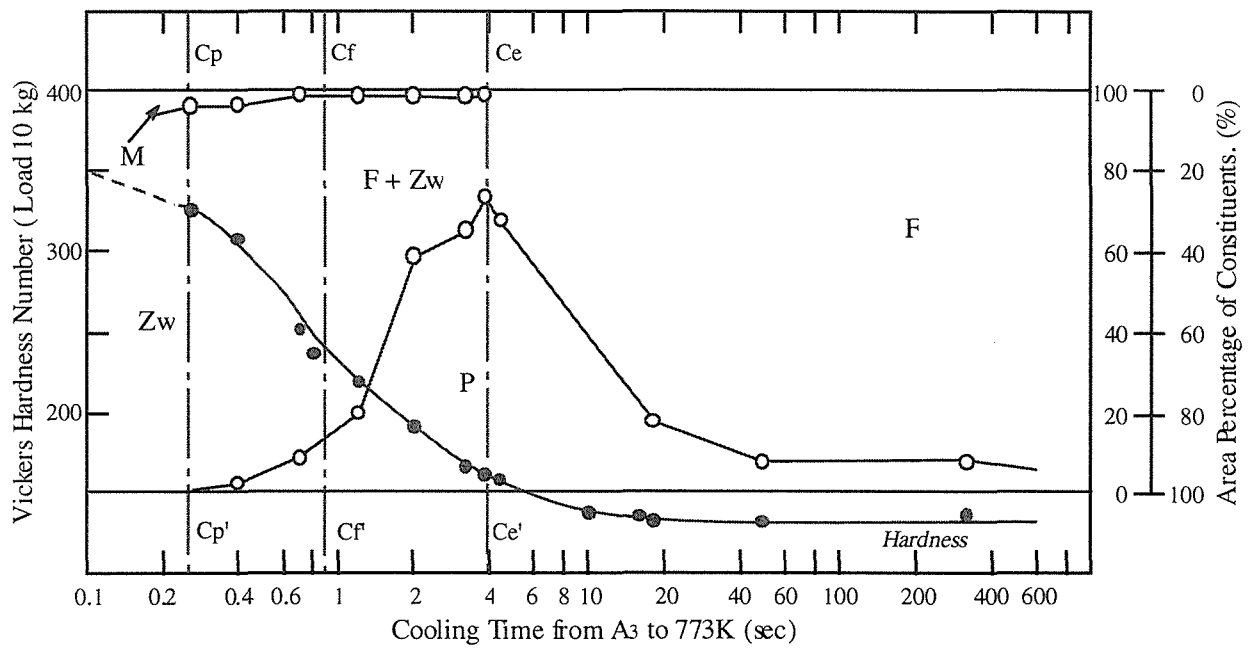
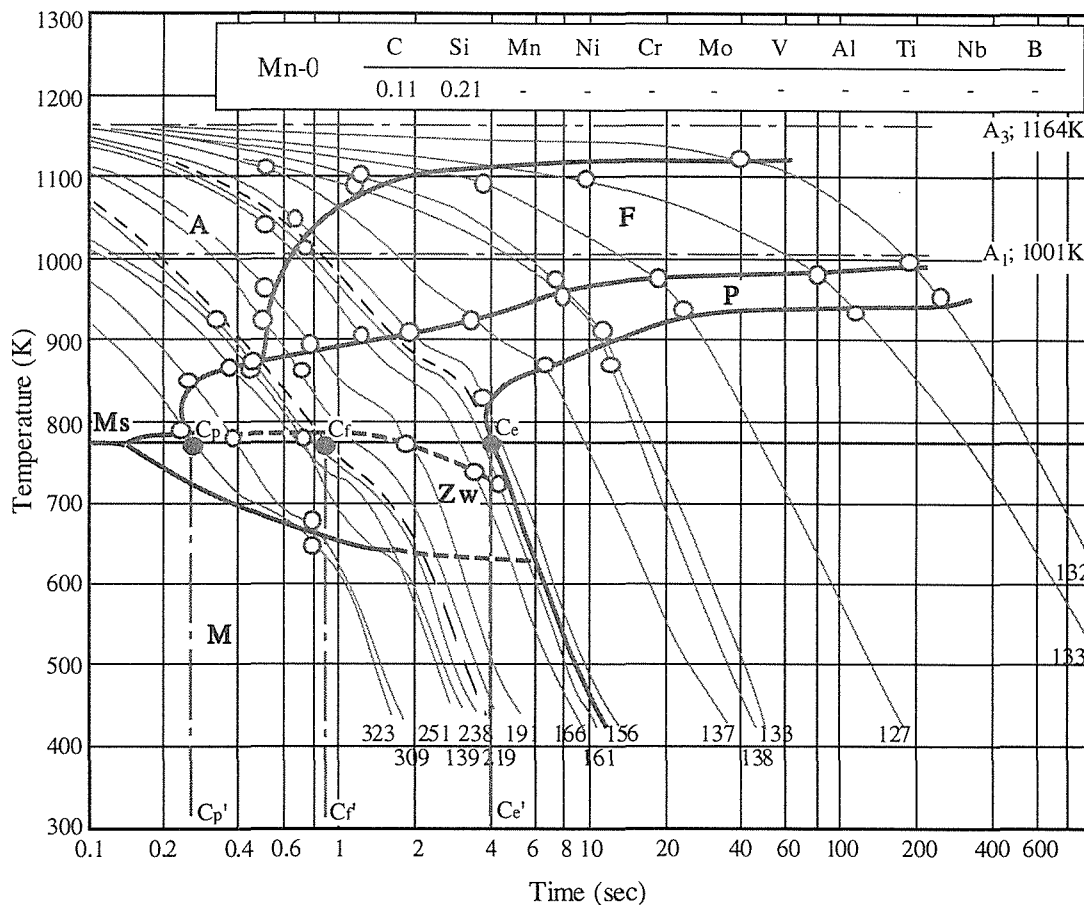
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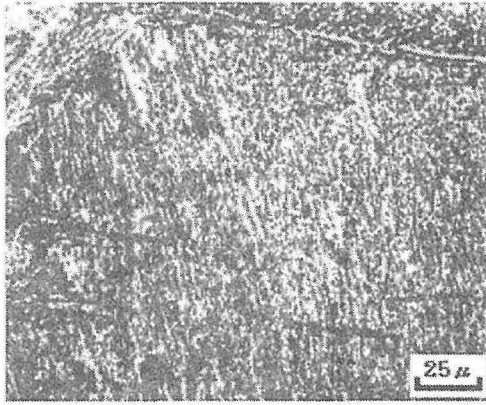


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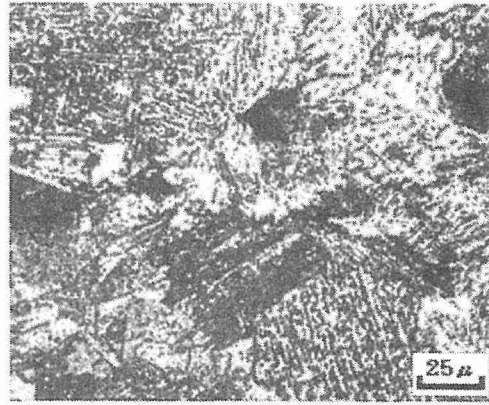


Time 600sec Hv 145

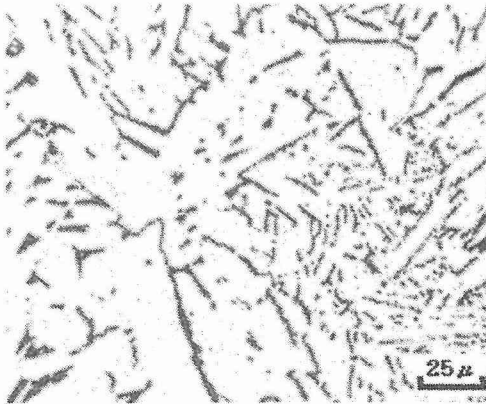




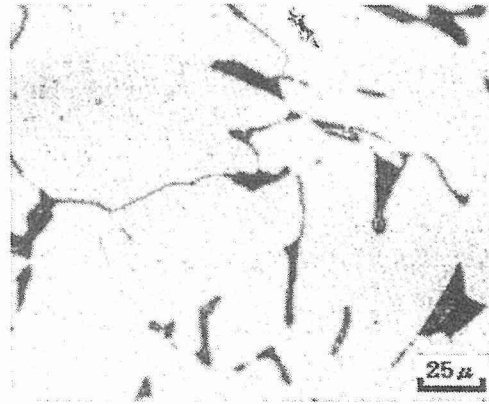
Time 0.3sec Hv 323



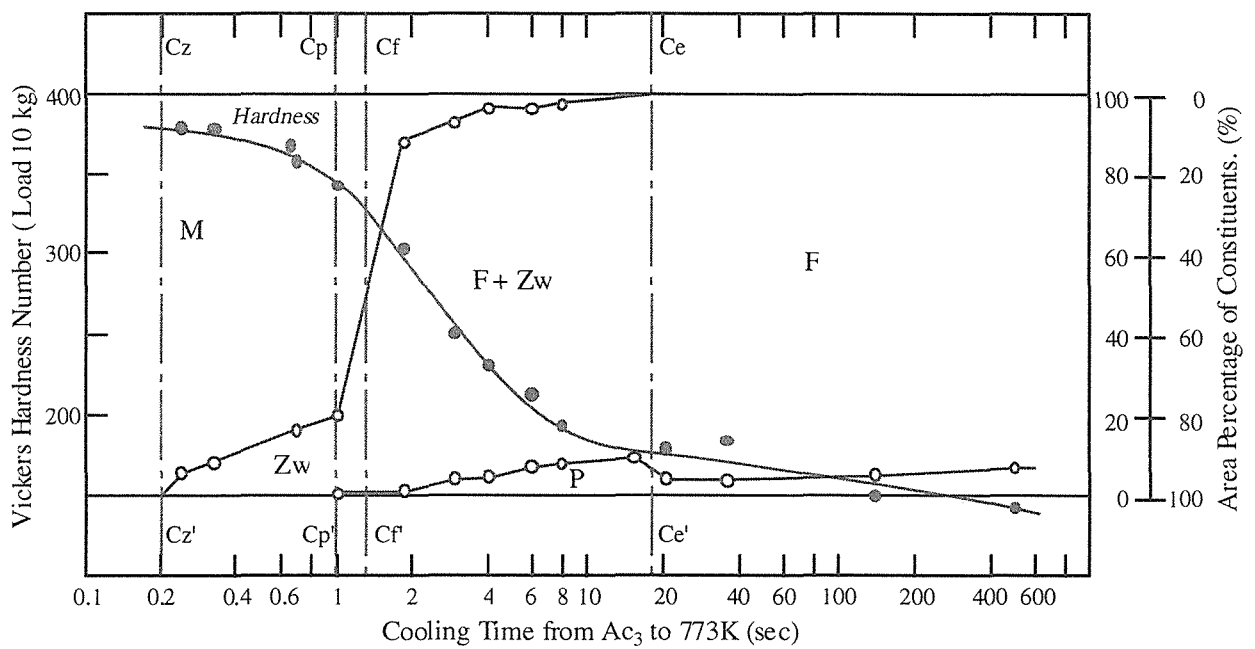
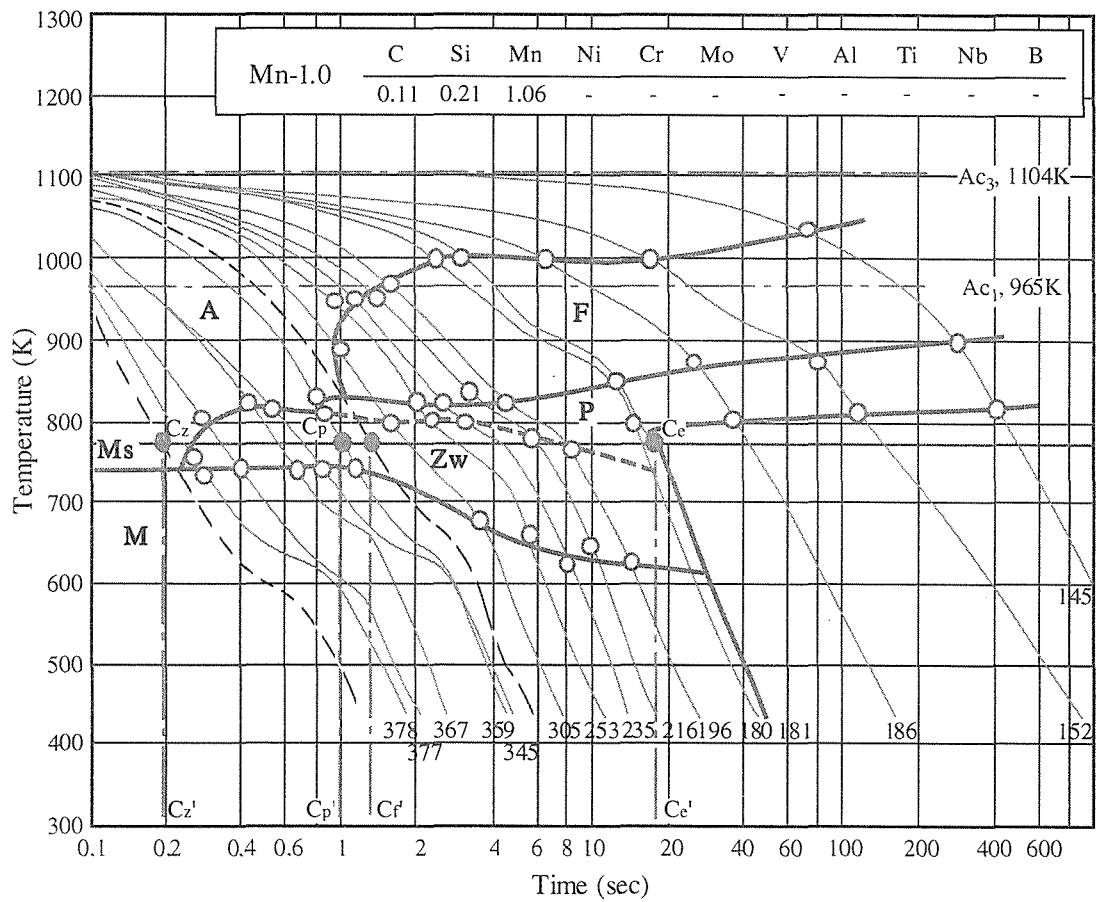
Time 1.3sec Hv 219

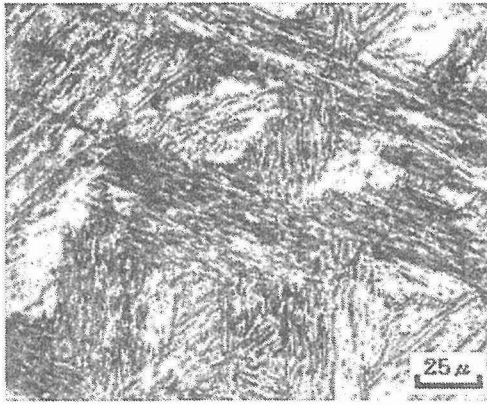


Time 18sec Hv 133

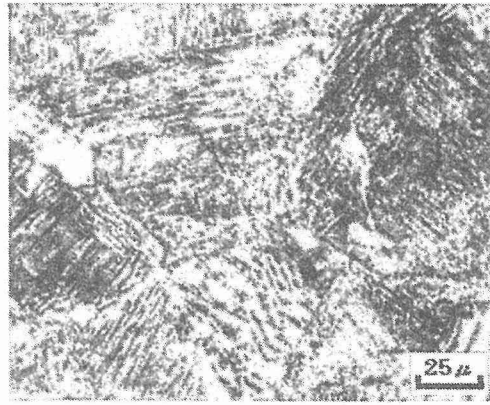


Time 250sec Hv 133

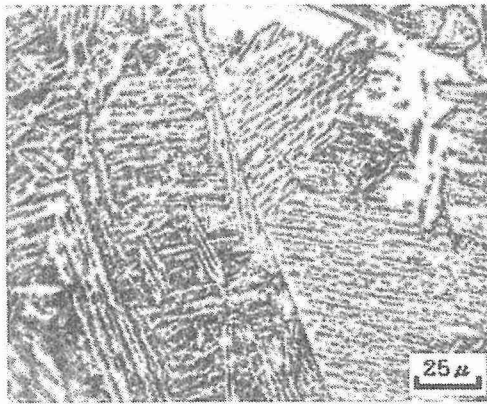




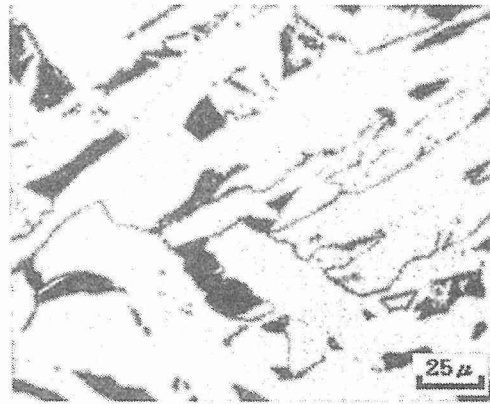
Time 0.25sec Hv 378



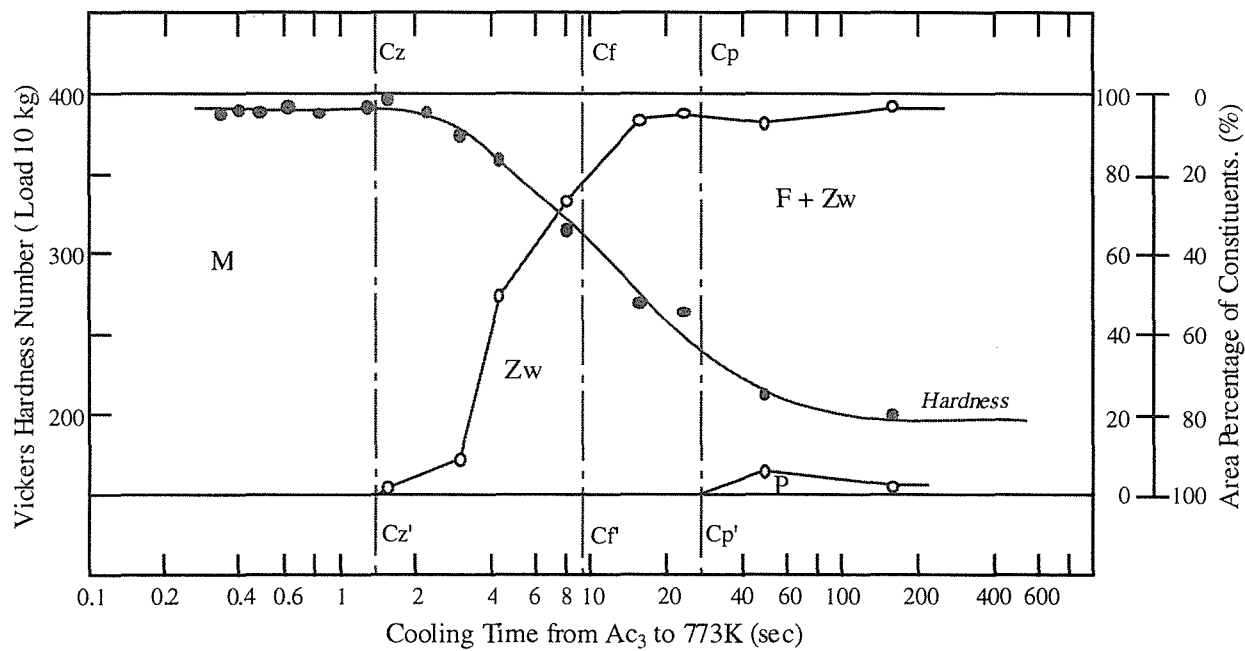
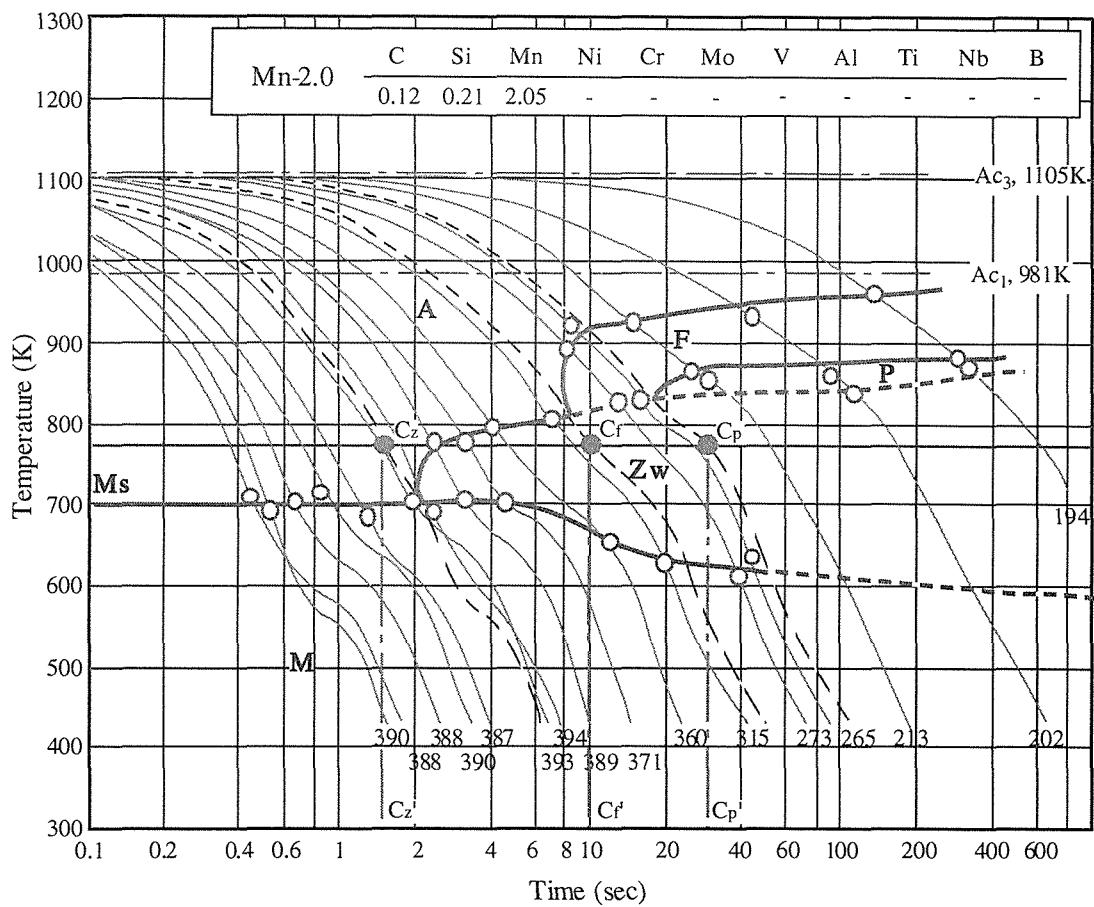
Time 1.8sec Hv 265

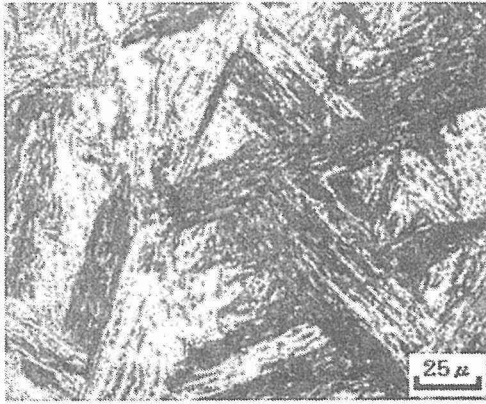


Time 7.9sec Hv 196

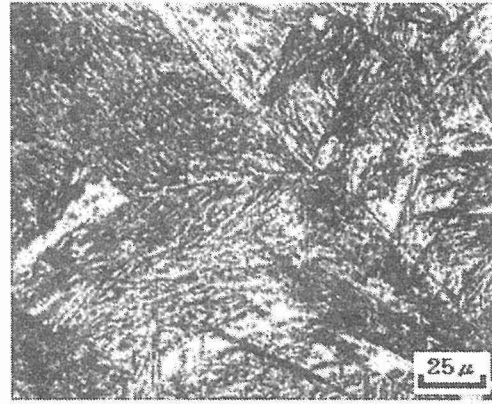


Time 500sec Hv 145

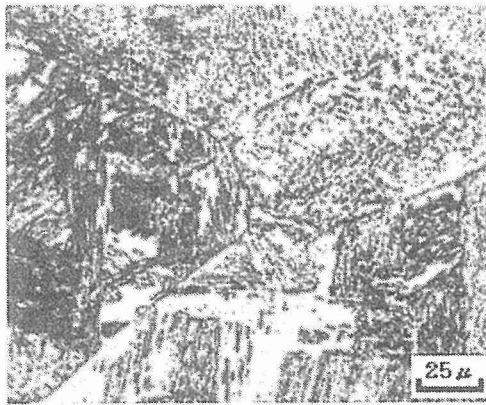




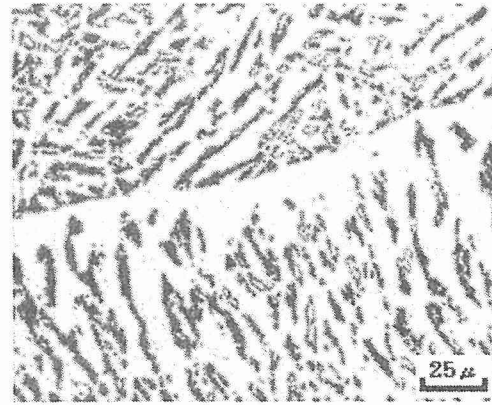
Time 0.5sec Hv 388



Time 4.8sec Hv 360



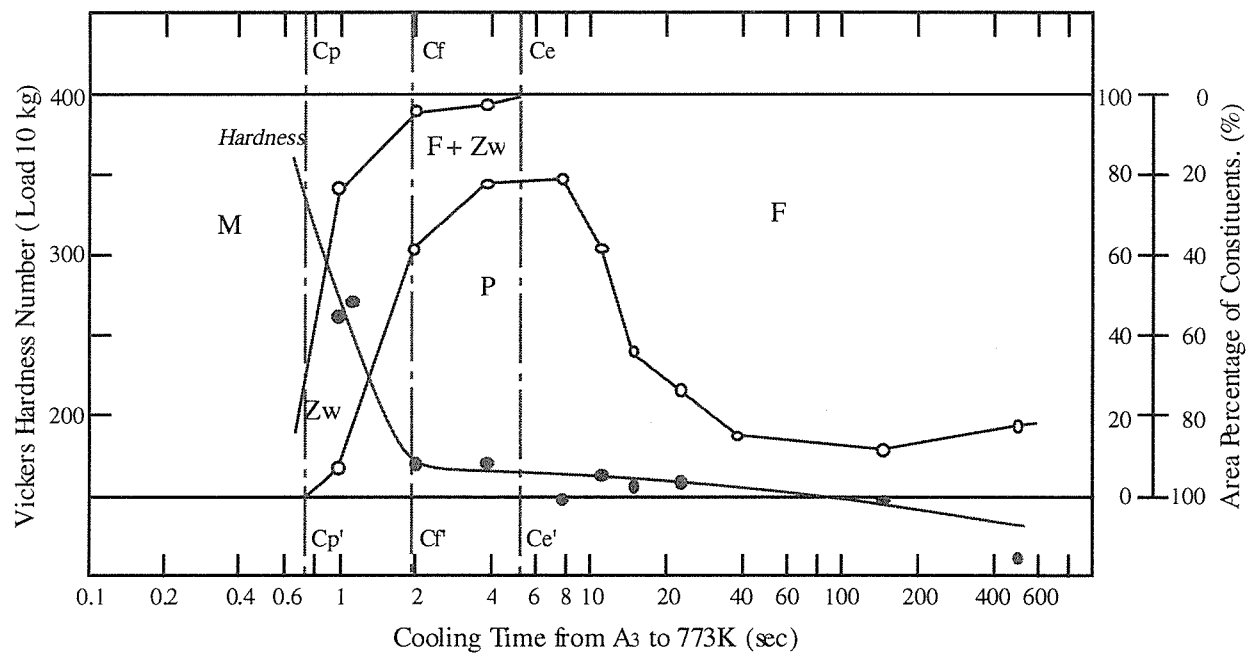
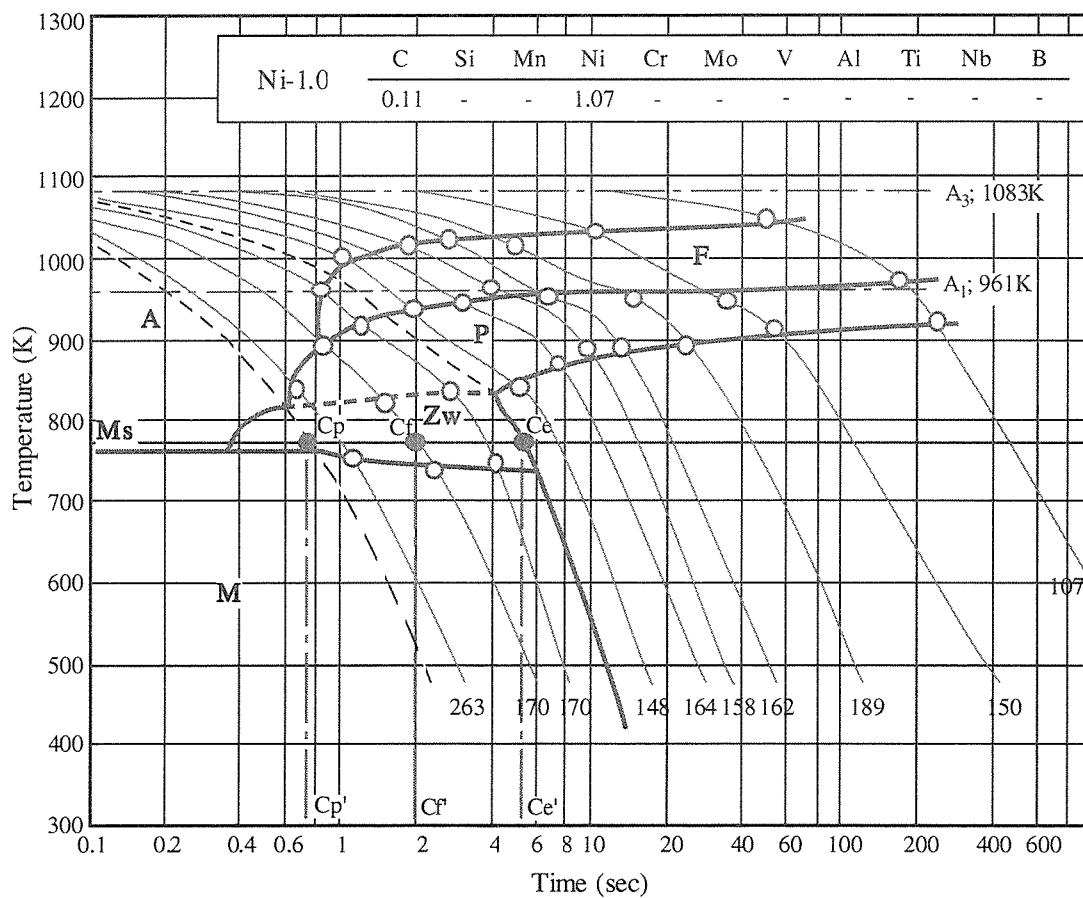
Time 18sec Hv 273

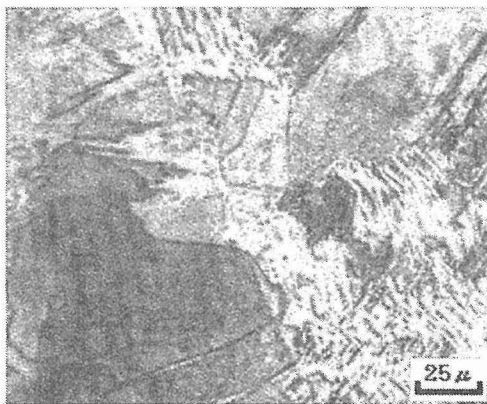


Time 700sec Hv 194

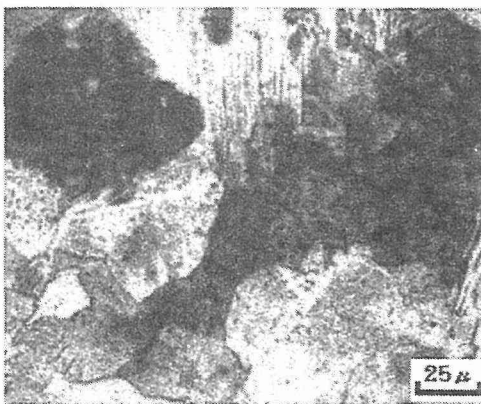
Fe-C-Ni Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Ni-1.0	0.11	-	-	-	-	1.07	-	-	-	-	-	-	-	-	36	4
Ni-2.5	0.14	-	-	-	-	2.43	-	-	-	-	-	-	-	-	38	4
Ni-3.5	0.11	-	-	-	-	3.49	-	-	-	-	-	-	-	-	40	4
Ni-5	0.16	-	-	-	-	5.06	-	-	-	-	-	-	-	-	42	4
Ni-7	0.14	-	-	-	-	7.02	-	-	-	-	-	-	-	-	44	4
Ni-9	0.1	-	-	-	-	9.11	-	-	-	-	-	-	-	-	46	4

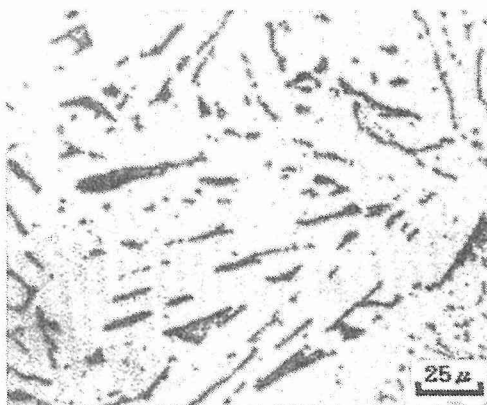




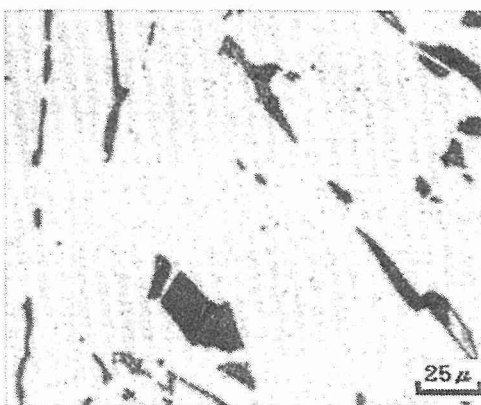
Time 2sec Hv 170



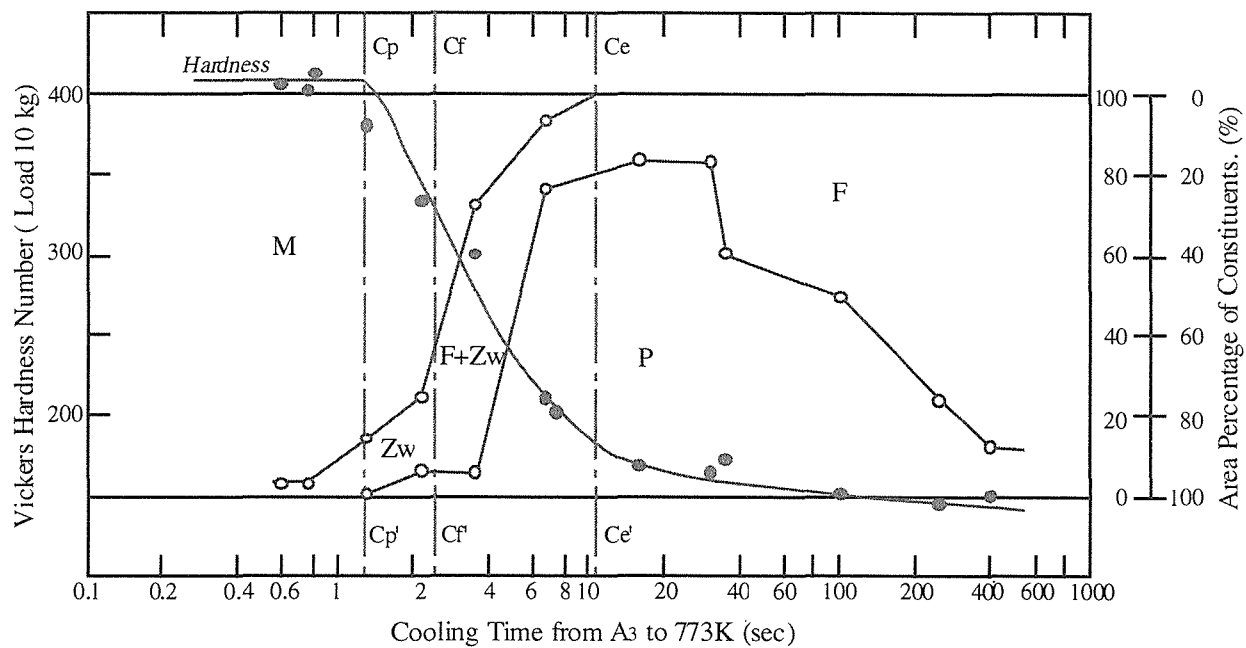
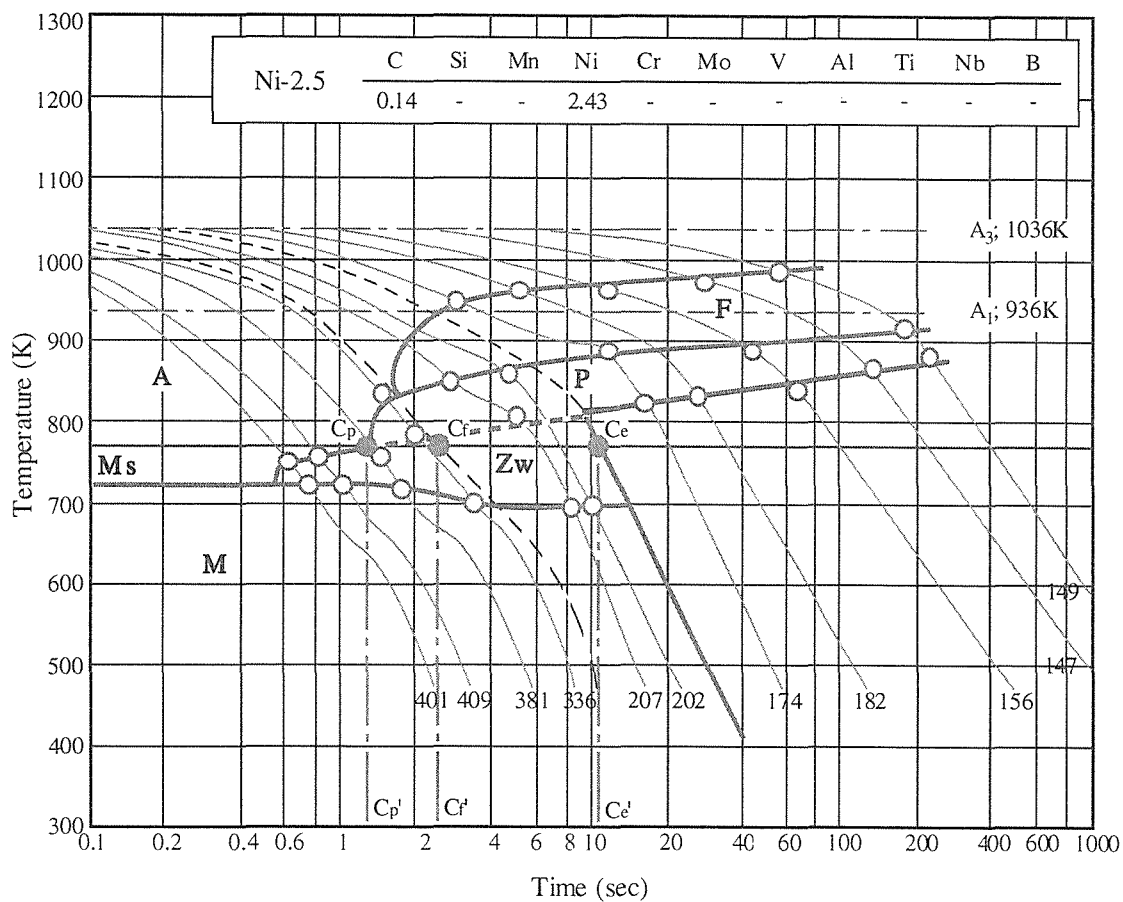
Time 3.8sec Hv 170

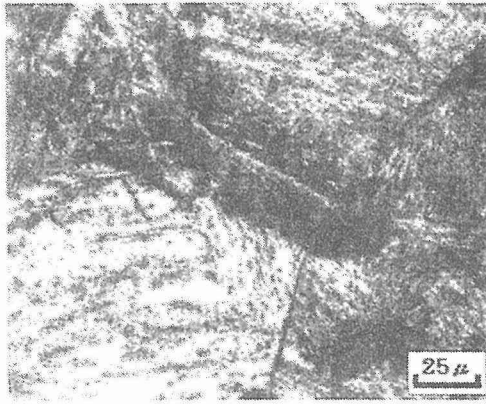


Time 16sec Hv 158

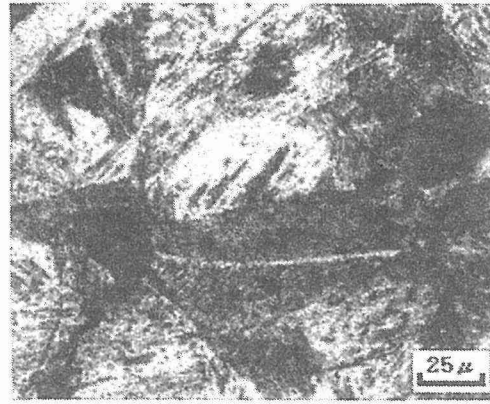


Time 480sec Hv 107

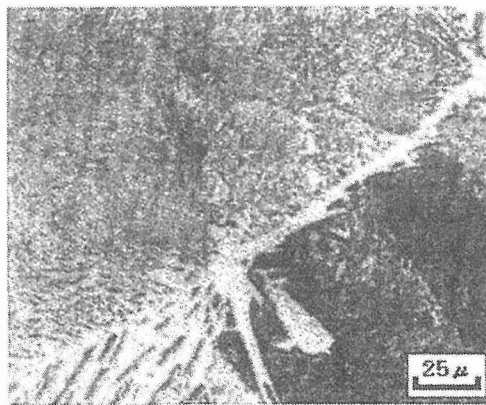




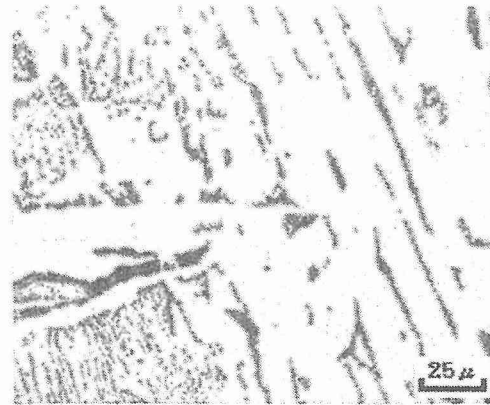
Time 1.4sec Hv 381



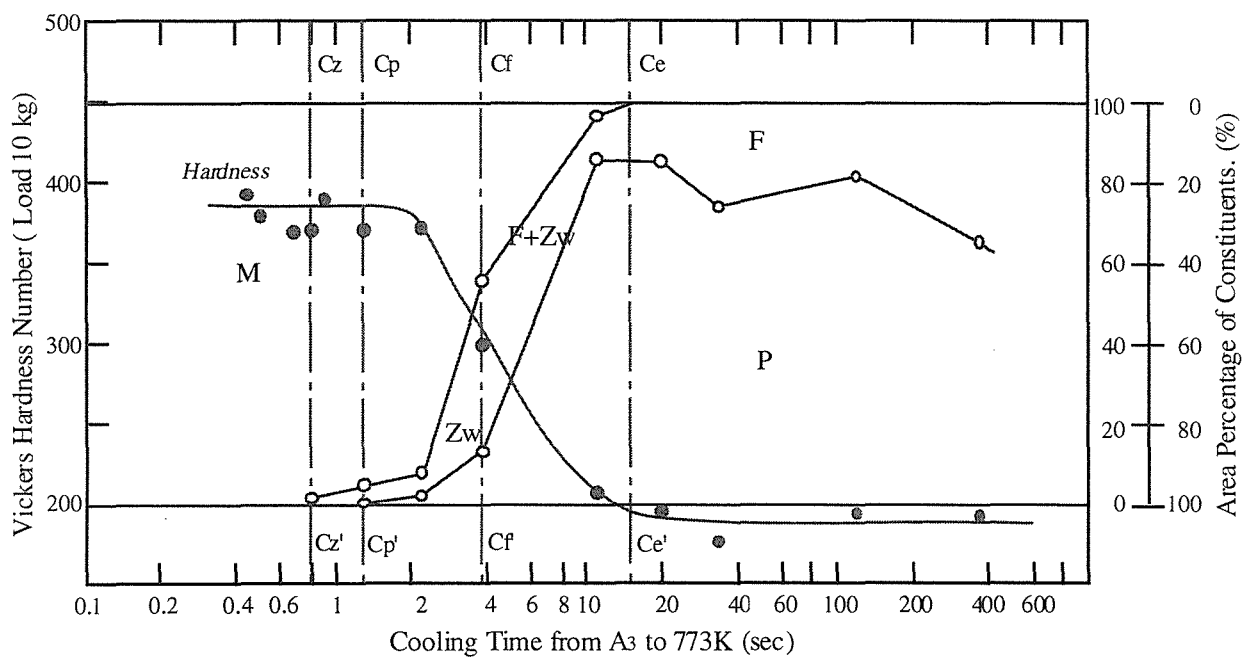
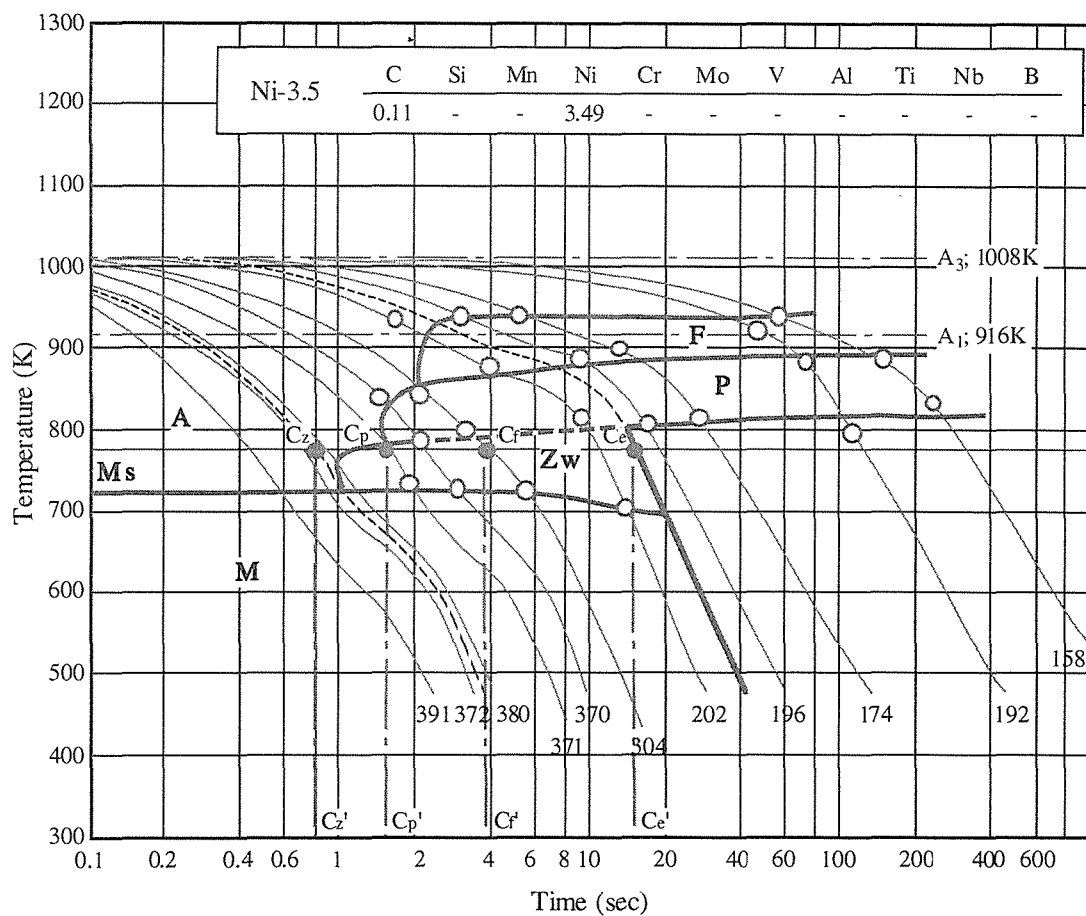
Time 2.2sec Hv 336

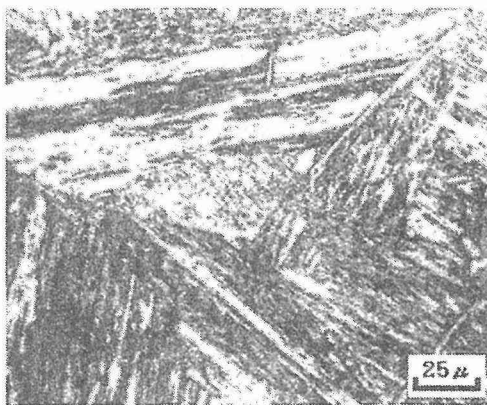


Time 37sec Hv 182

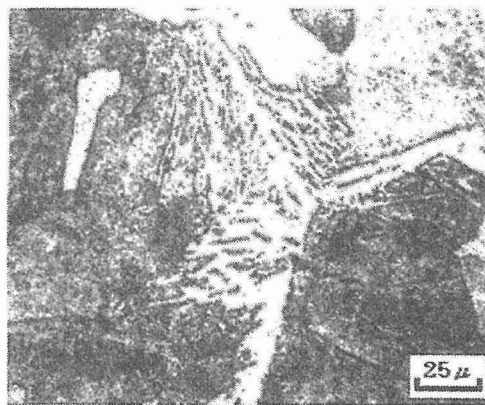


Time 400sec Hv 149

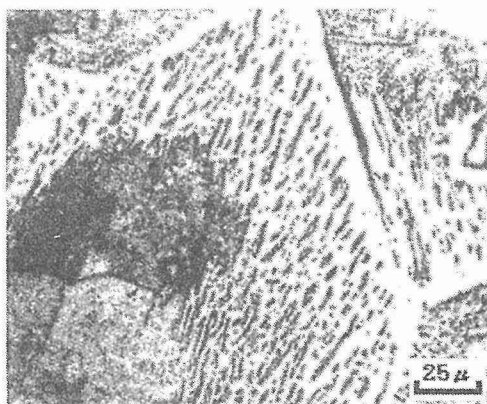




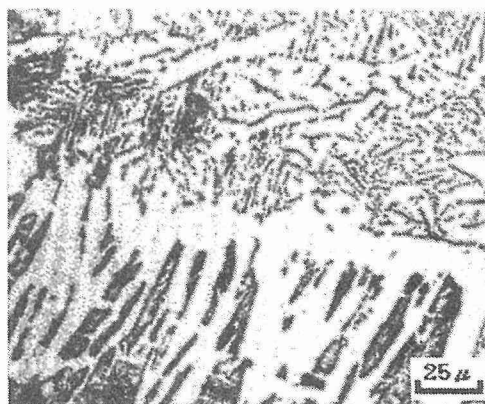
Time 0.42sec Hv 391



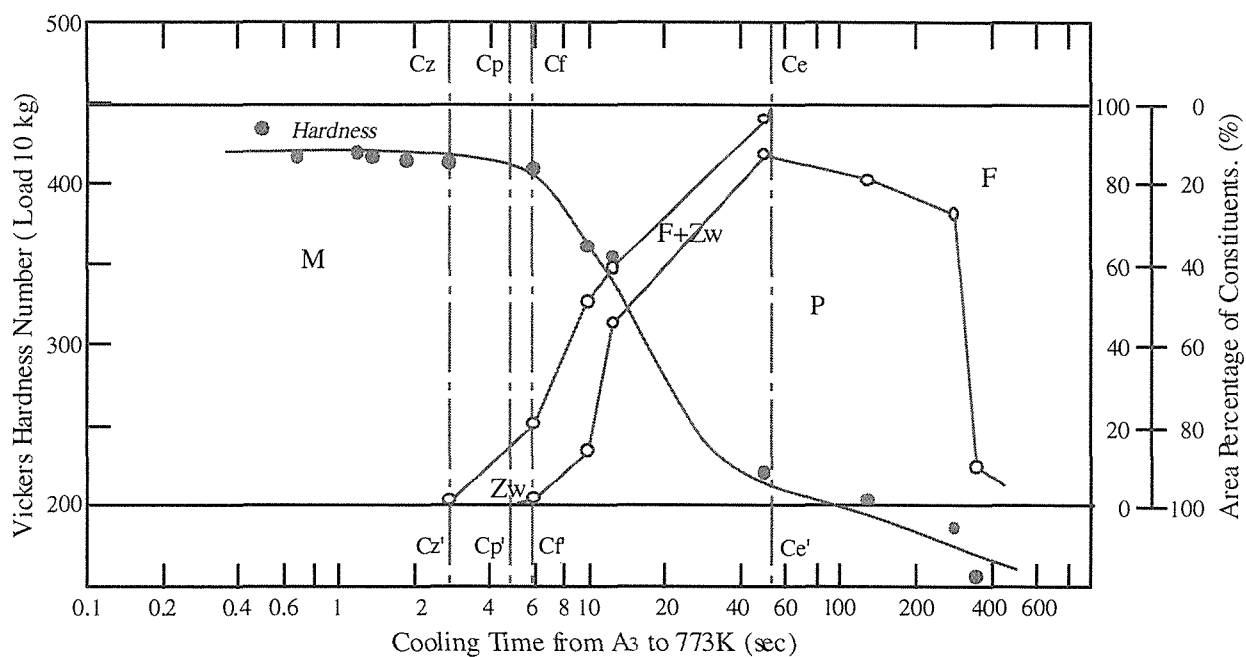
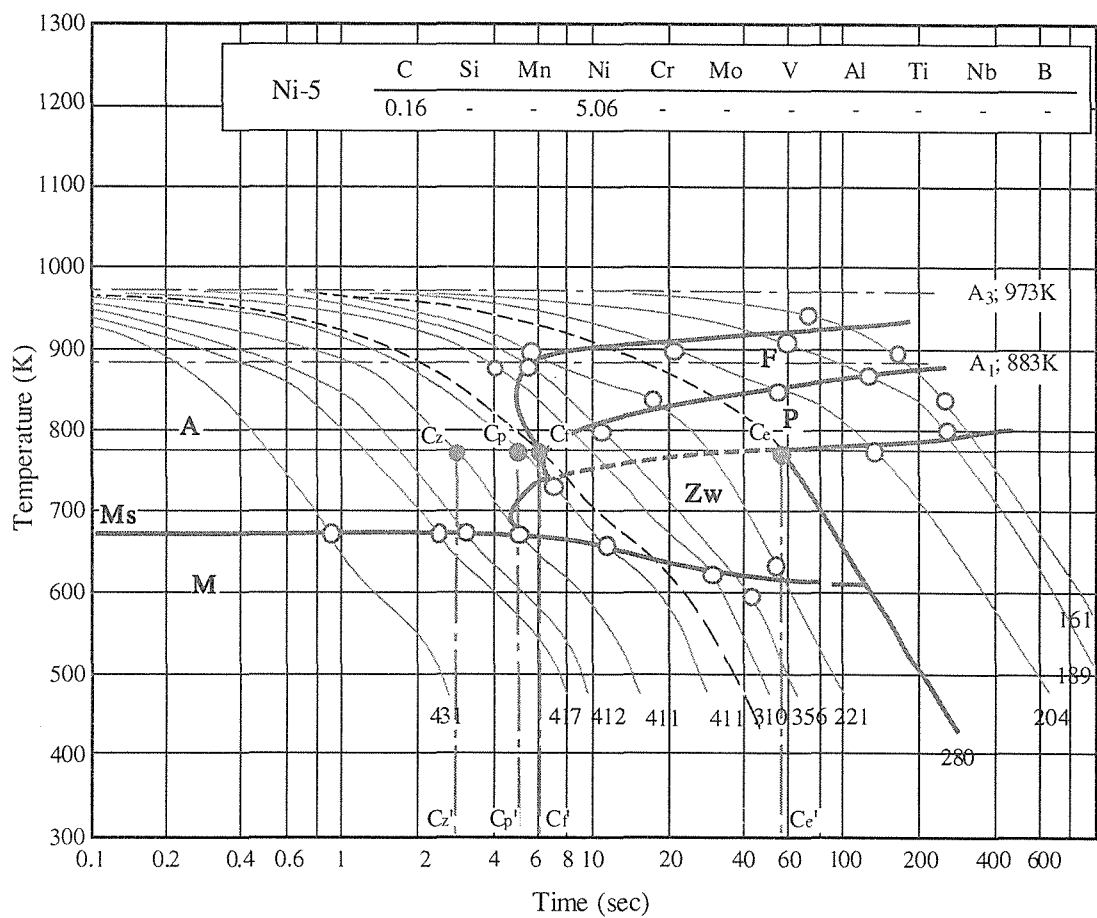
Time 12.2sec Hv 202

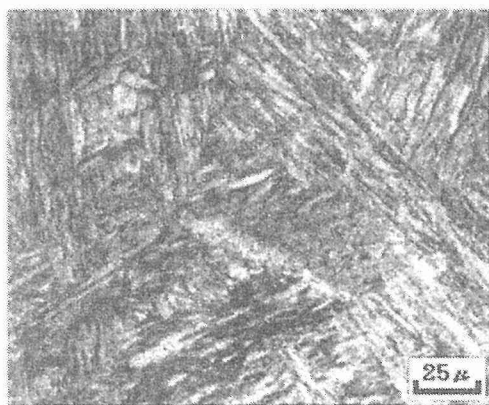


Time 19sec Hv 196

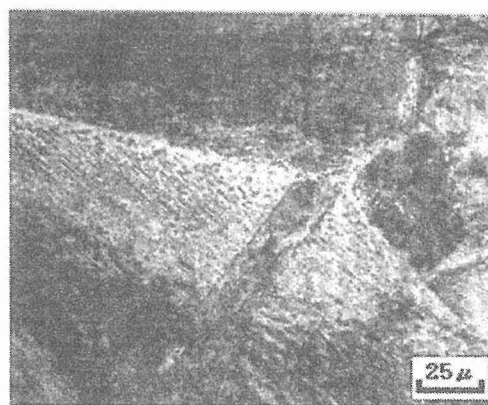


Time 310sec Hv 158

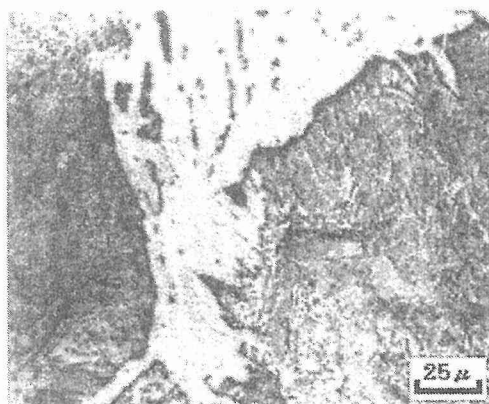




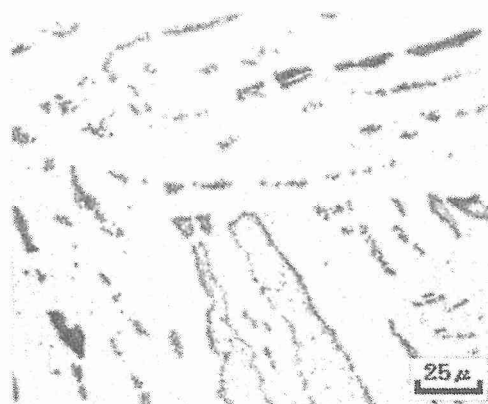
Time 3sec Hv 411



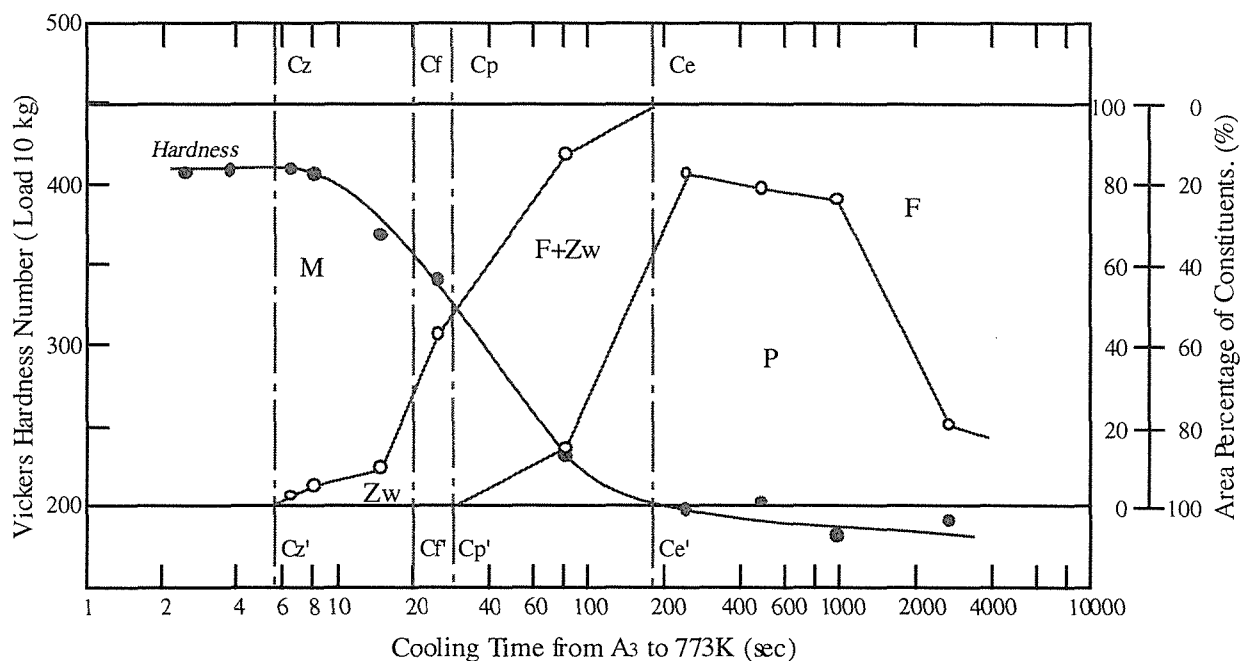
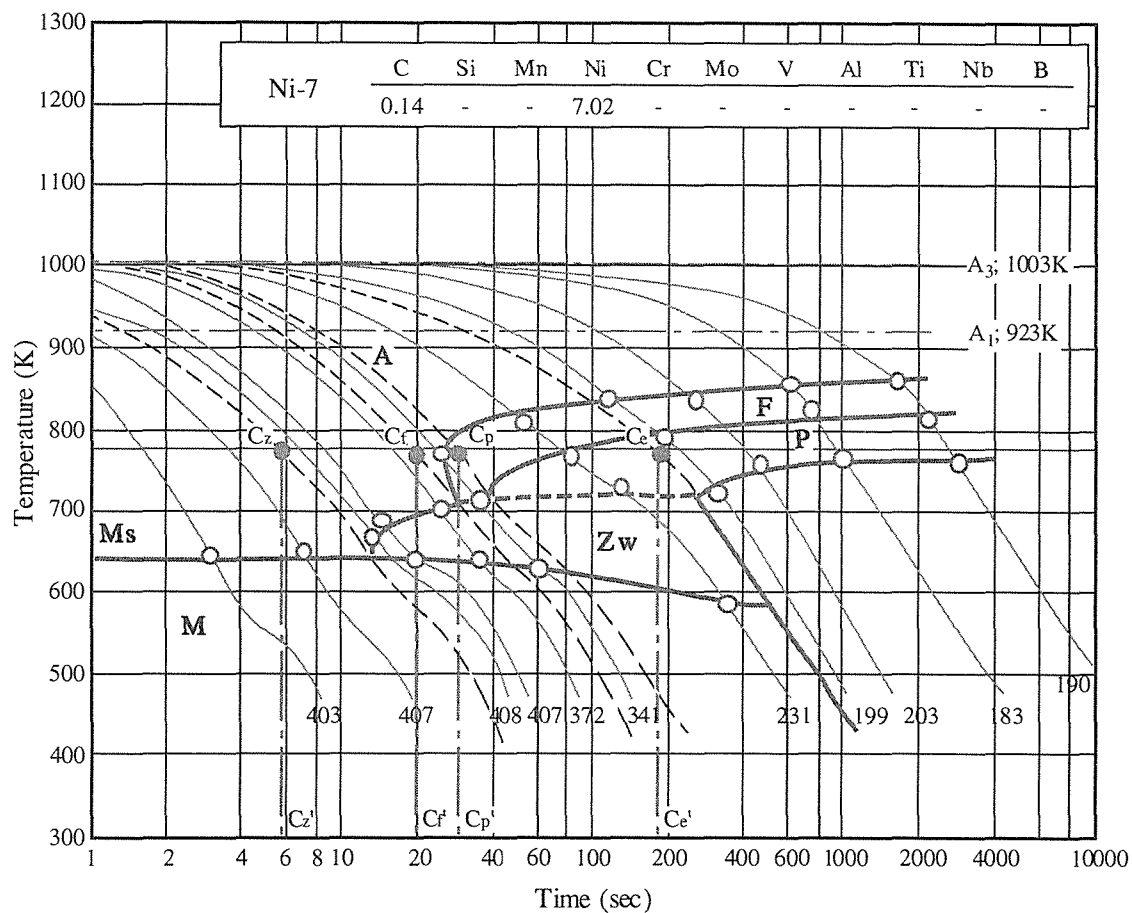
Time 6sec Hv 410

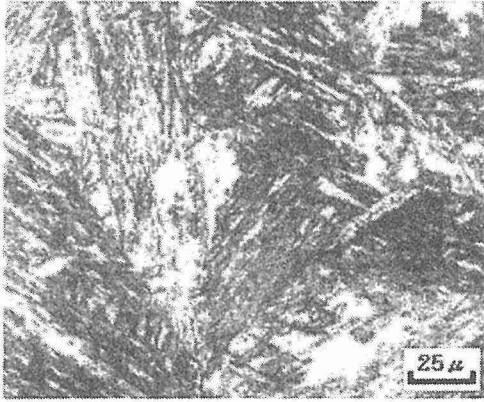


Time 150sec Hv 204

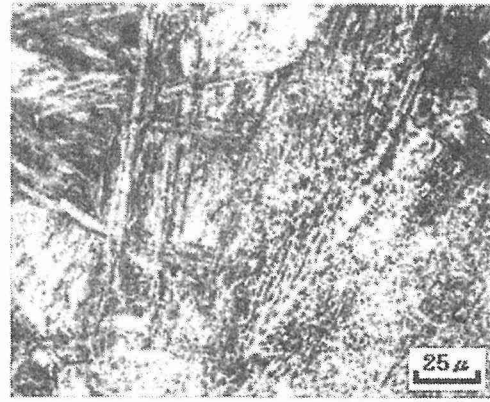


Time 380sec Hv 161

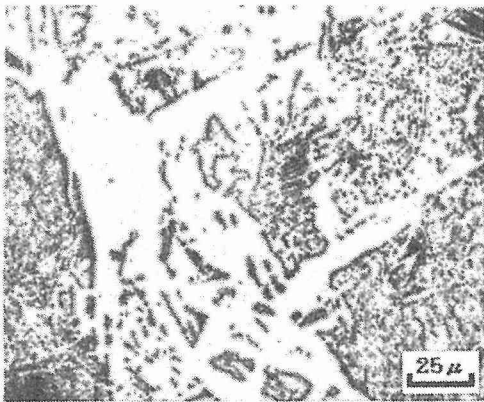




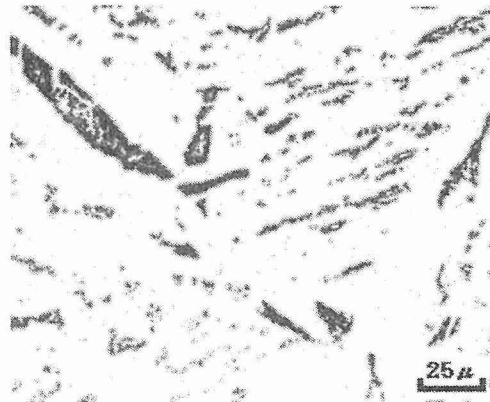
Time 9sec Hv 407



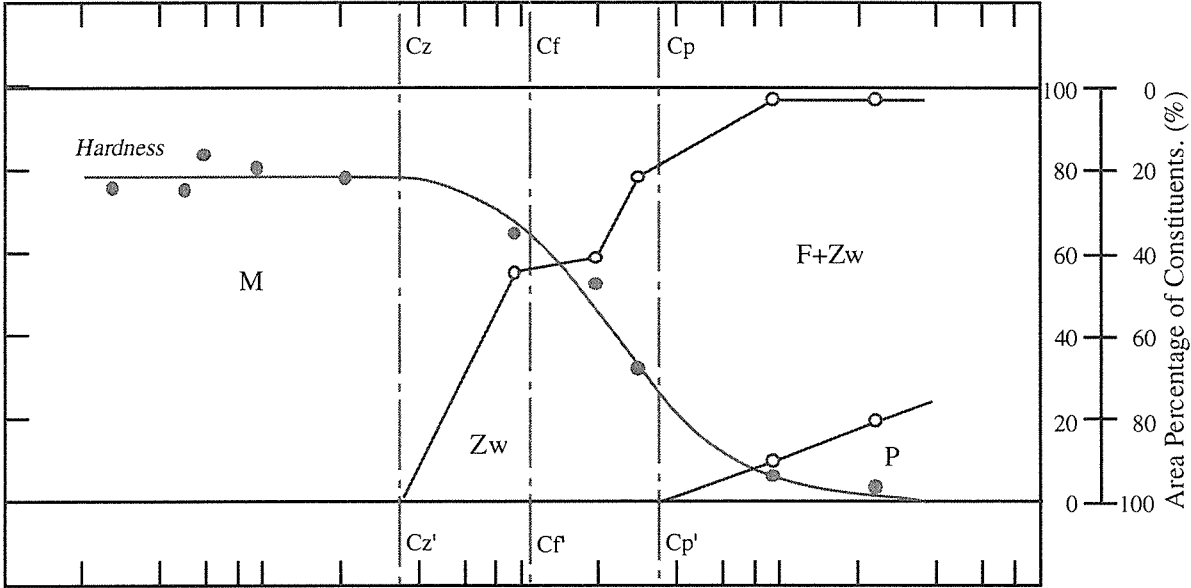
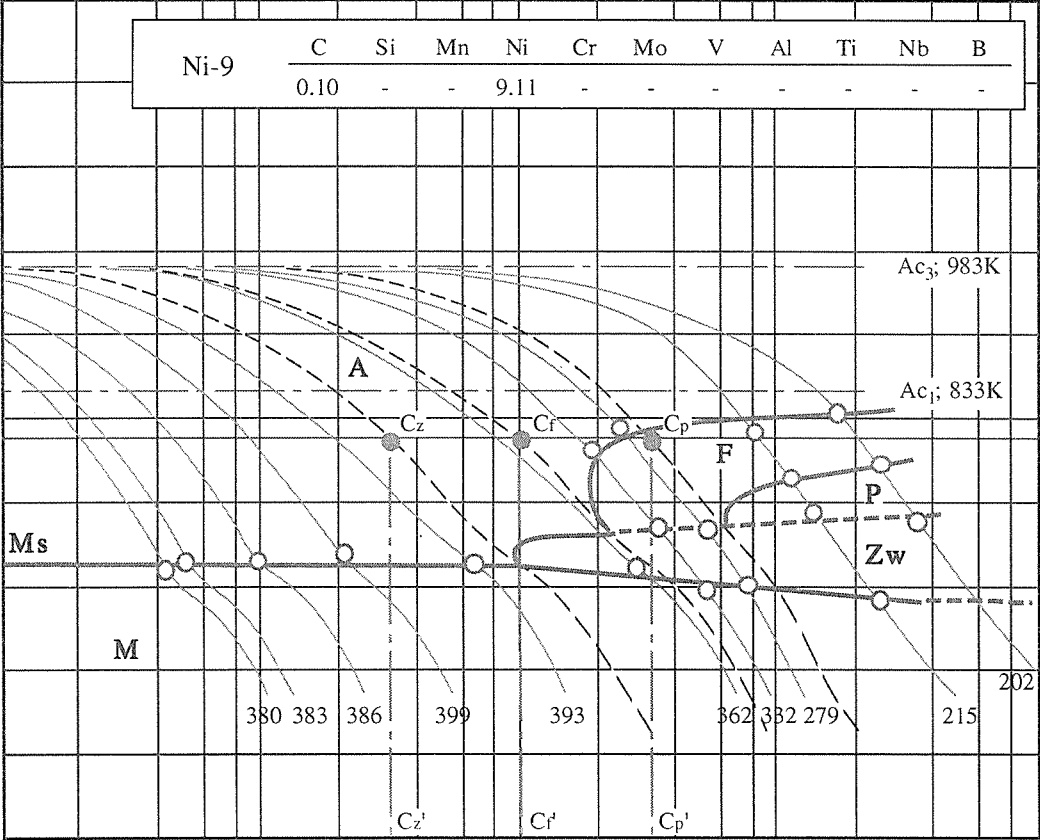
Time 30sec Hv 341

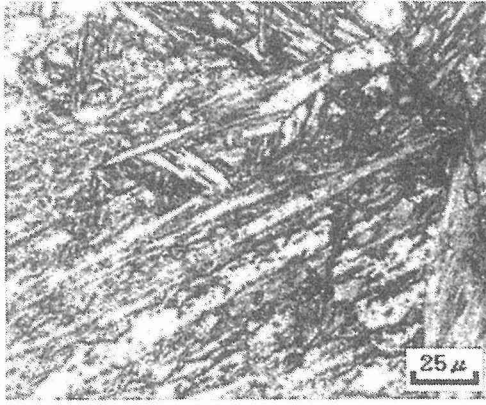


Time 1000sec Hv 183

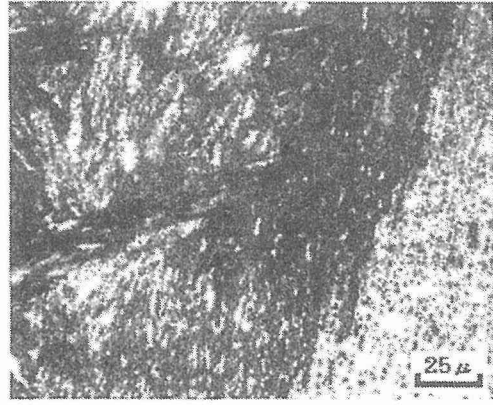


Time 3000sec Hv 190

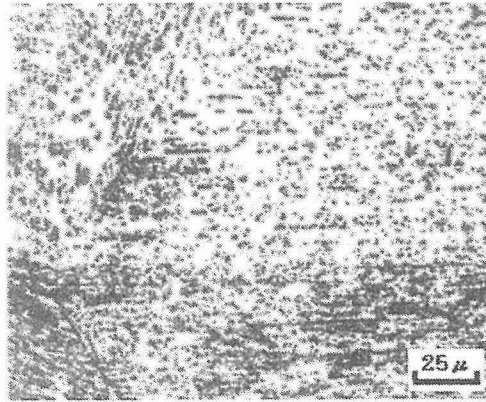




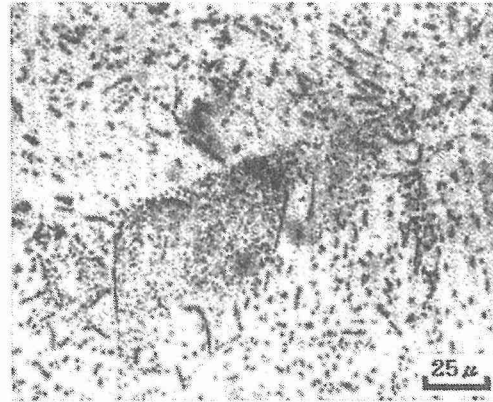
Time 2.5sec Hv 383



Time 88sec Hv 362



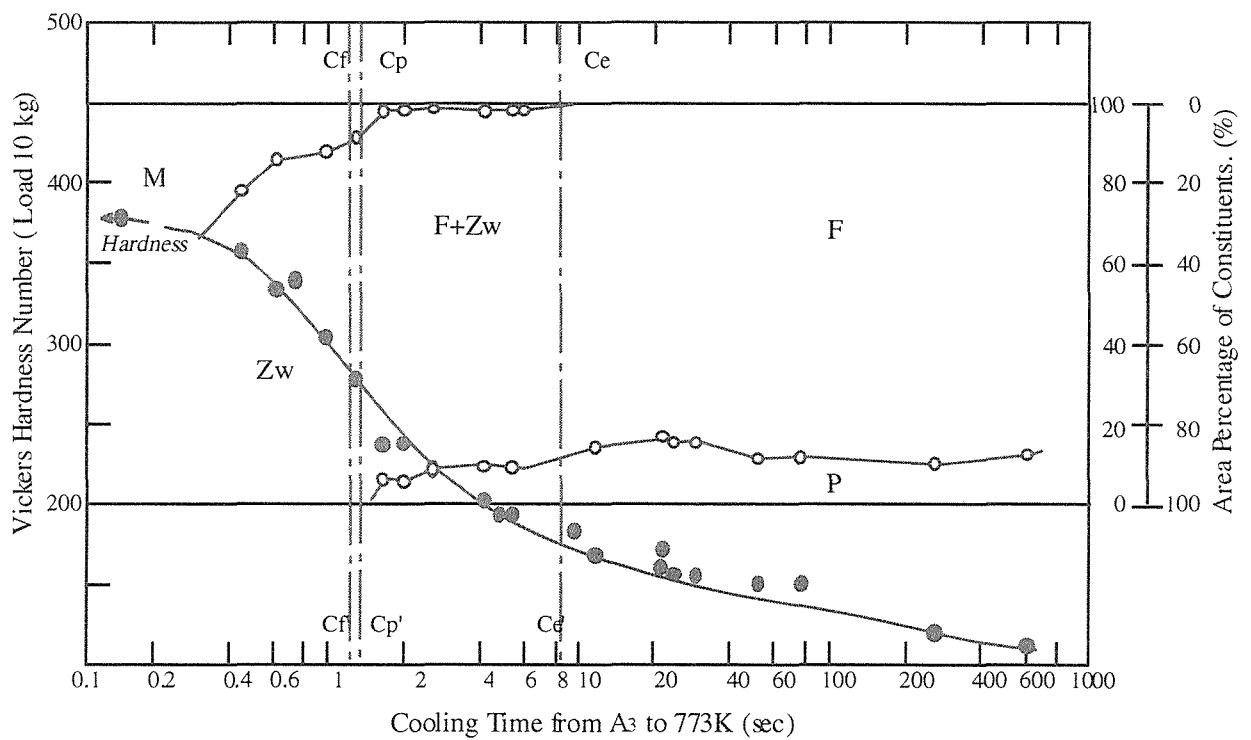
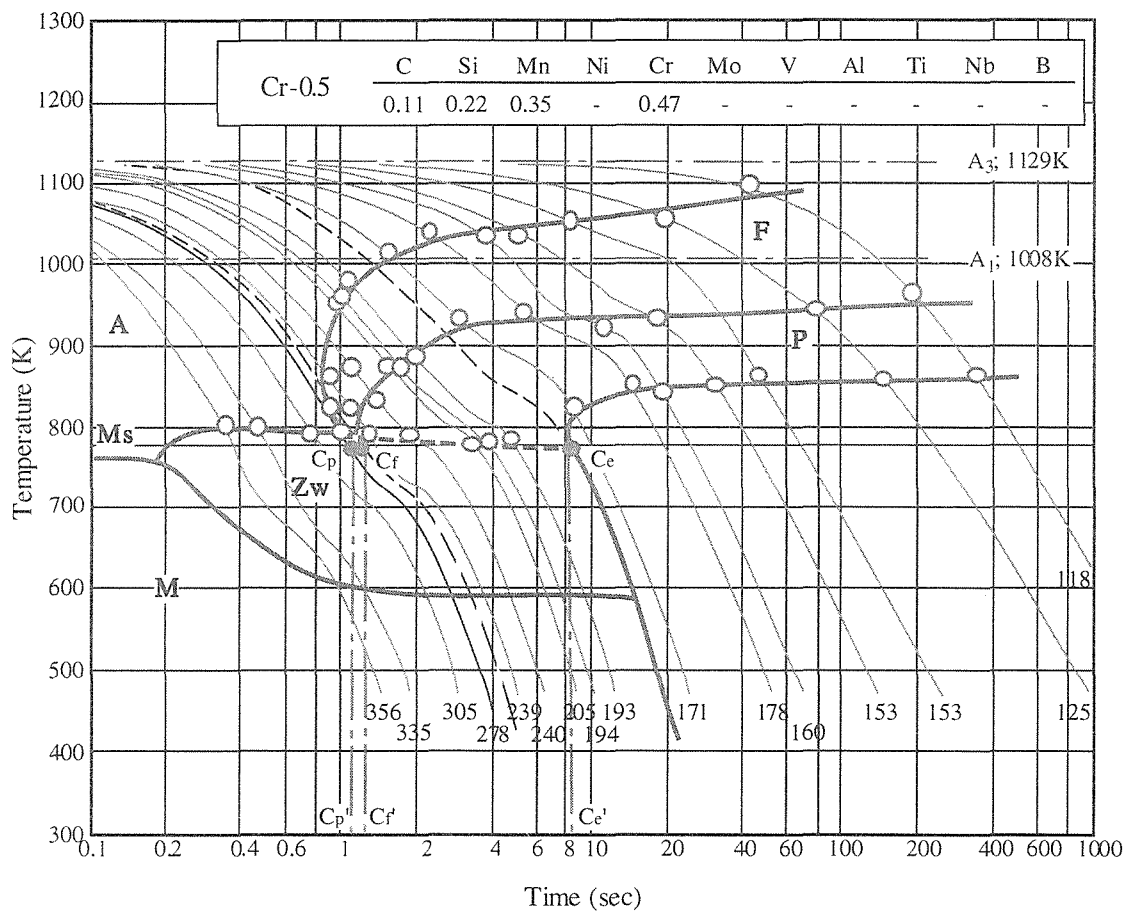
Time 180sec Hv 332

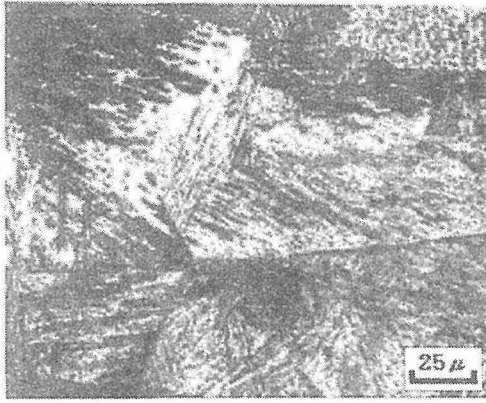


Time 2000sec Hv 202

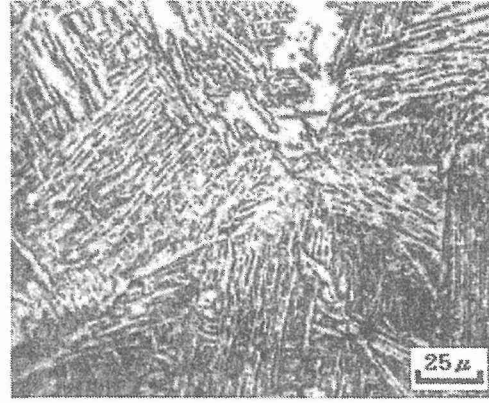
Fe-C-Cr Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Cr-0.5	0.11	0.22	0.35	-	-	-	0.47	-	-	-	-	-	-	-	50	5
Cr-1	0.1	0.23	0.35	-	-	-	1	-	-	-	-	-	-	-	52	5
Cr-2	0.1	0.23	0.35	-	-	-	1.97	-	-	-	-	-	-	-	54	5
Cr-4	0.09	0.22	0.37	-	-	-	3.86	-	-	-	-	-	-	-	56	5

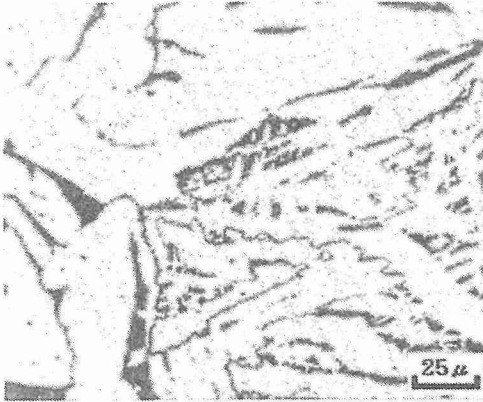




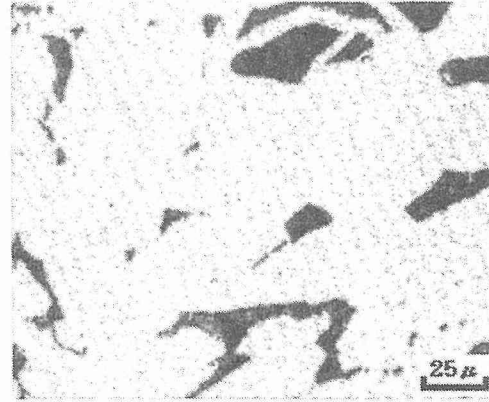
Time 0.38sec Hv 356



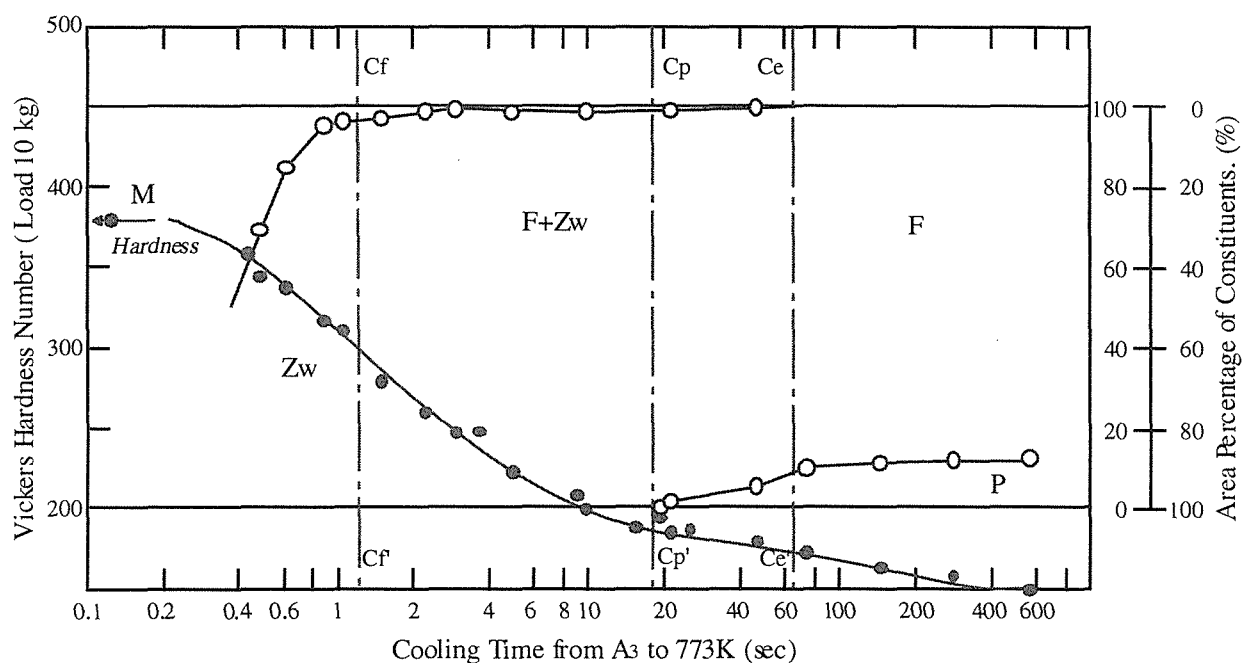
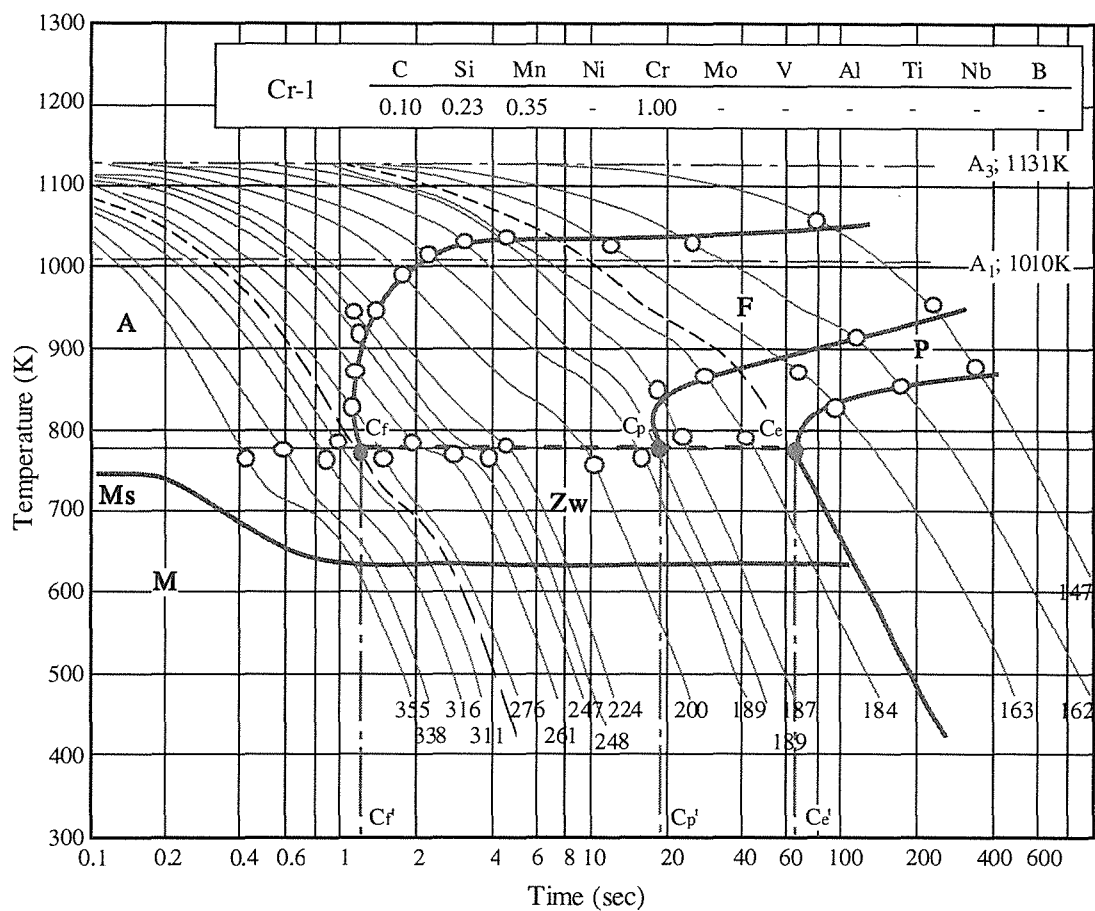
Time 4sec Hv 194

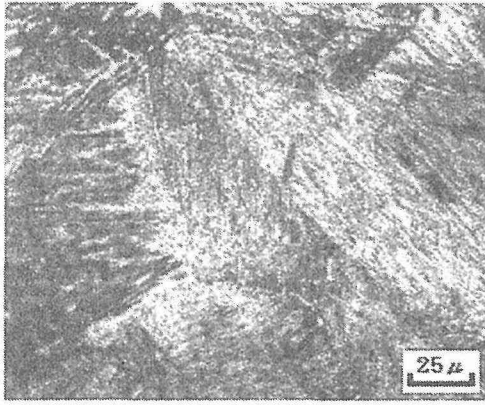


Time 45sec Hv 153

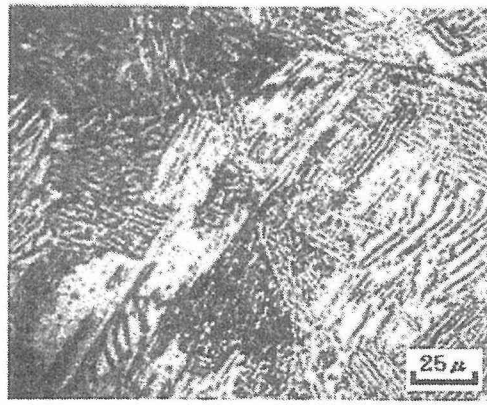


Time 500sec Hv 118

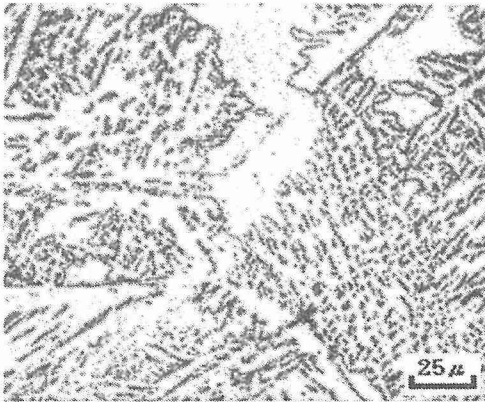




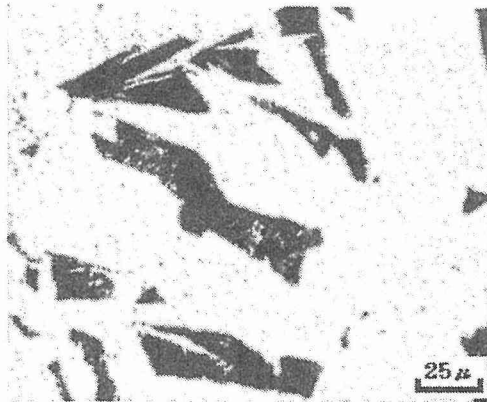
Time 0.6sec Hv 338



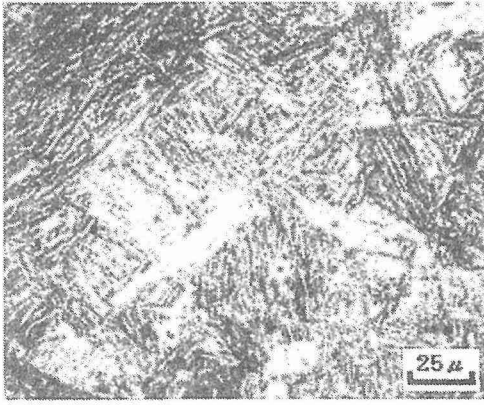
Time 4.8sec Hv 224



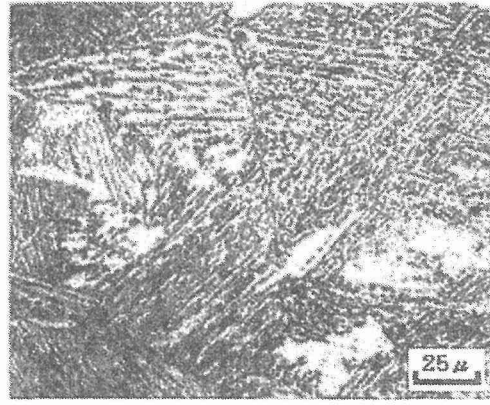
Time 19sec Hv 189



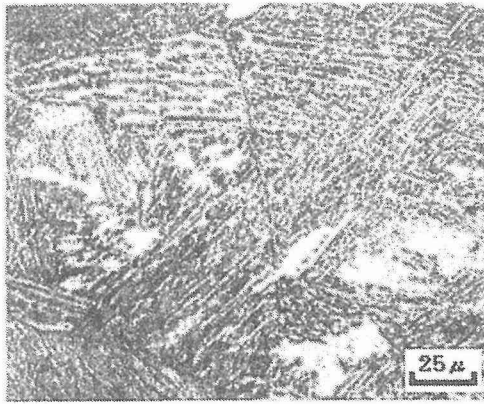
Time 540sec Hv 147



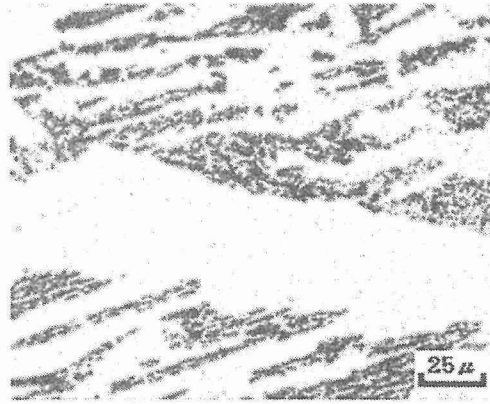
Time 0.6sec Hv 383



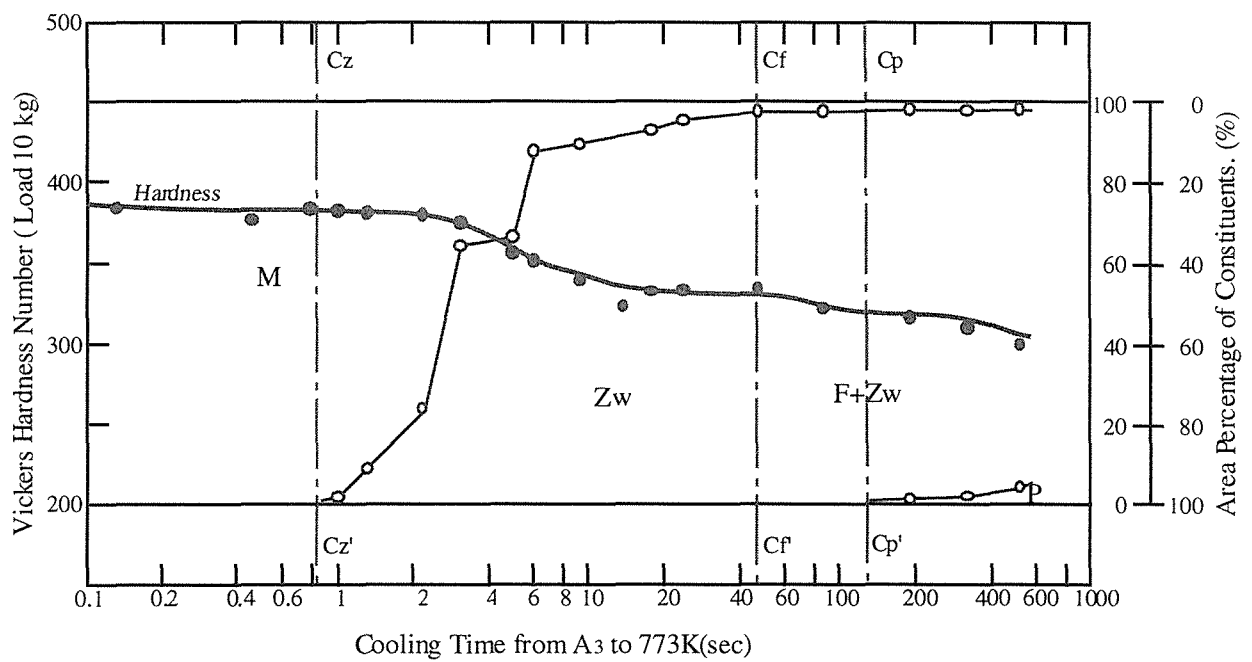
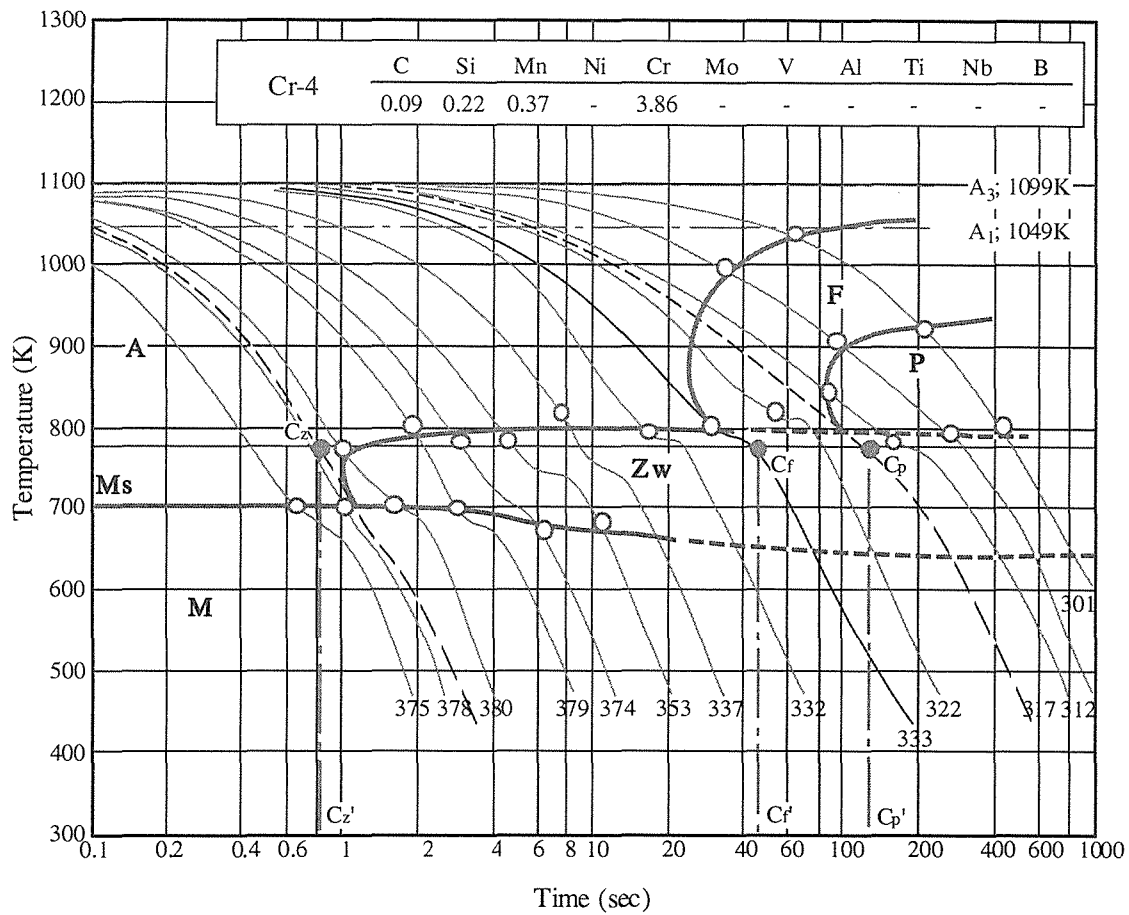
Time 11sec Hv 262

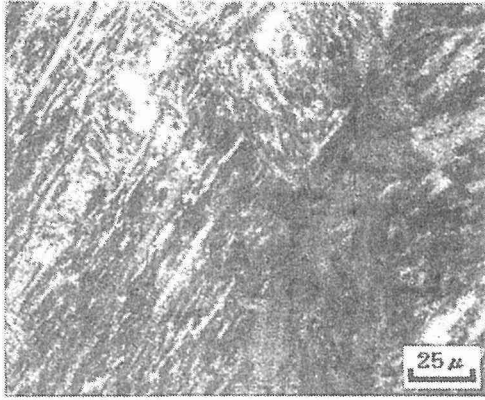


Time 22sec Hv 244

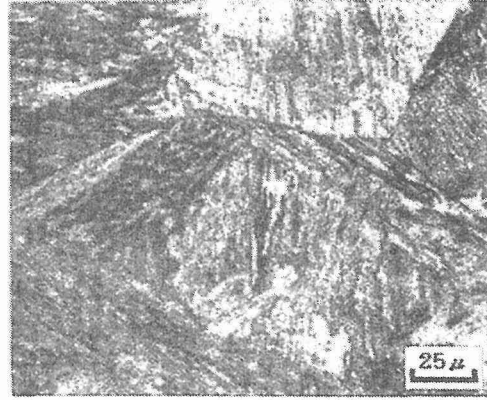


Time 500sec Hv 177

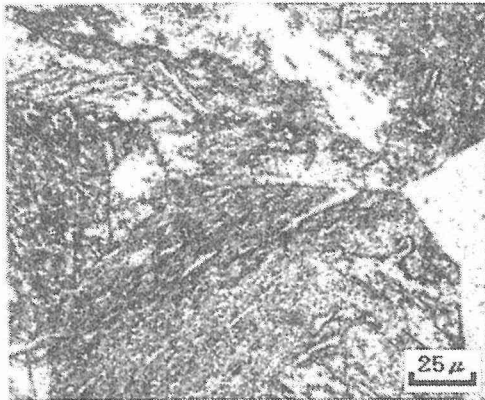




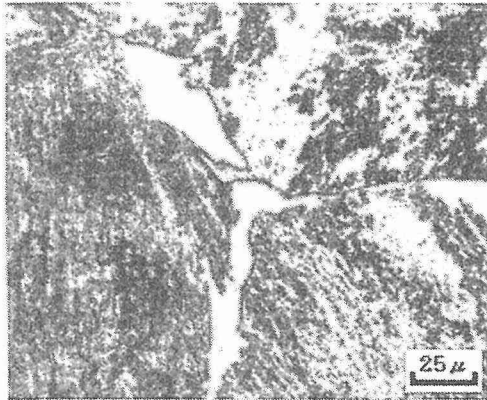
Time 0.80sec Hv 378



Time 9sec Hv 337



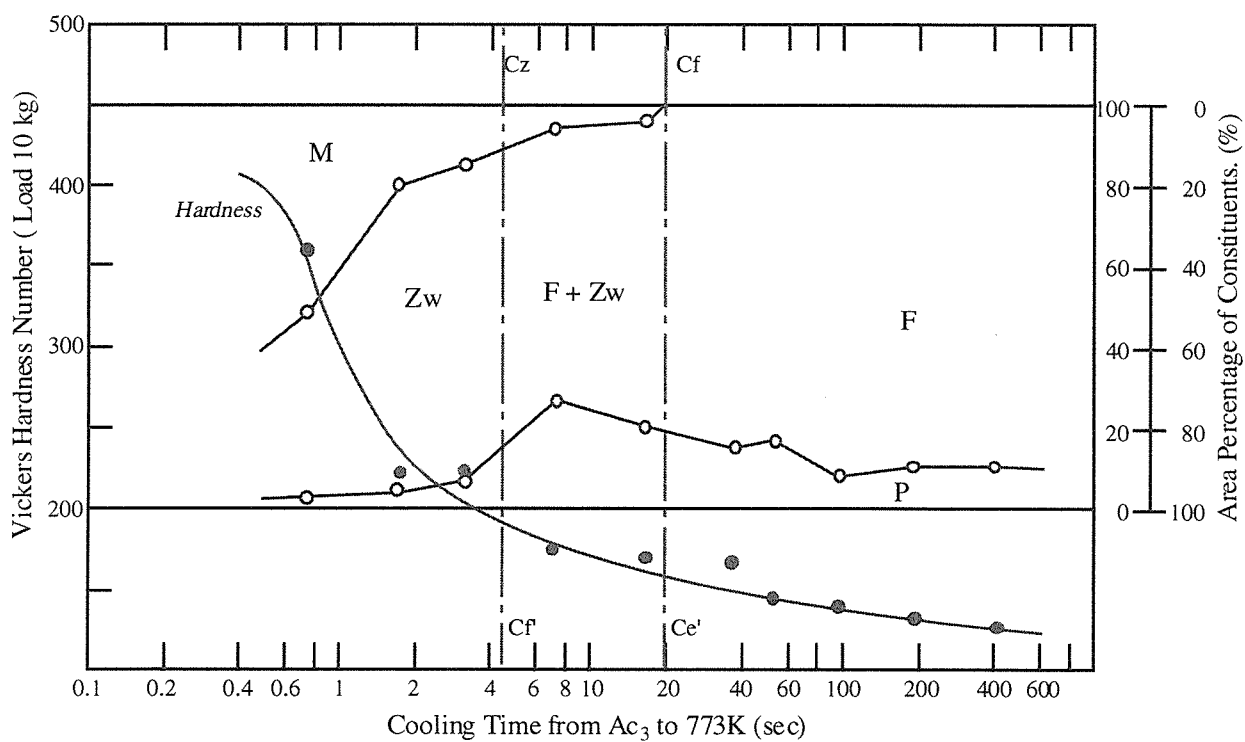
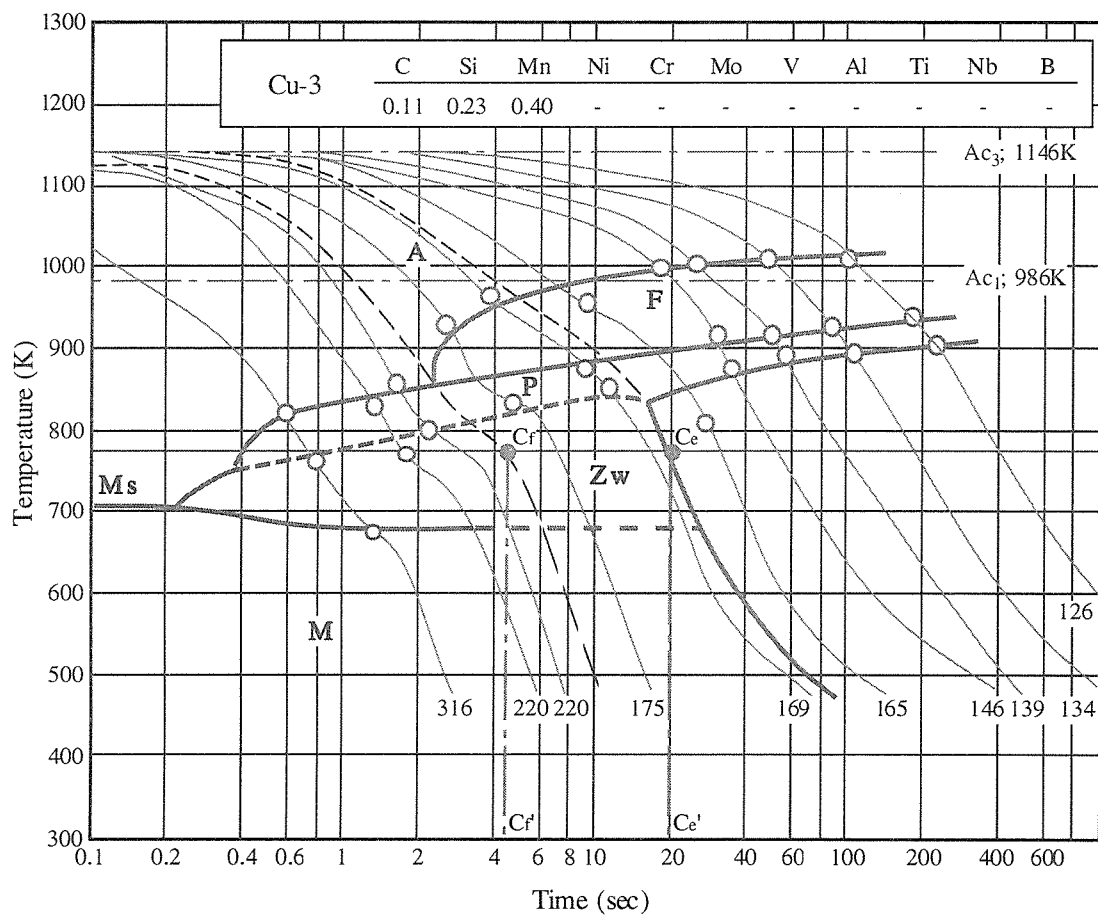
Time 45sec Hv 333

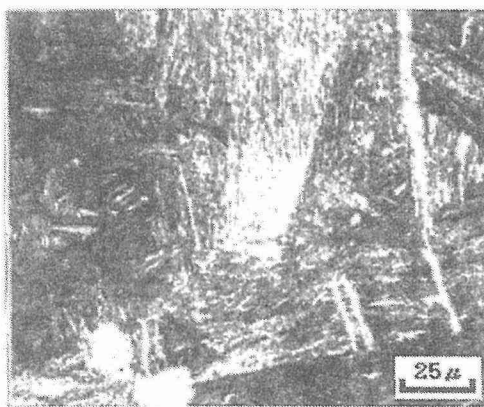


Time 200sec Hv 312

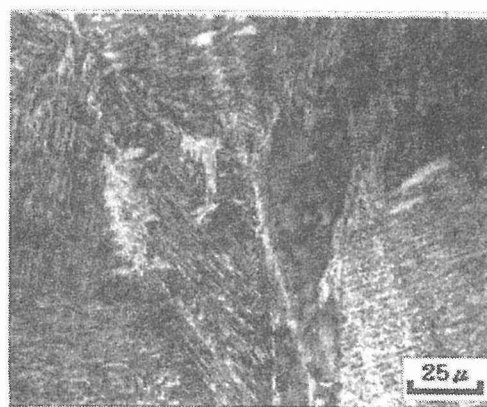
Fe-C-Cu Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Cu-3	0.11	0.23	0.4	-	-	-	-	0.42	-	-	-	-	-	-	60	P

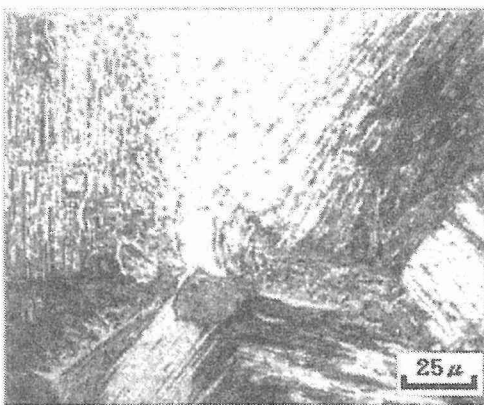




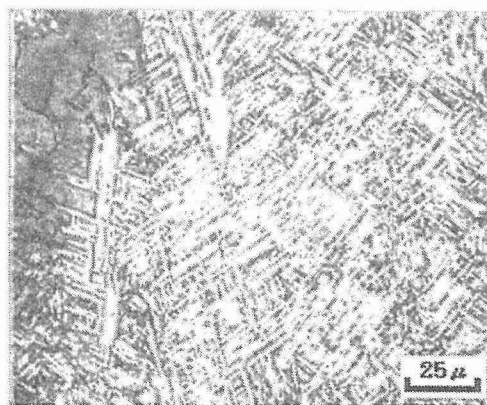
Time 0.7sec Hv 316



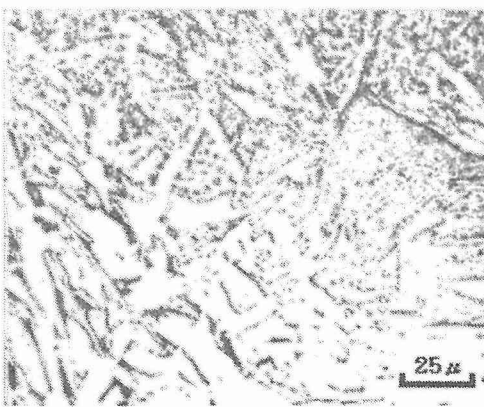
Time 1.8sec Hv 220



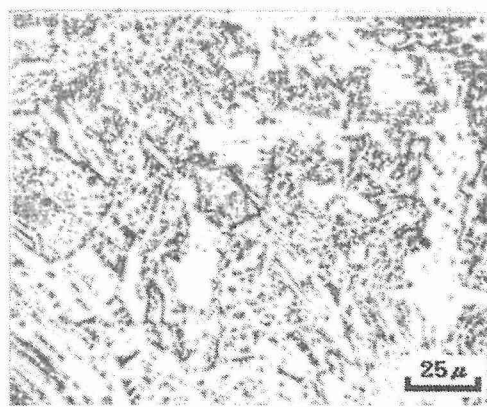
Time 3sec Hv 220



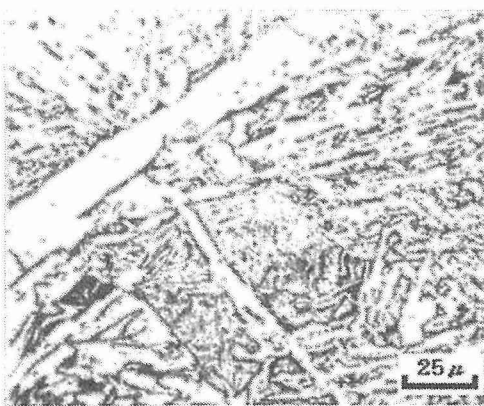
Time 7sec Hv 175



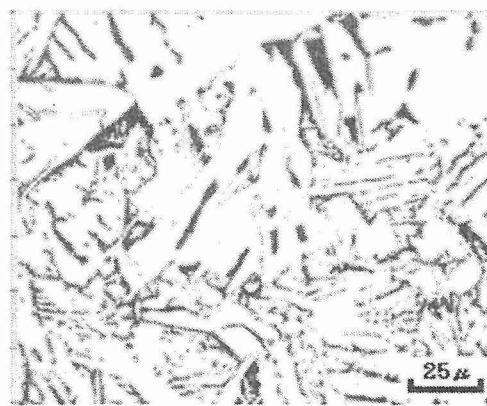
Time 18sec Hv 169



Time 32sec Hv 165



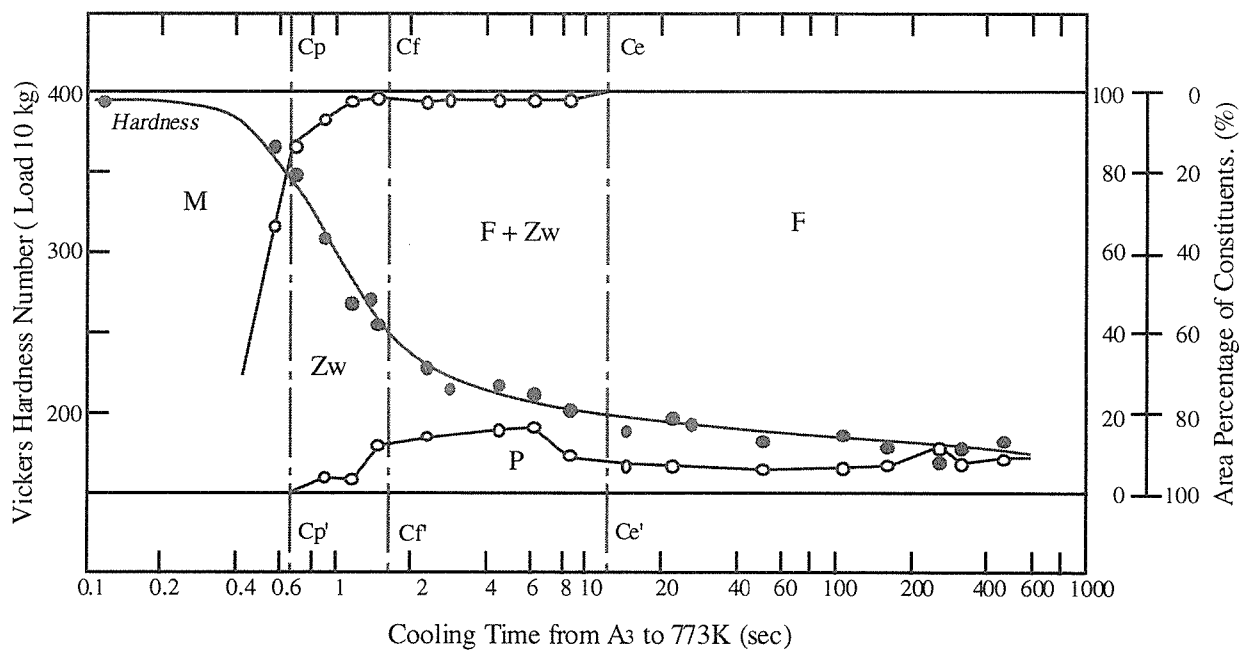
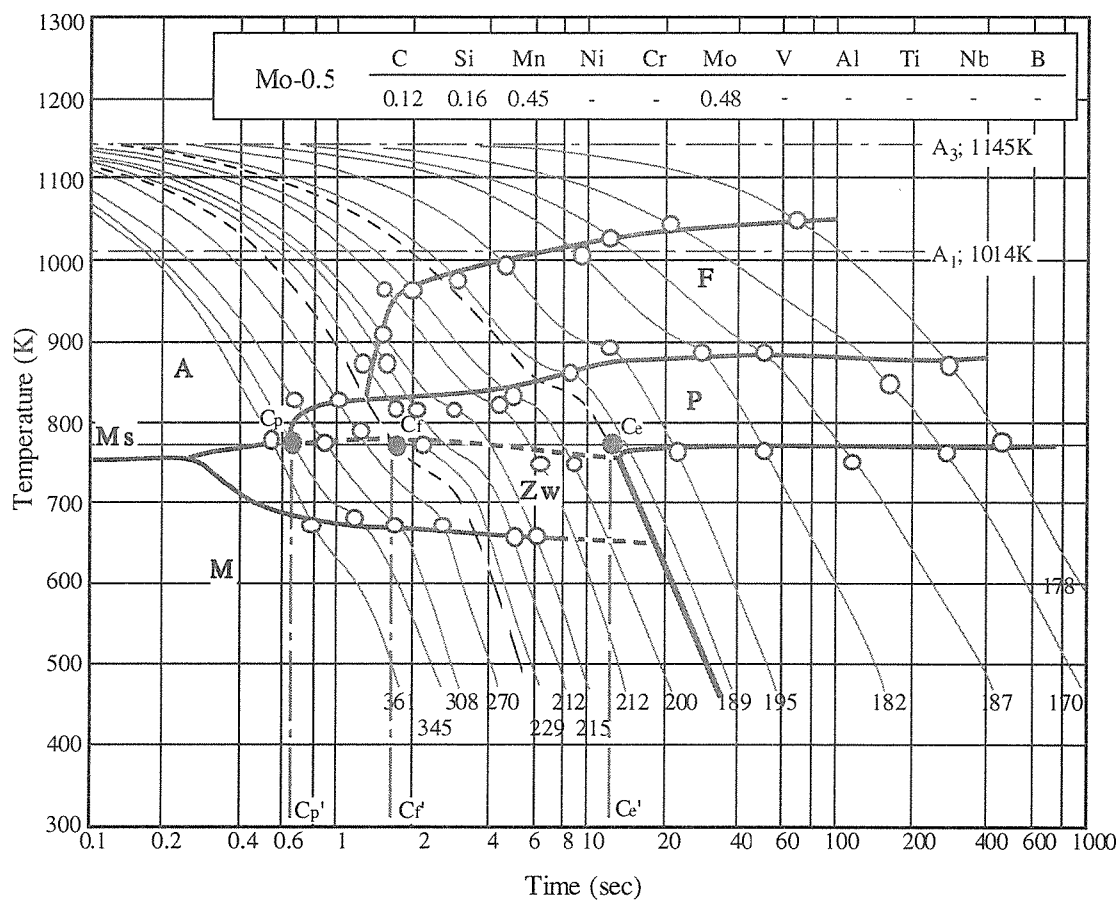
Time 50sec Hv 146

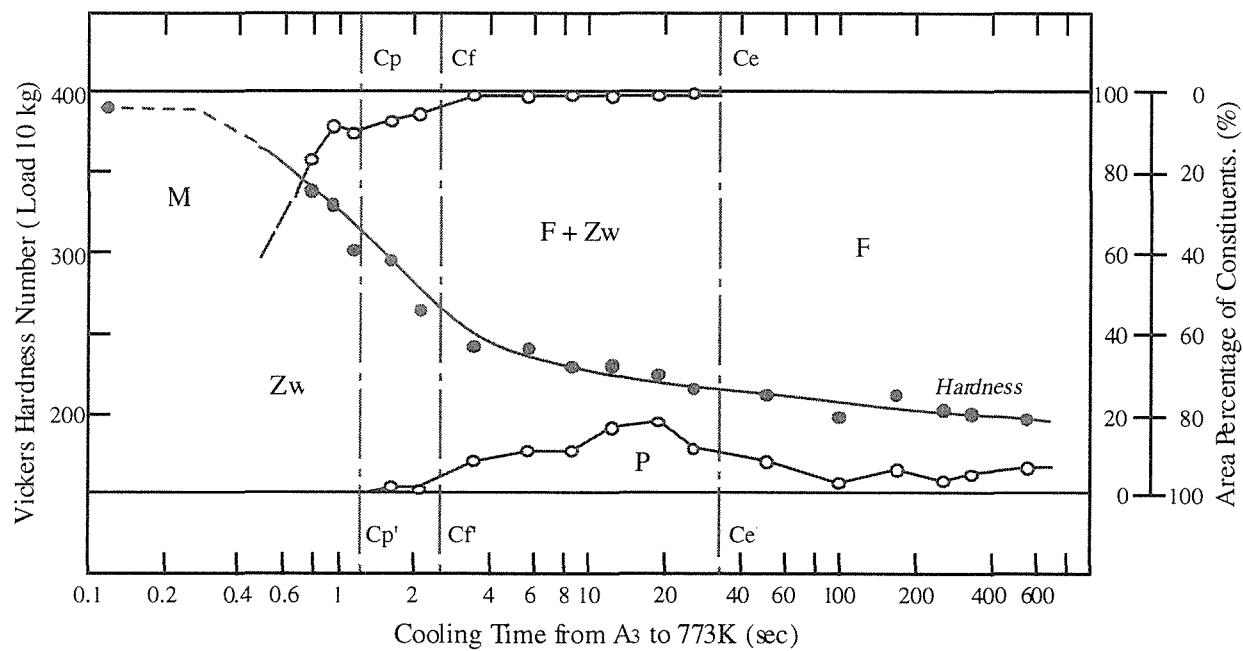
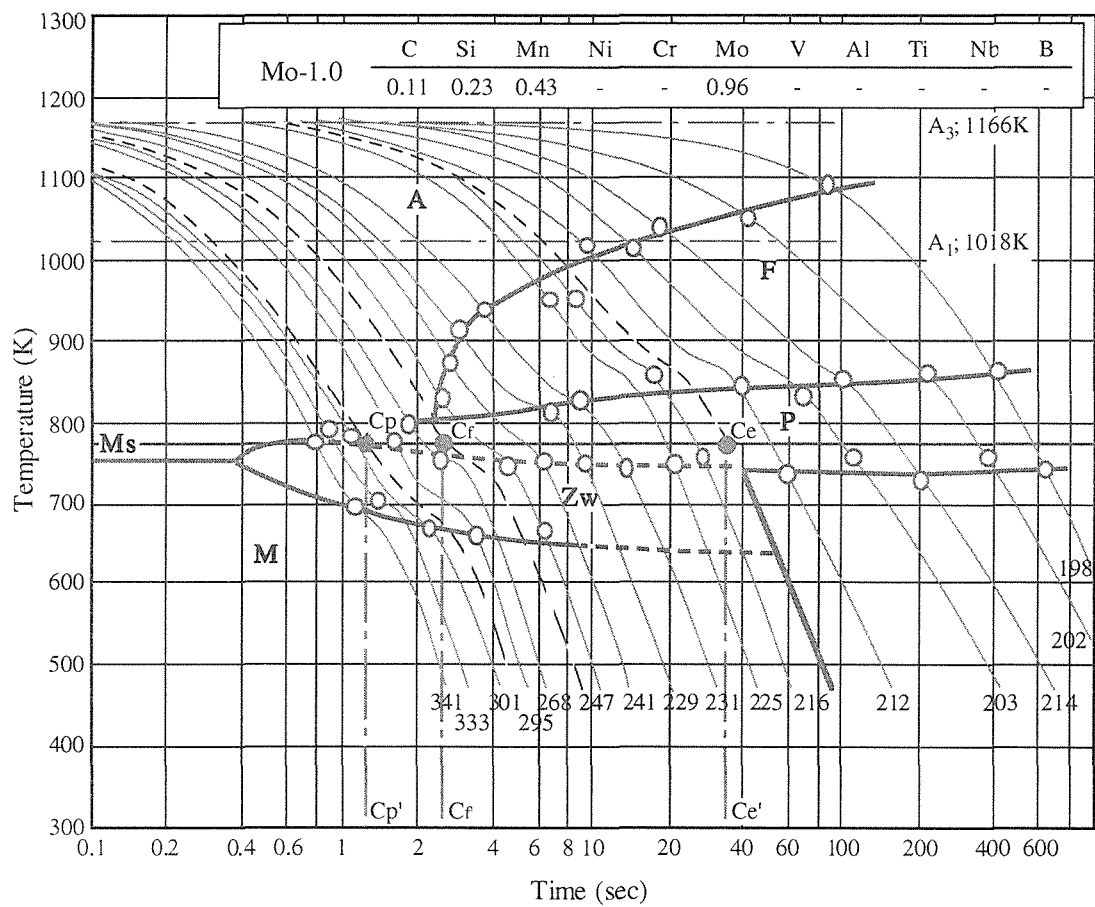


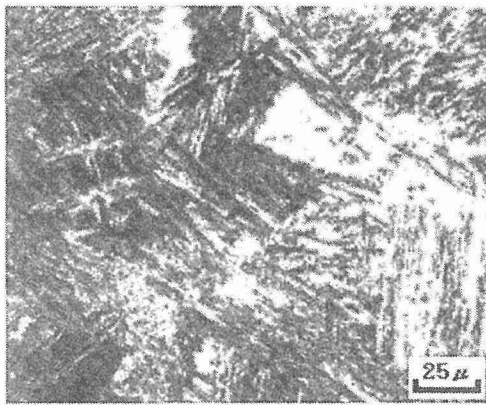
Time 100sec Hv 139

Fe-C-Mo Alloy

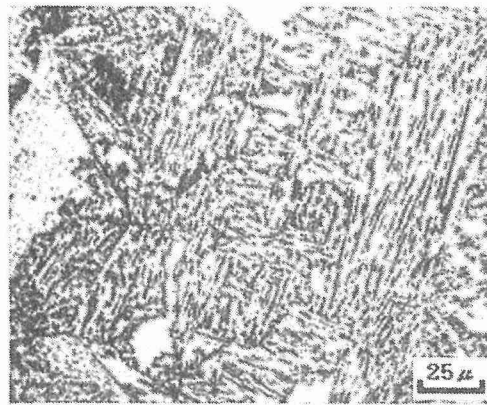
Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Mo-0.5	0.12	0.16	0.45	-	-	-	-	-	0.48	-	-	-	-	-	64	P
Mo-1.0	0.11	0.23	0.43	-	-	-	-	-	0.96	-	-	-	-	-	66	6
Mo-1.6	0.11	0.22	0.37	-	-	-	-	-	1.66	-	-	-	-	-	68	6



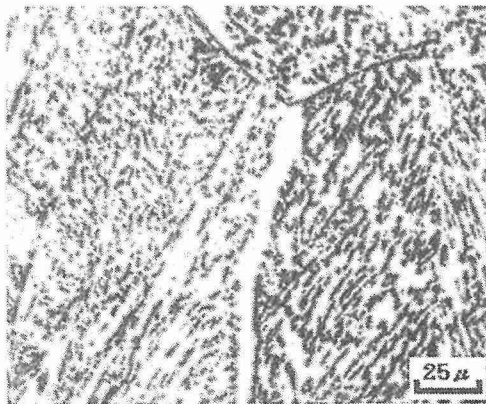




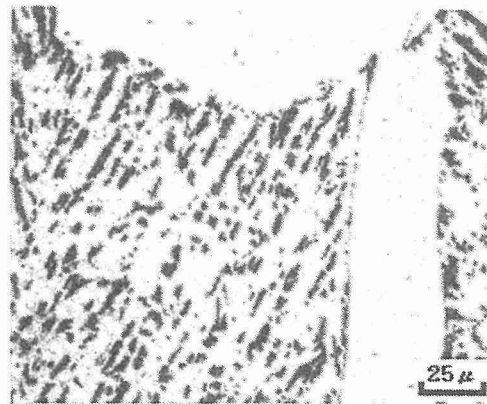
Time 0.8sec Hv 341



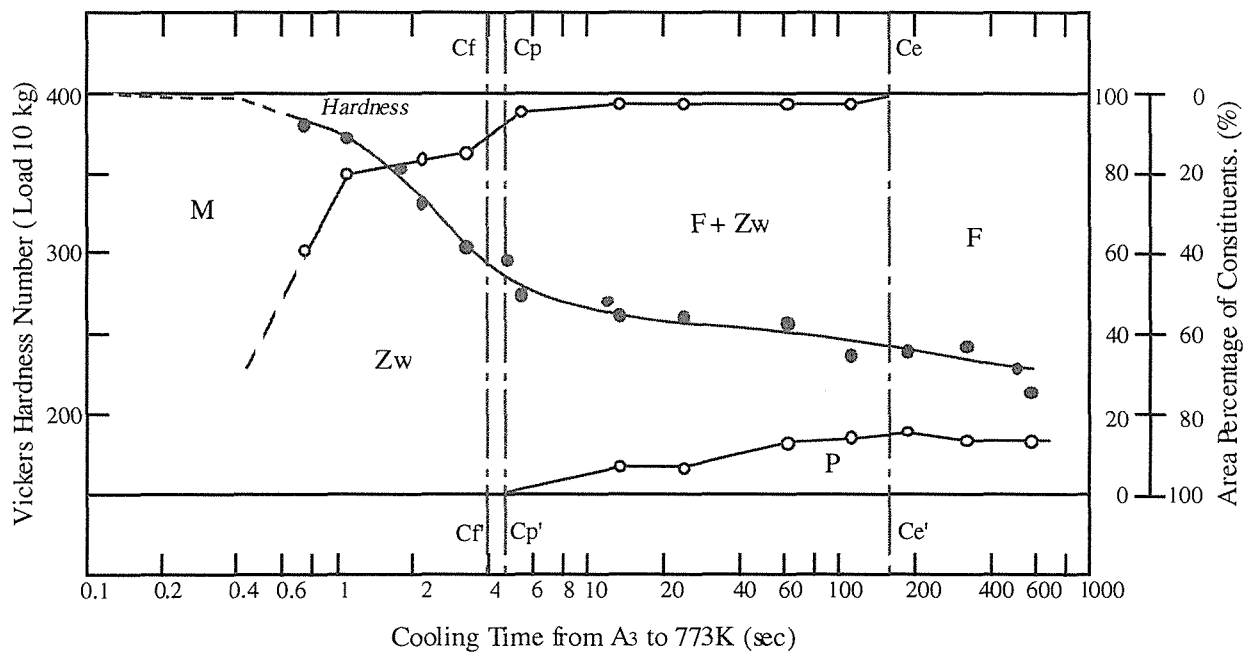
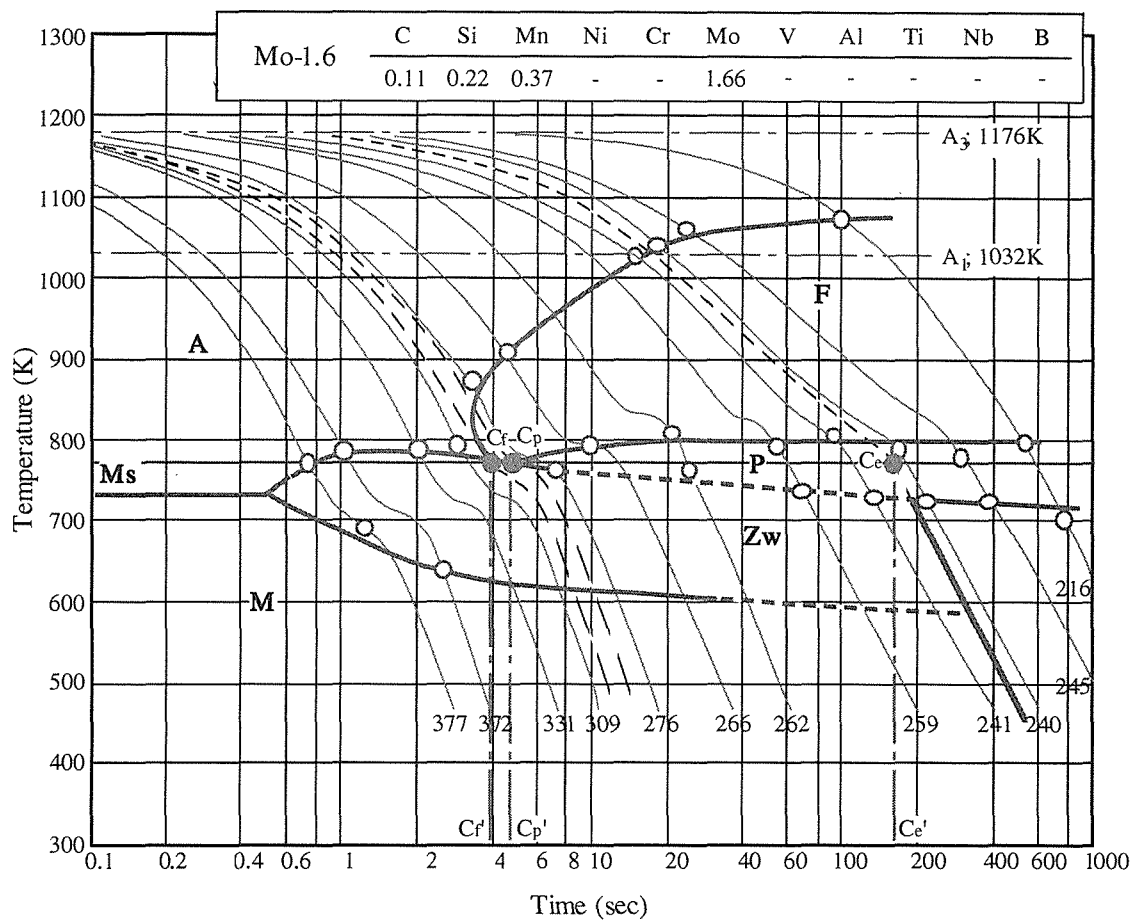
Time 5.3sec Hv 241

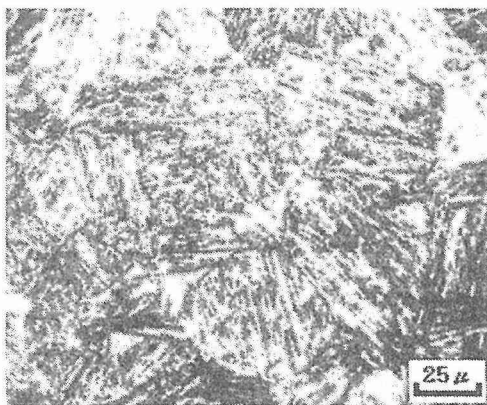


Time 25sec Hv 216

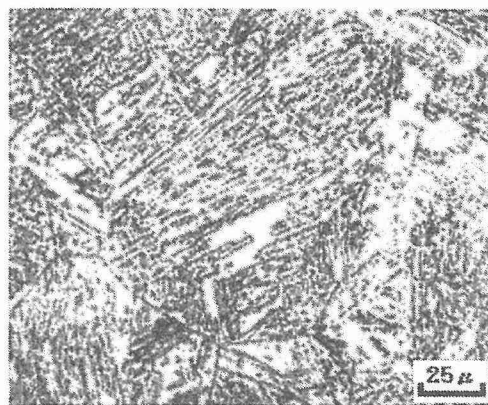


Time 350sec Hv 202

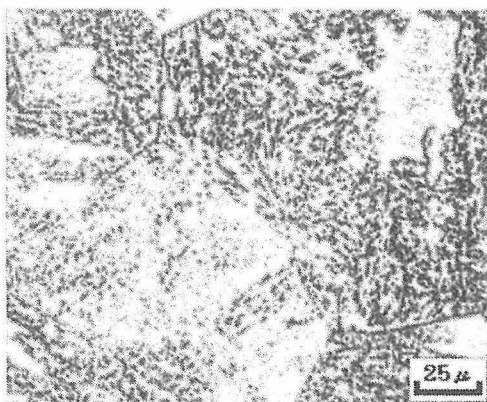




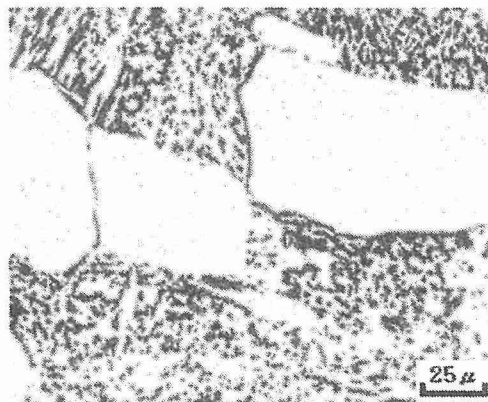
Time 0.75sec Hv 377



Time 7sec Hv 276



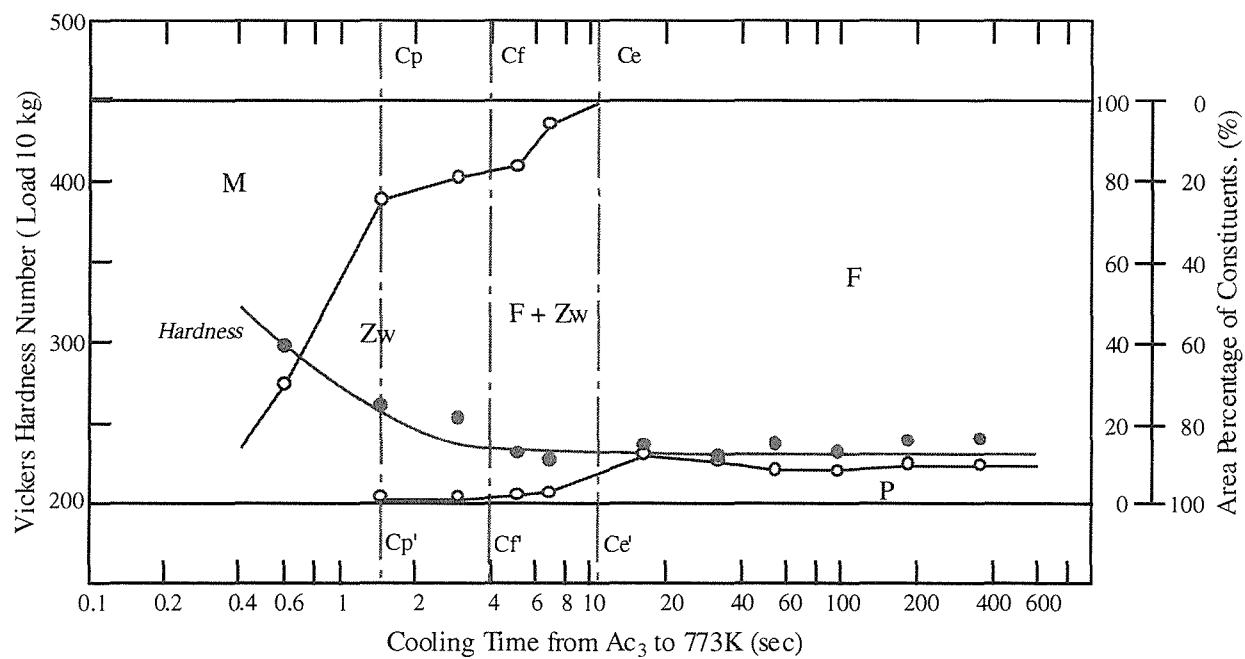
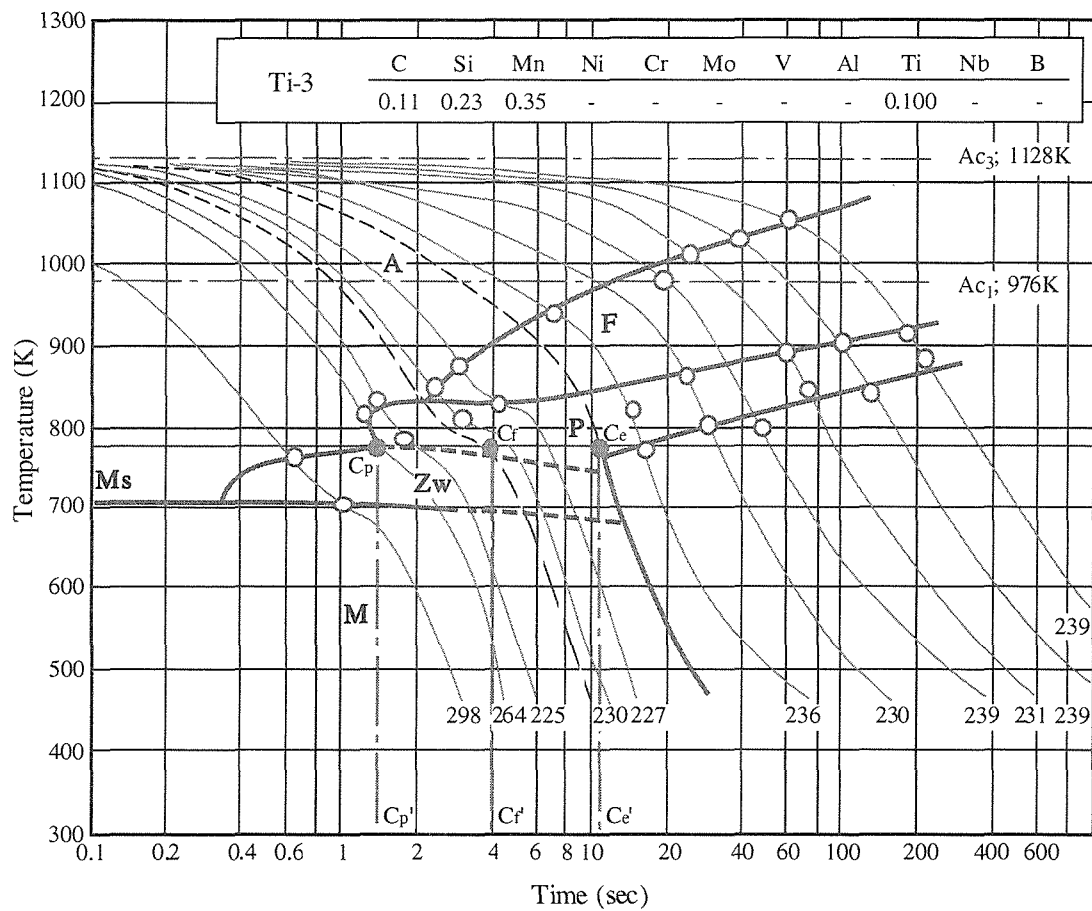
Time 25sec Hv 262

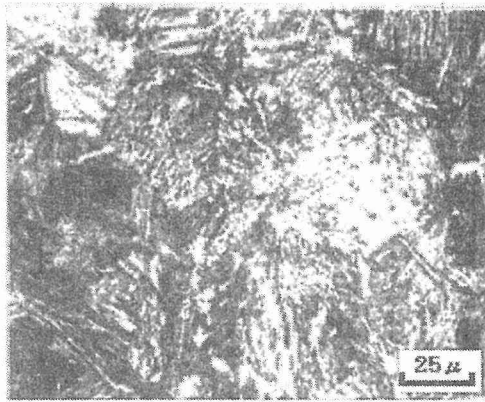


Time 590sec Hv 216

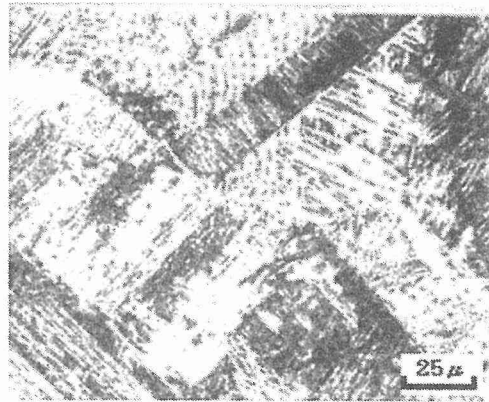
Fe-C-Ti Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Ti-3	0.11	0.23	0.35	-	-	-	-	-	-	-	0.1	-	-	-	72	P

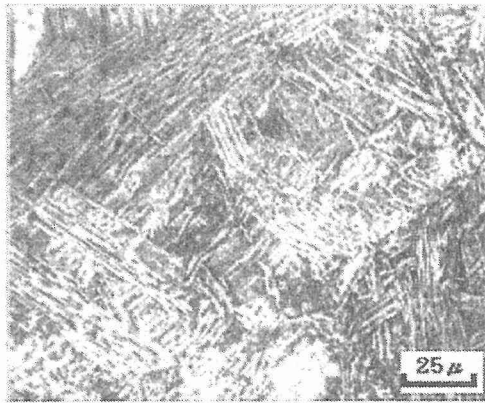




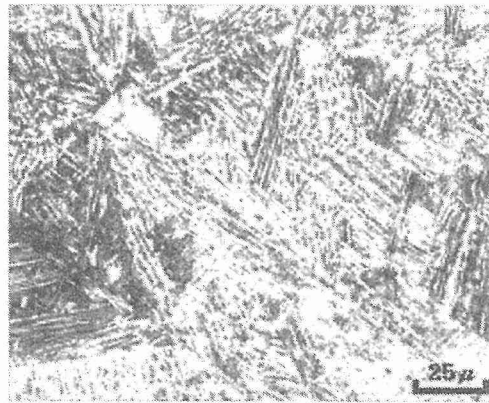
Time 0.6sec Hv 298



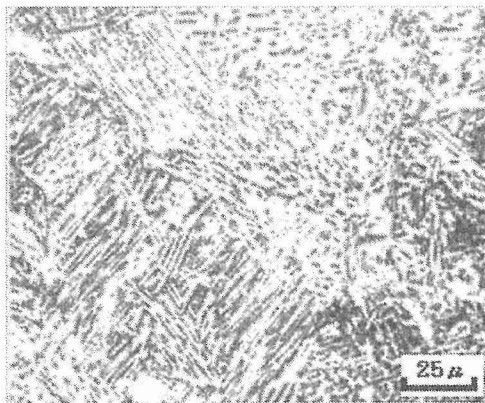
Time 1.5sec Hv 264



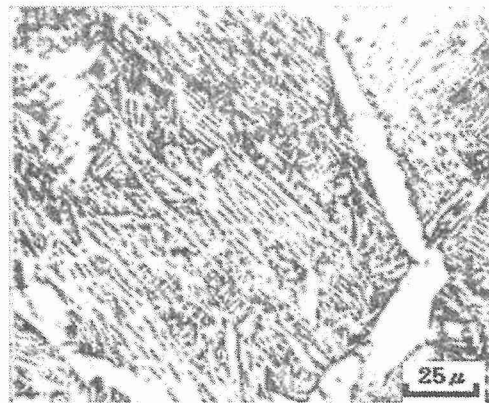
Time 2sec Hv 225



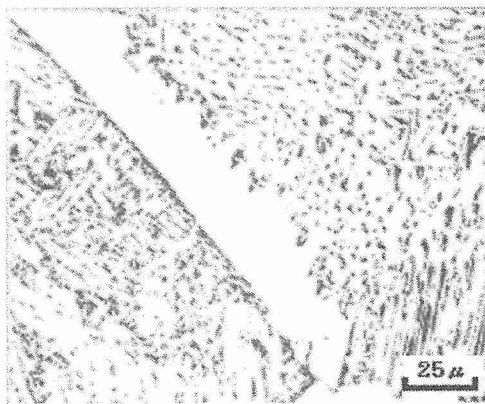
Time 4.8sec Hv 230



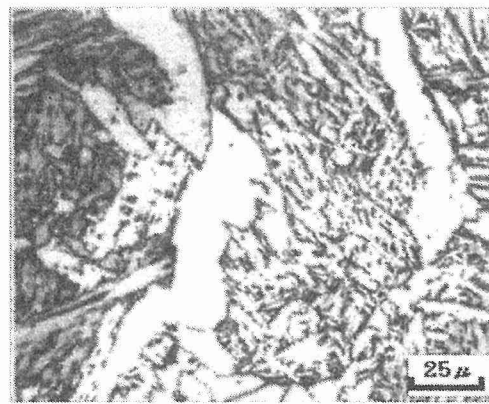
Time 6.5sec Hv 227



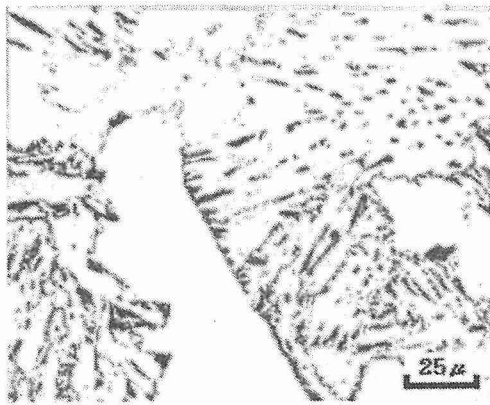
Time 17sec Hv 236



Time 32sec Hv 230



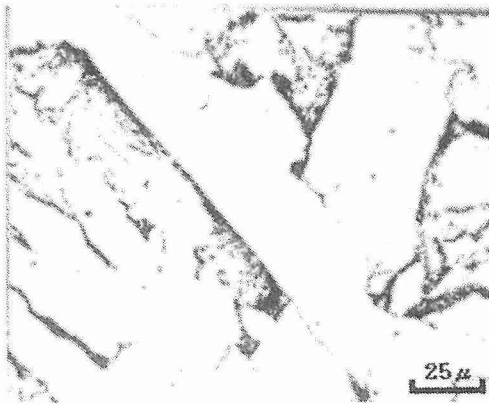
Time 52sec Hv 239



Time 90sec Hv 231



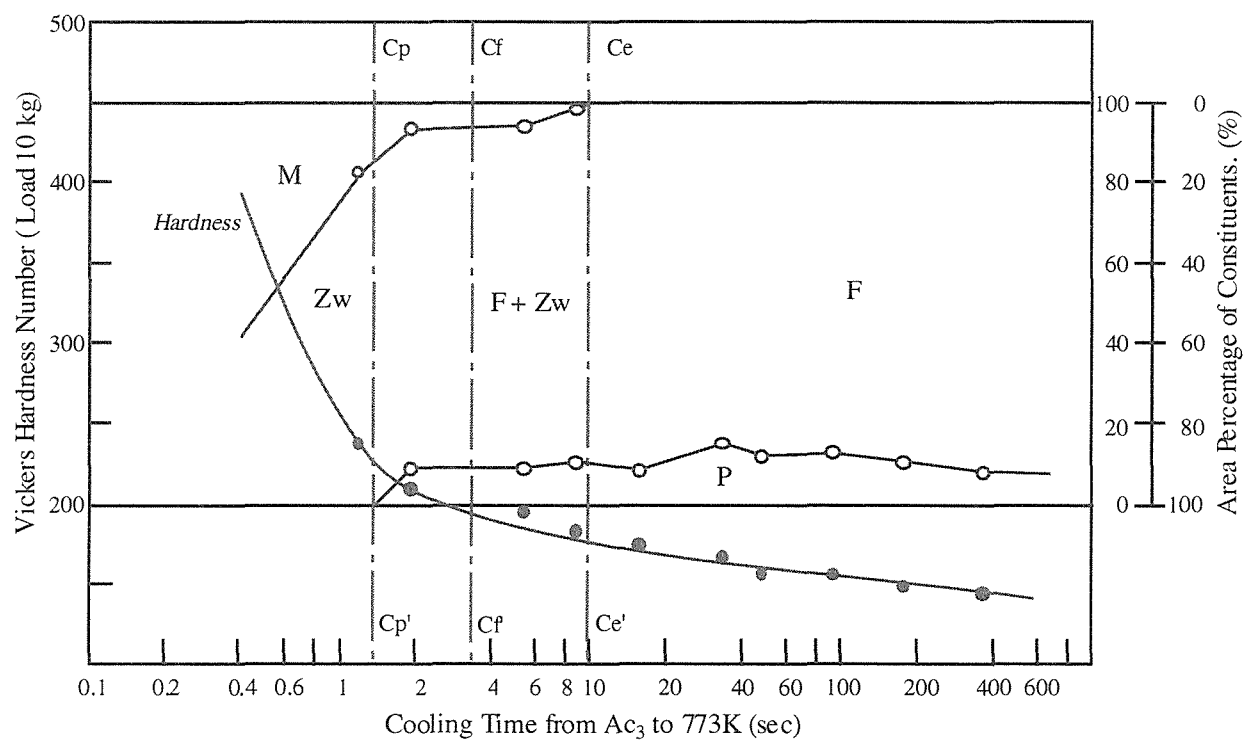
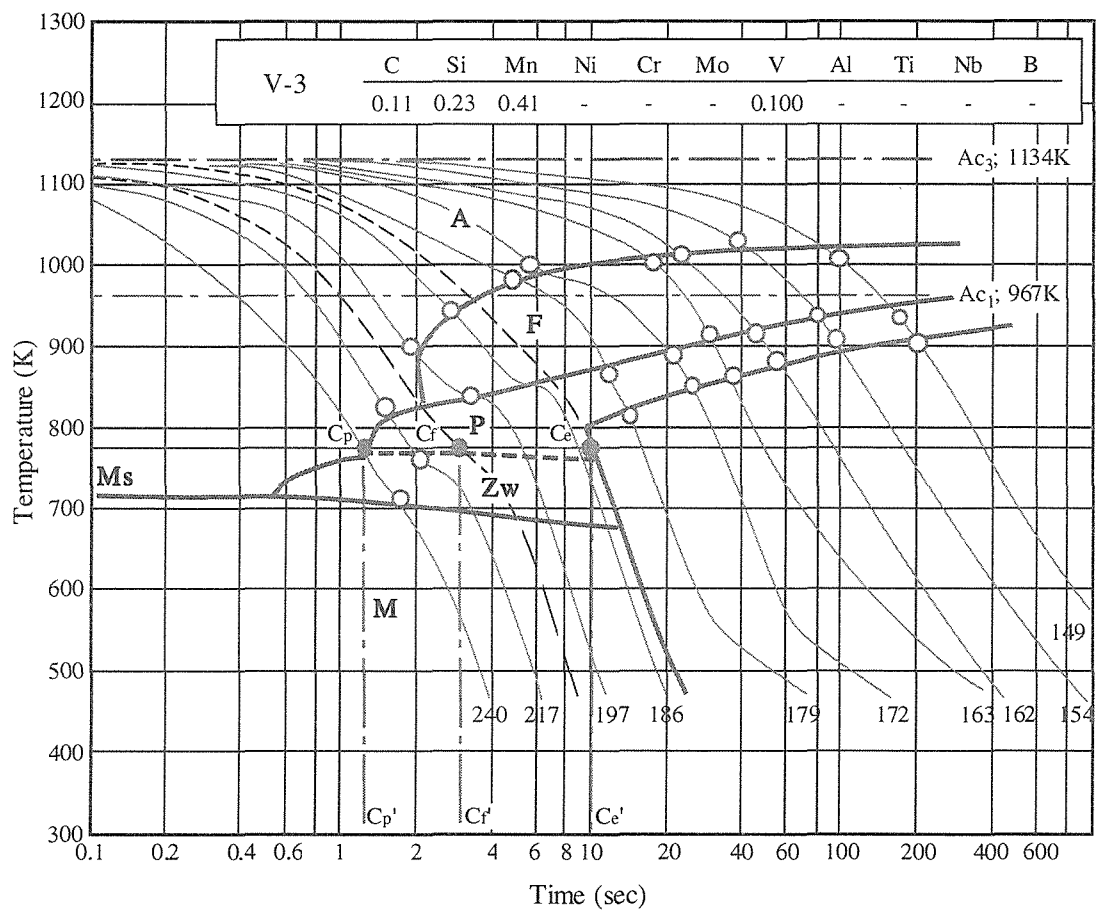
Time 180sec Hv 239

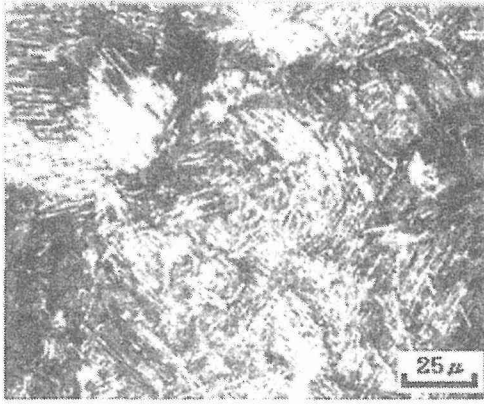


Time 350sec Hv 239

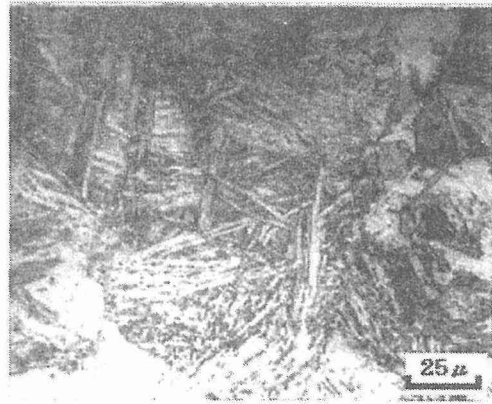
Fe-C-V Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
V-3	0.11	0.23	0.41	-	-	-	-	-	-	0.1	-	-	-	-	76	P

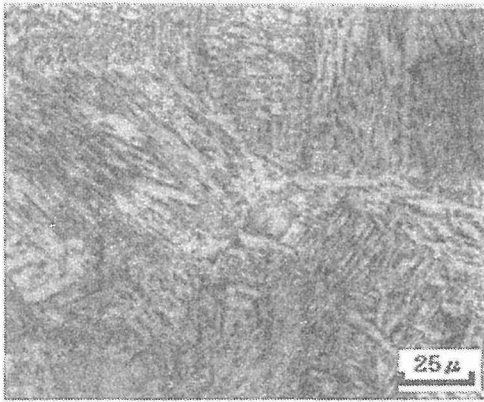




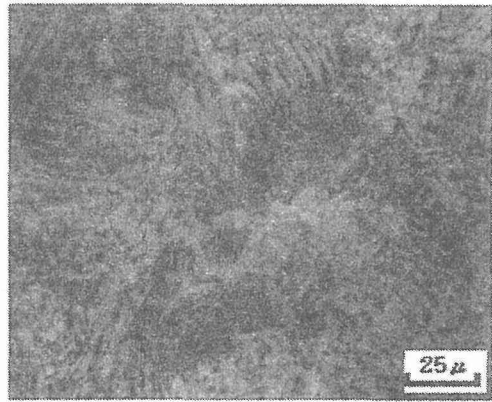
Time 1.3sec Hv 240



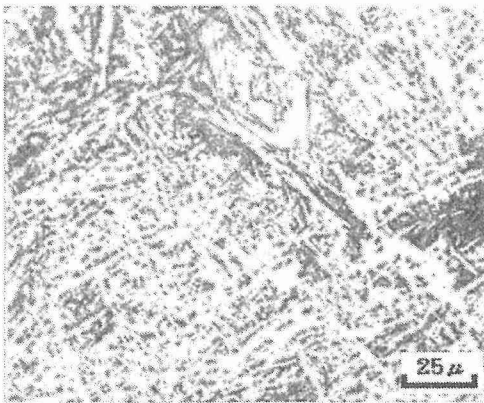
Time 1.9sec Hv 217



Time 5.3sec Hv 197



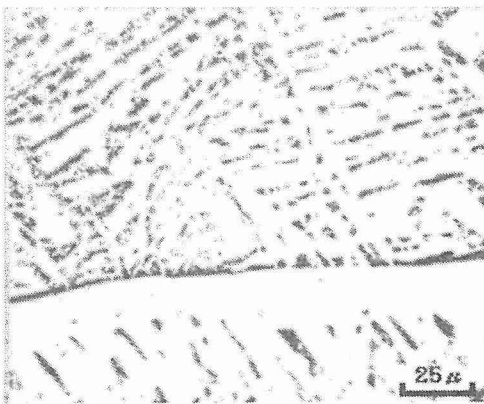
Time 9sec Hv 186



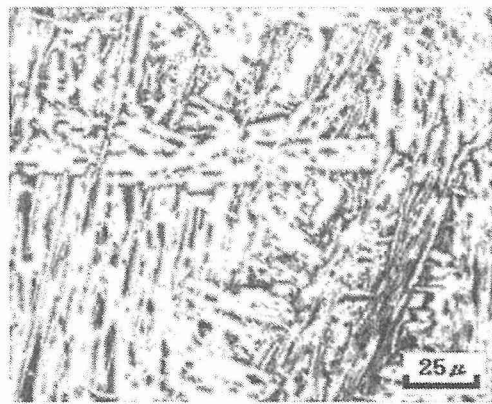
Time 16sec Hv 179



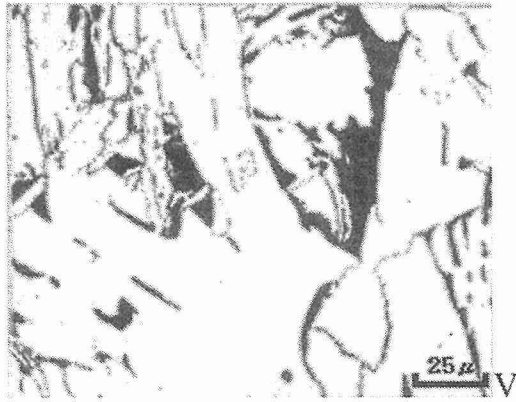
Time 34sec Hv 172



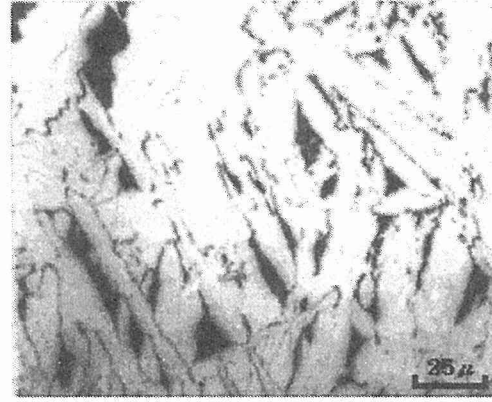
Time 50sec Hv 163



Time 90sec Hv 162



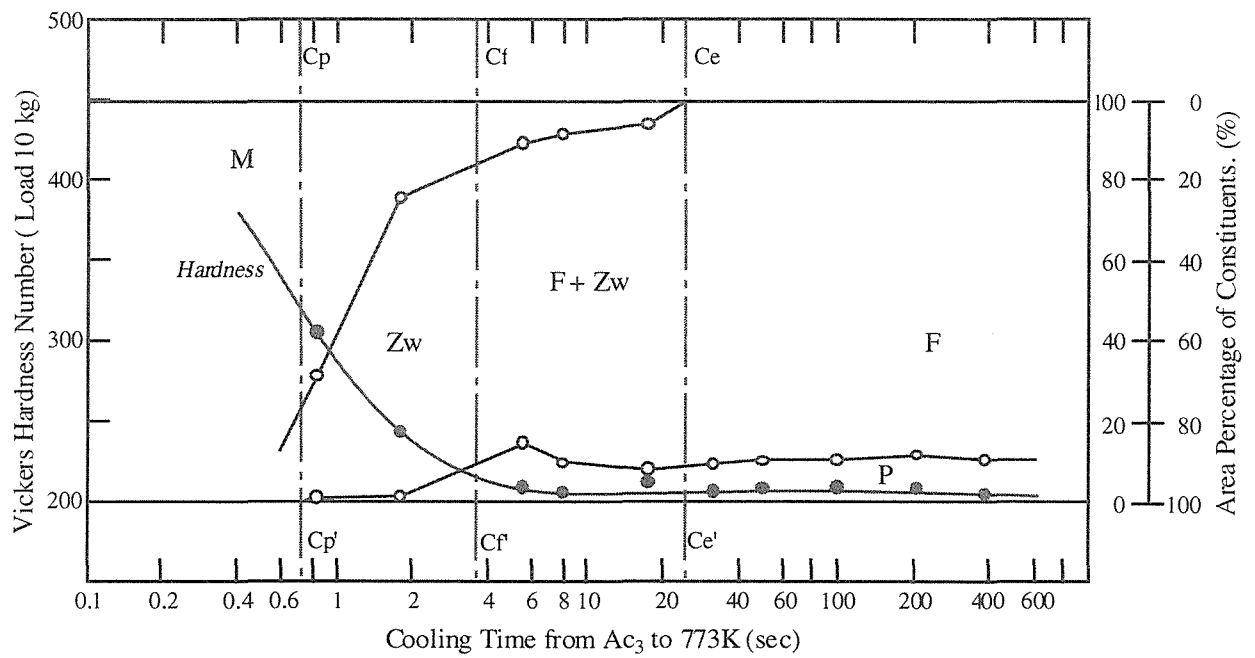
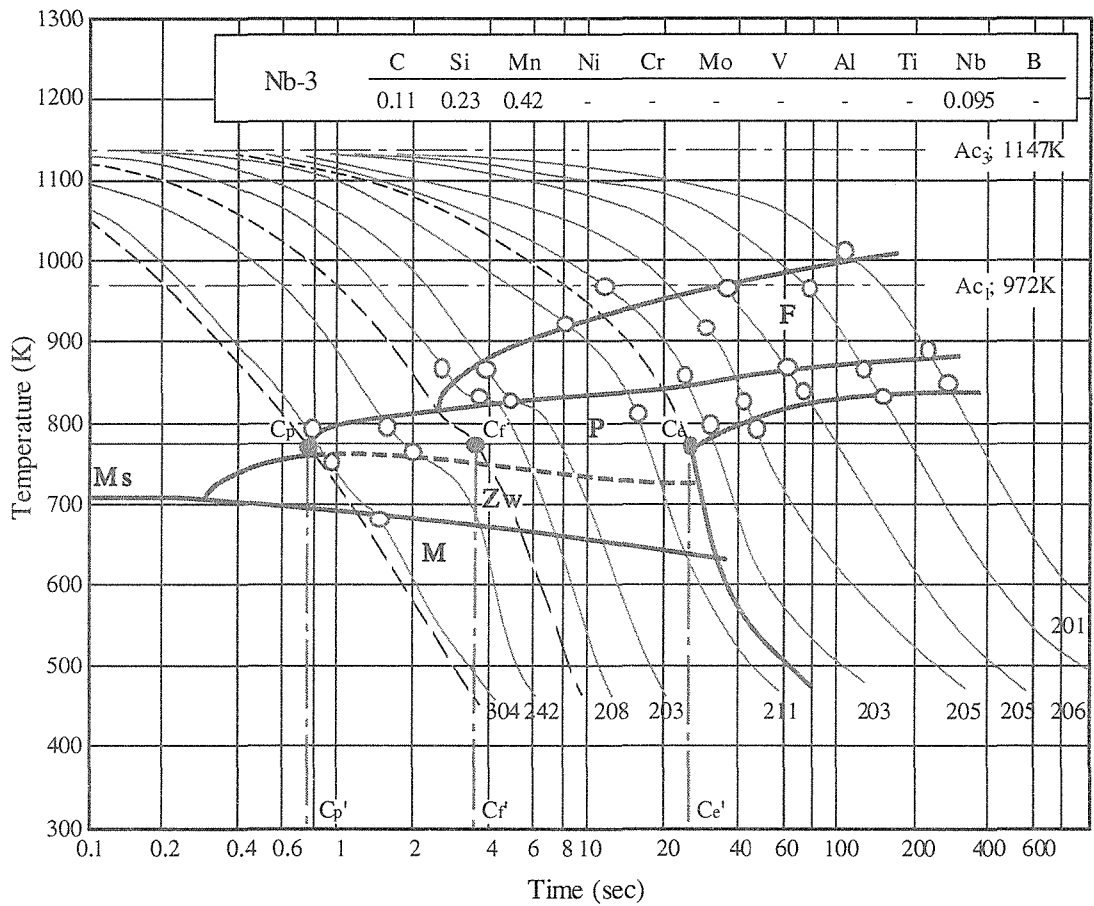
Time 180sec Hv 154

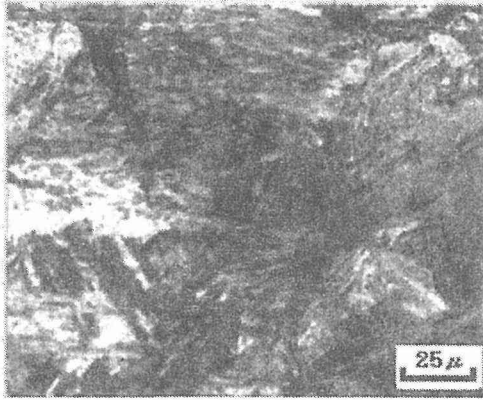


Time 380sec Hv 149

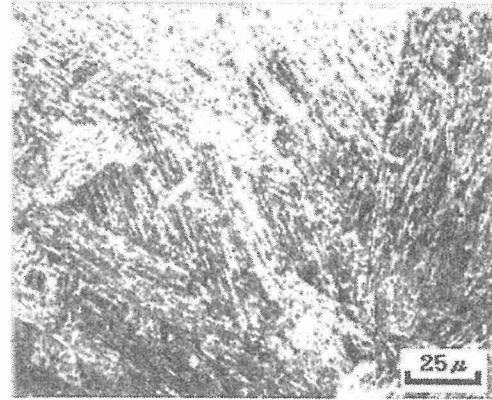
Fe-C-Nb Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Nb-3	0.11	0.23	0.42	-	-	-	-	-	-	-	-	0.095	-	-	80	P
Nb-2	0.17	0.22	0.4	-	-	-	-	-	-	-	-	0.11	-	-	84	P

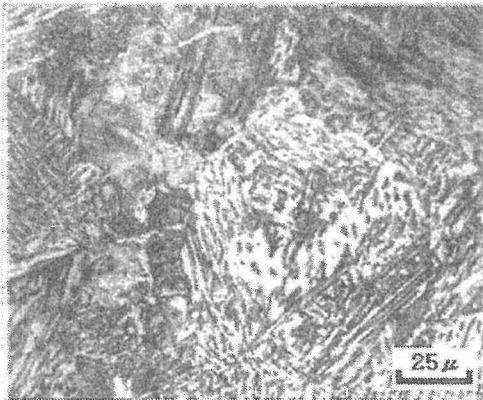




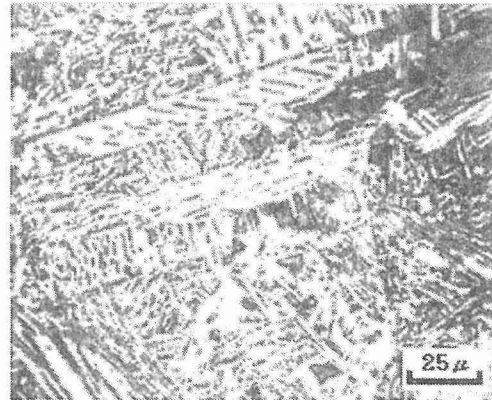
Time 0.8sec Hv 304



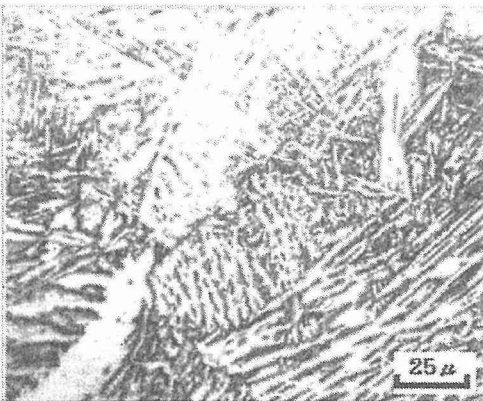
Time 1.8sec Hv 242



Time 5.2sec Hv 208



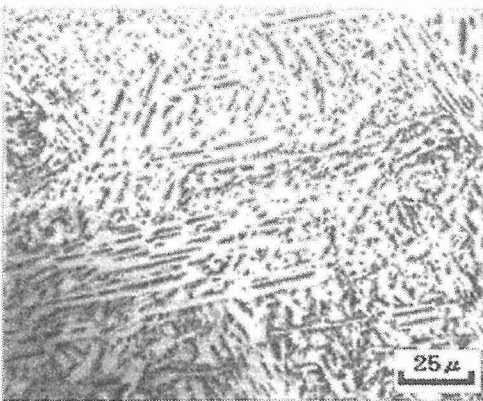
Time 8sec Hv 203



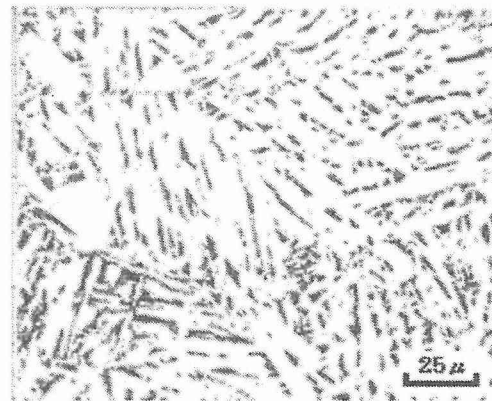
Time 18sec Hv 211



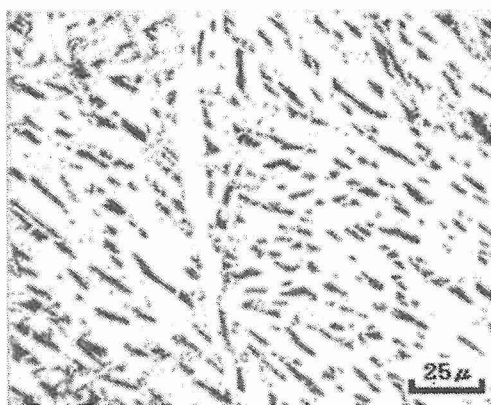
Time 35sec Hv 203



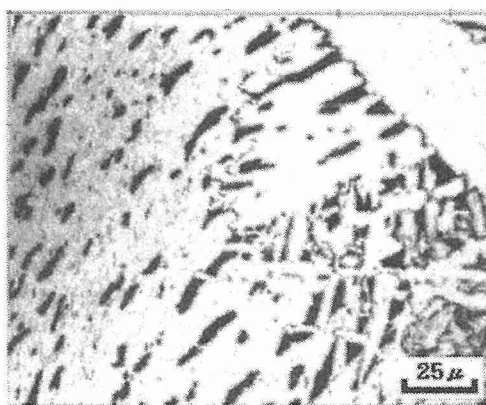
Time 50sec Hv 205



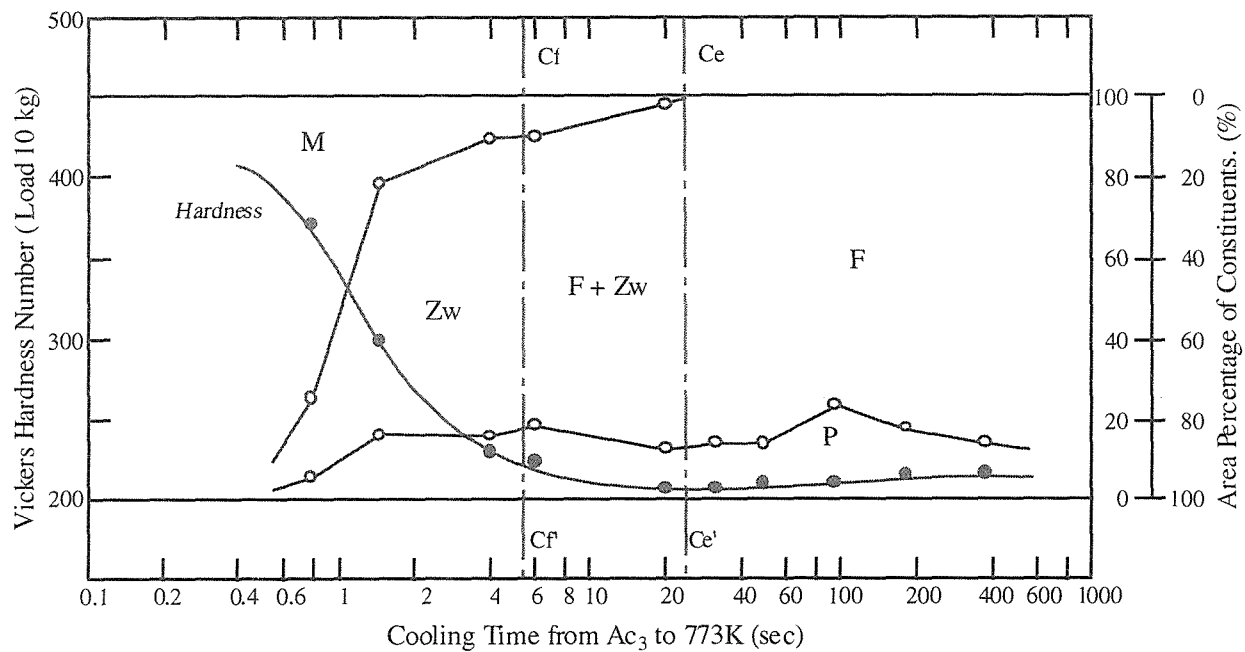
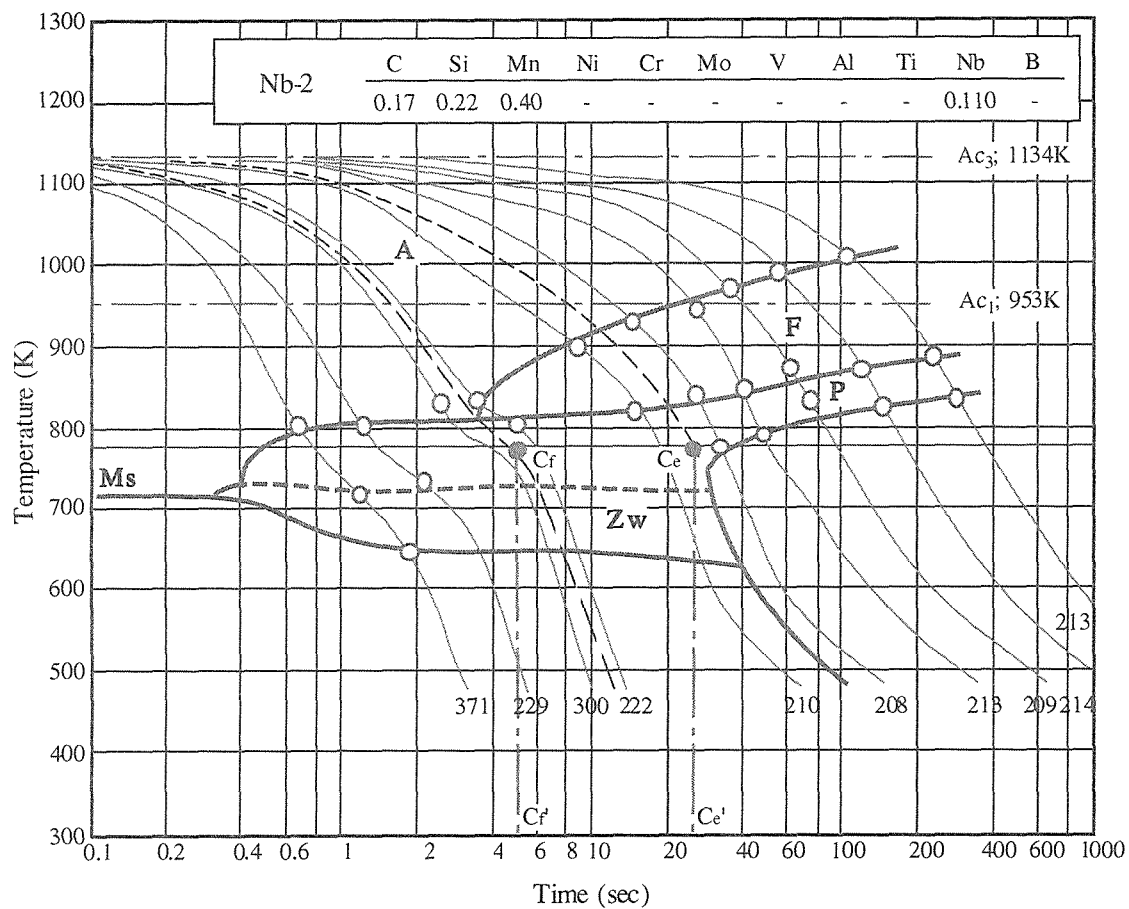
Time 100sec Hv 205

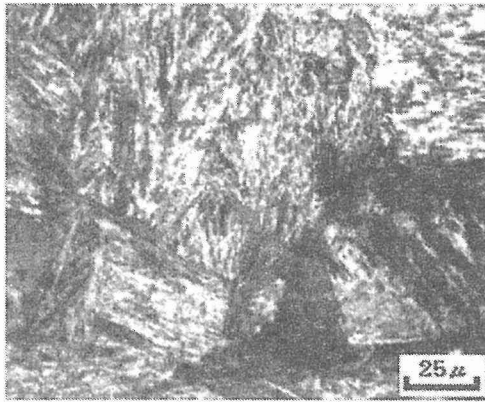


Time 200sec Hv 206

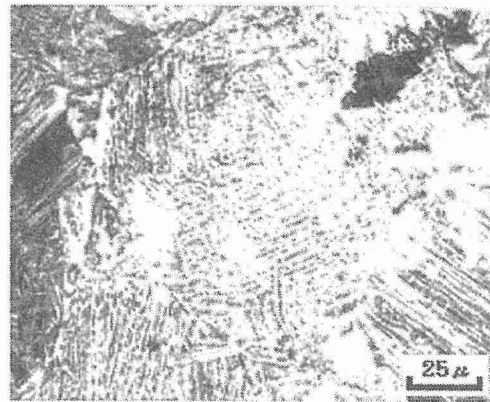


Time 380sec Hv 201

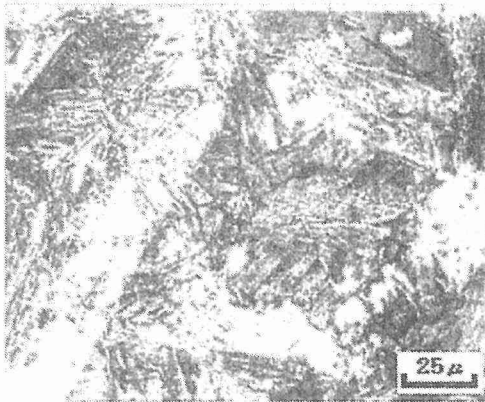




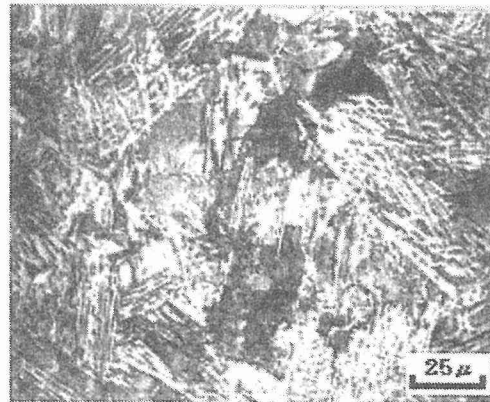
Time 0.8sec Hv 371



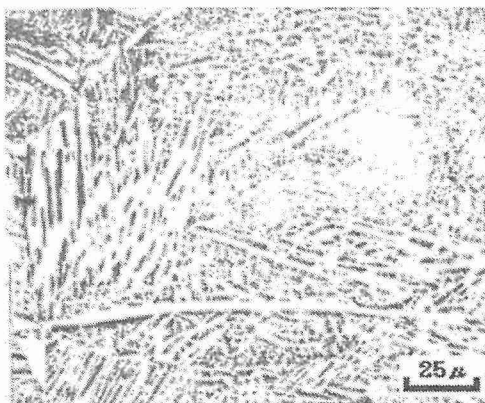
Time 1.5sec Hv 229



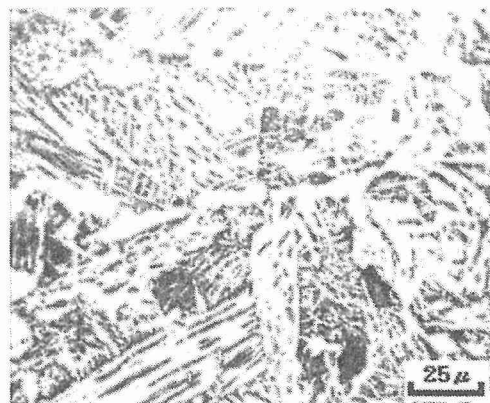
Time 4sec Hv 300



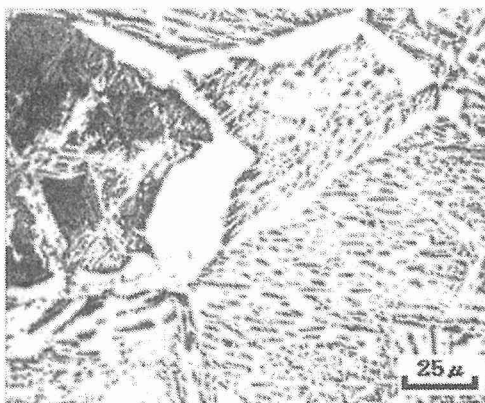
Time 6sec Hv 222



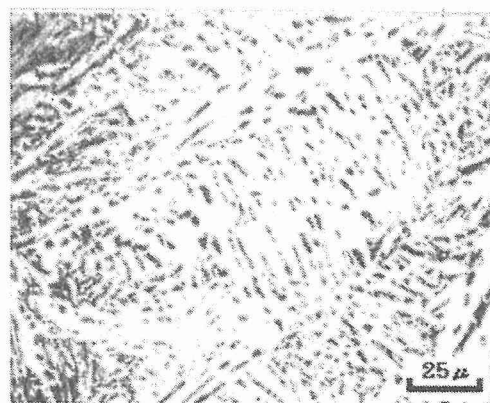
Time 18sec Hv 210



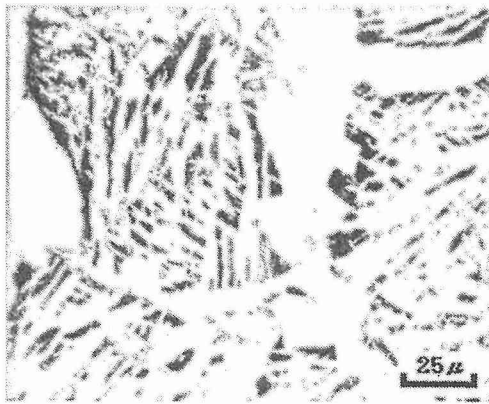
Time 35sec Hv 208



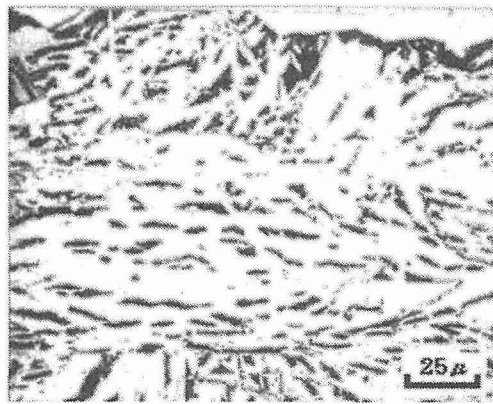
Time 50sec Hv 213



Time 99sec Hv 209



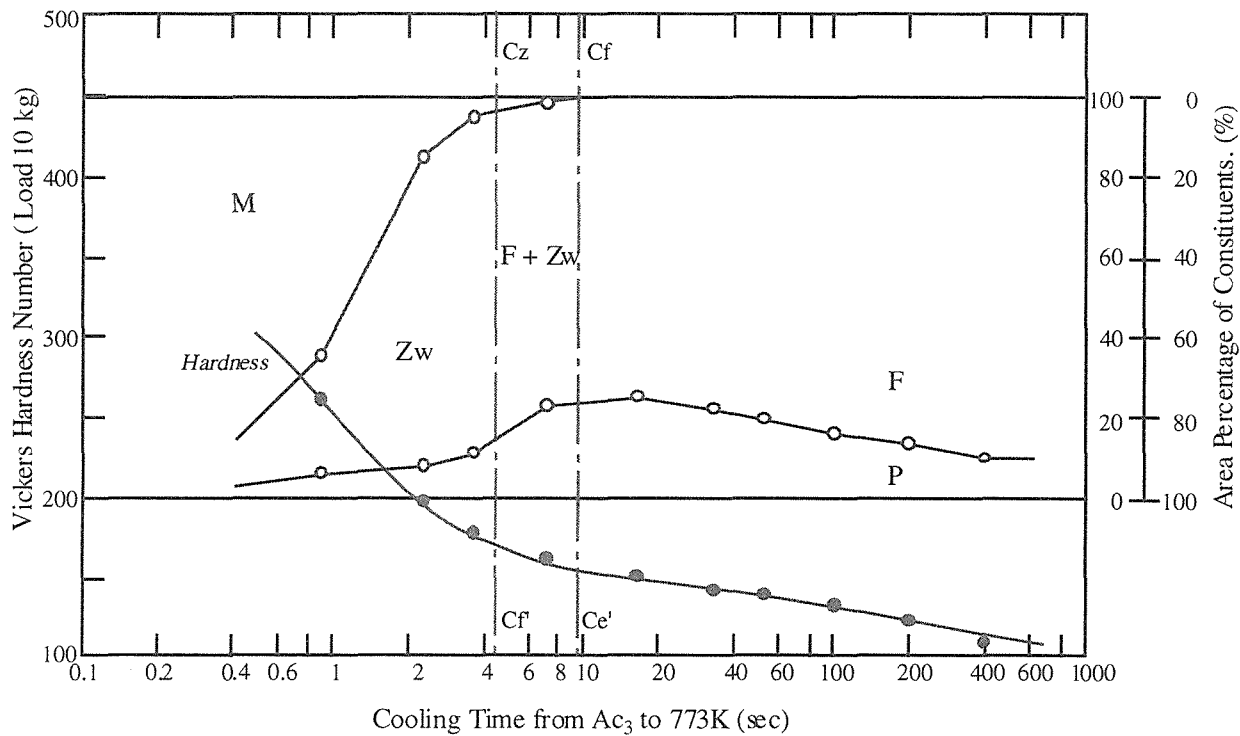
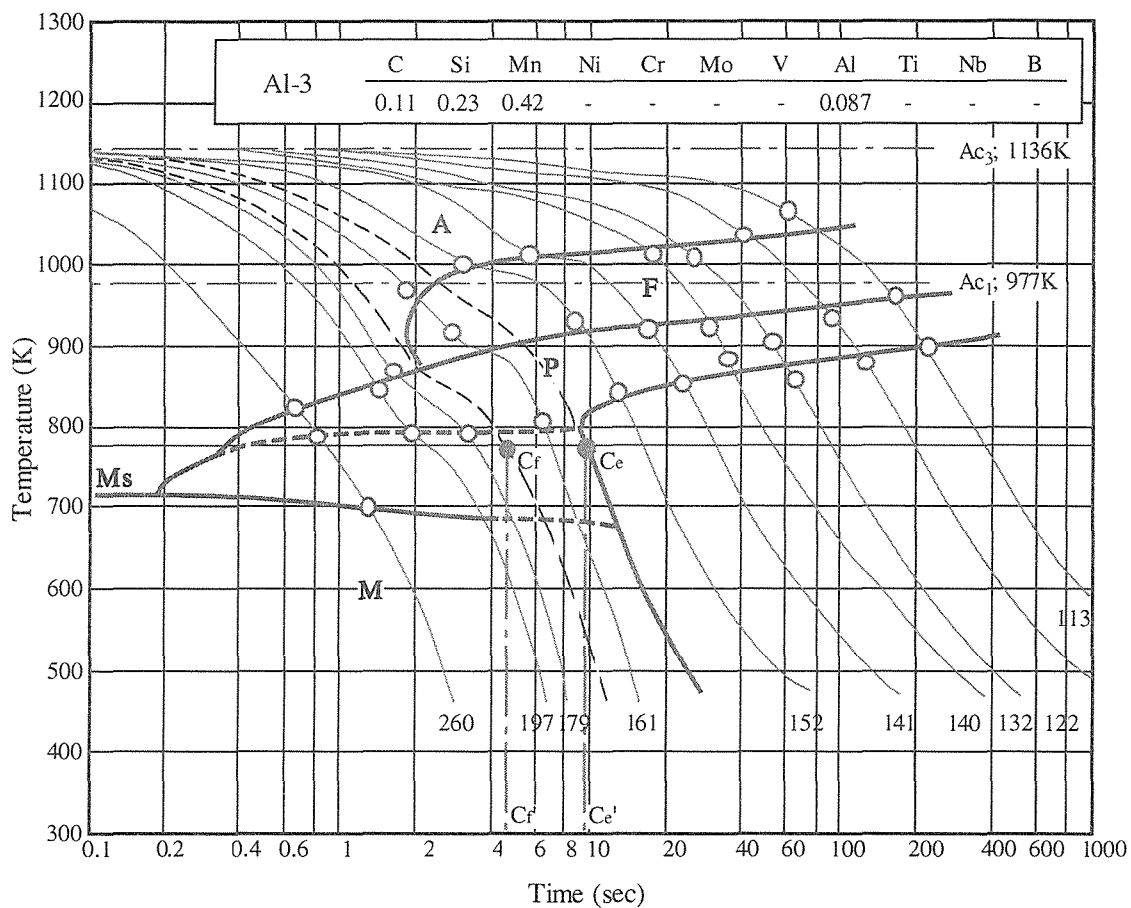
Time 180sec Hv 214

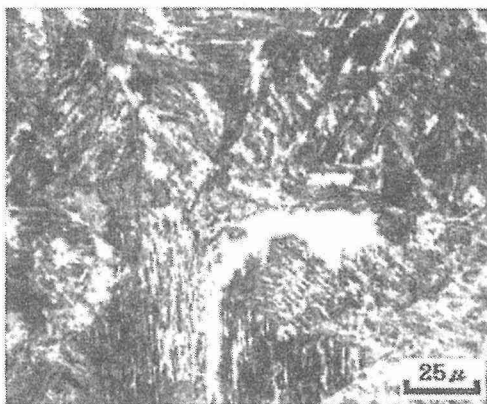


Time 380sec Hv 213

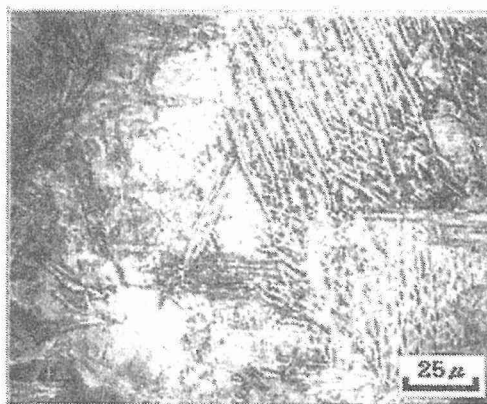
Fe-C-Al Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
Al-3	0.11	0.23	0.42	-	-	-	-	-	-	-	-	-	0.087	-	88	P





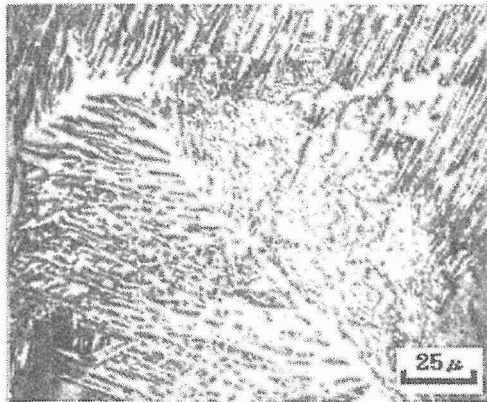
Time 0.9sec Hv 260



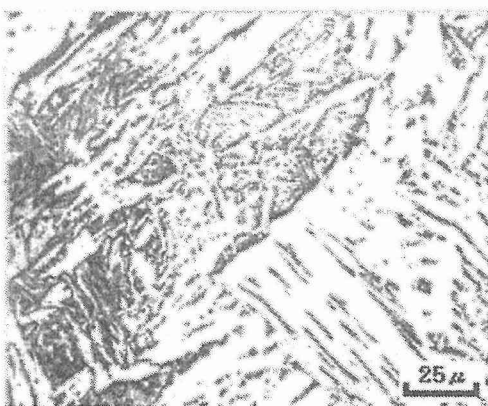
Time 2.2sec Hv 197



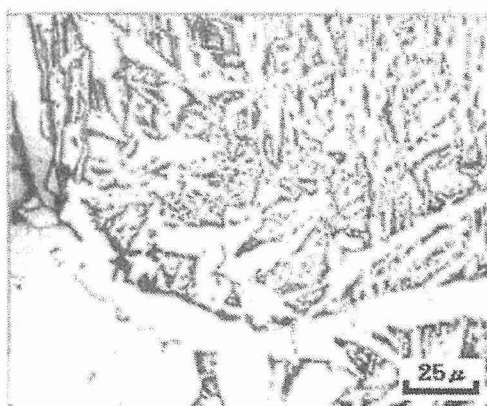
Time 3.6sec Hv 179



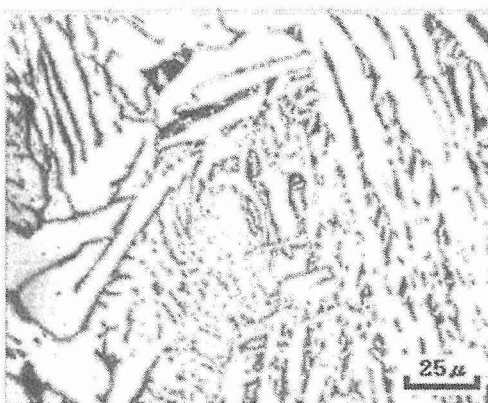
Time 7sec Hv 161



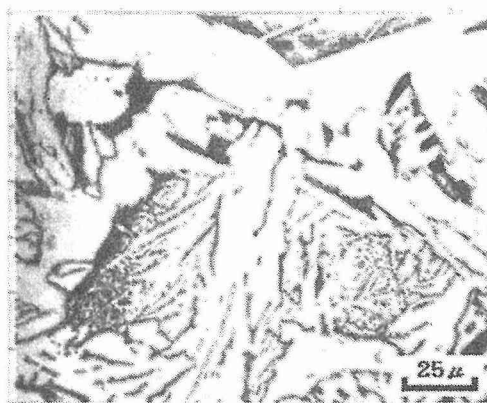
Time 17sec Hv 152



Time 32sec Hv 141



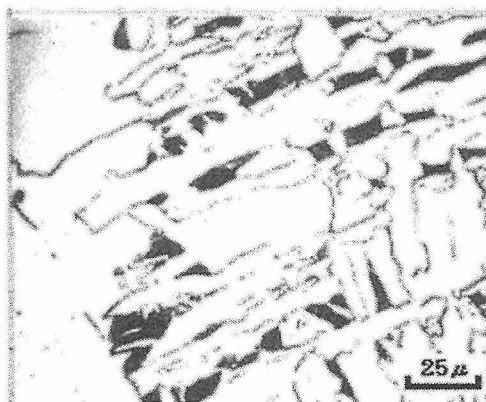
Time 52sec Hv 140



Time 90sec Hv 132



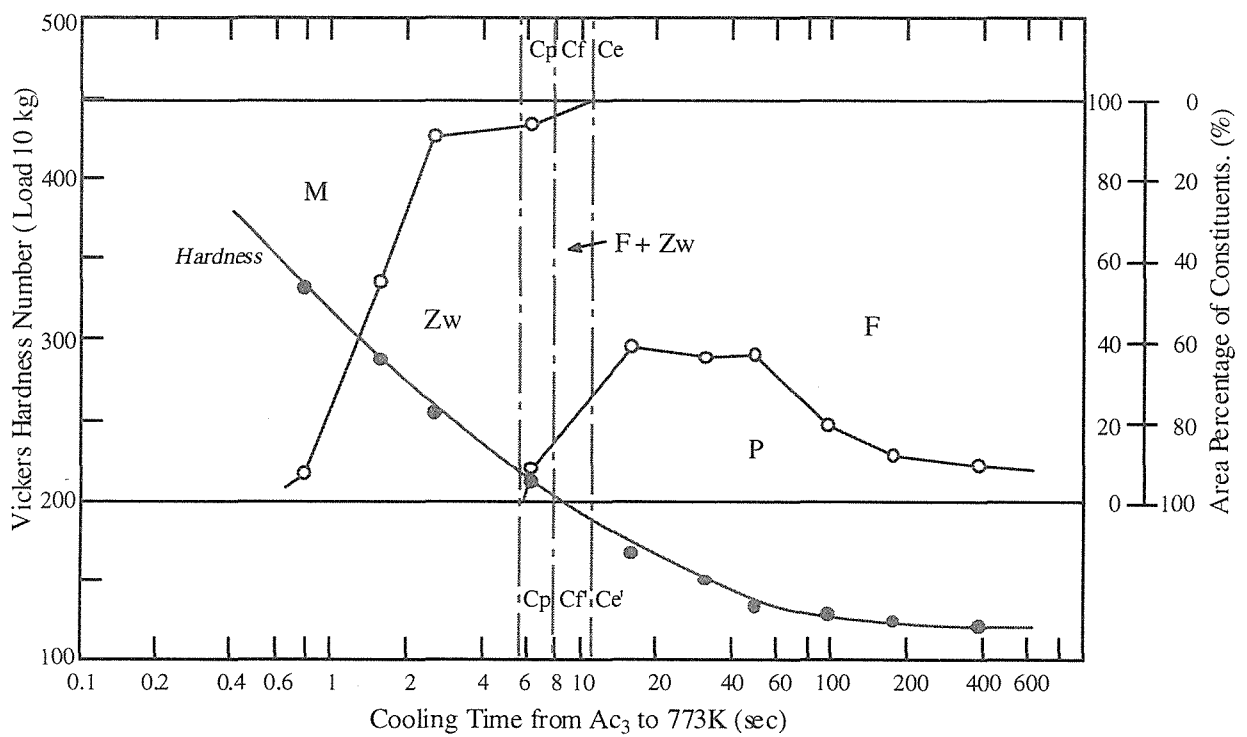
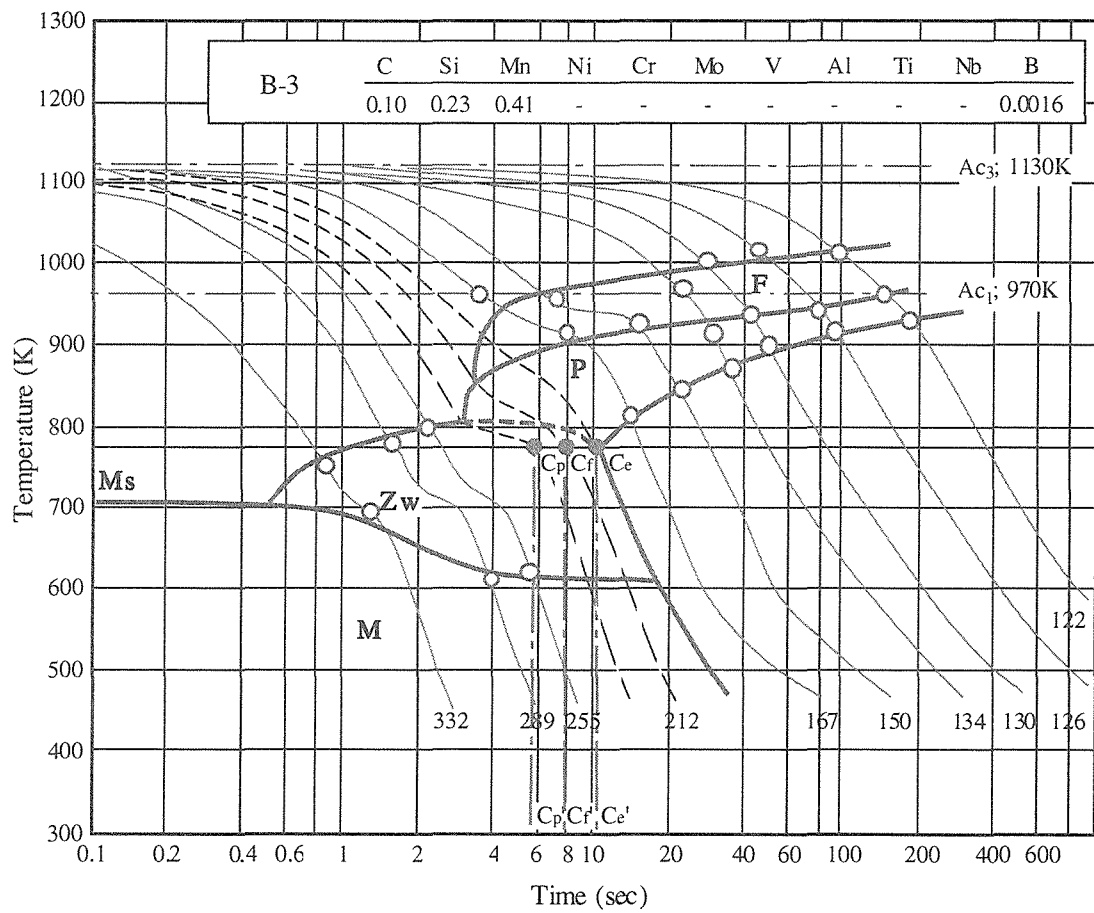
Time 200sec Hv 122

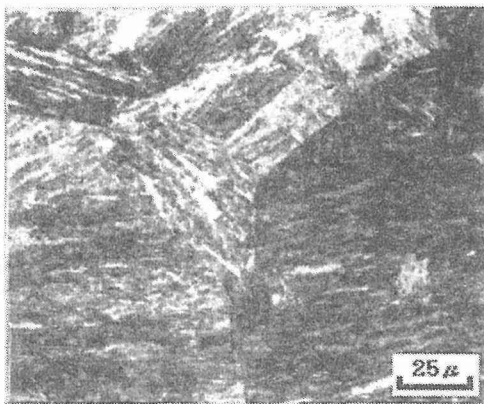


Time 400sec Hv 113

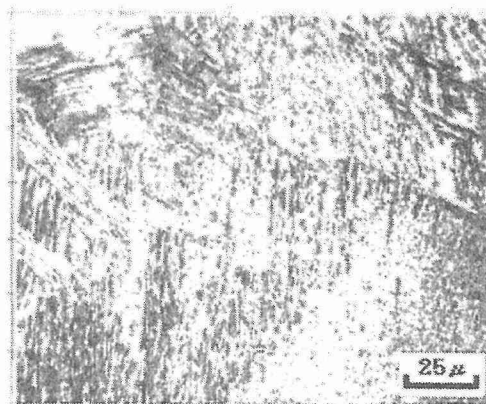
Fe-C-B Alloy

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
B-3	0.1	0.23	0.41	-	-	-	-	-	-	-	-	-	-	0.0016	92	P

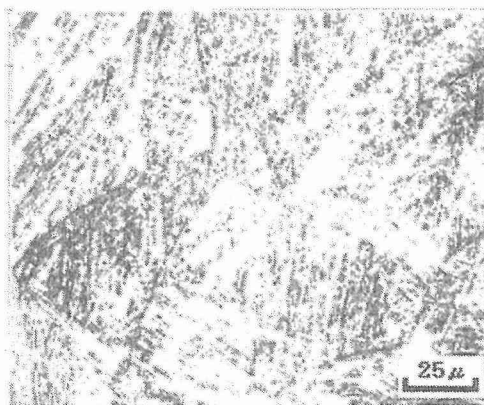




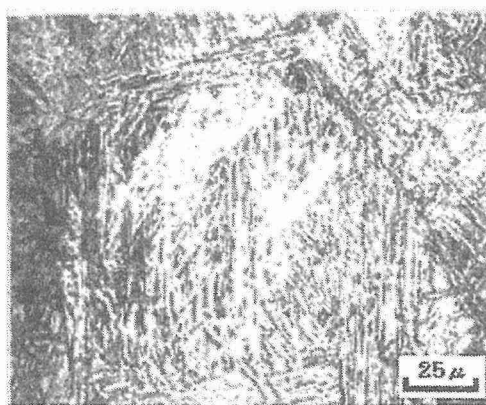
Time 0.8sec Hv 332



Time 1.7sec Hv 289



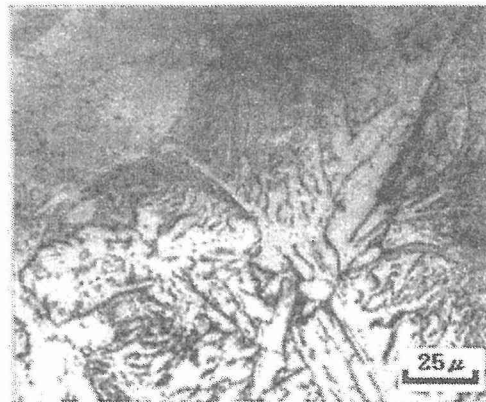
Time 2.7sec Hv 255



Time 8sec Hv 212



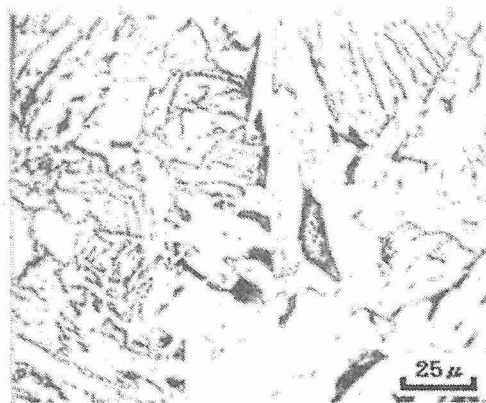
Time 17sec Hv 167



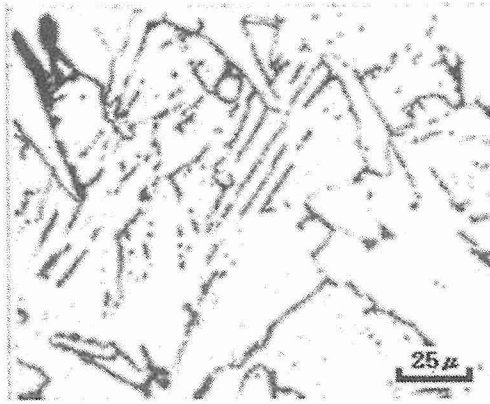
Time 30sec Hv 150



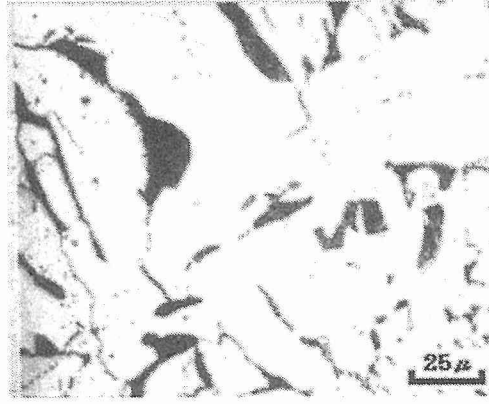
Time 50sec Hv 134



Time 90sec Hv 130



Time 180sec Hv 126

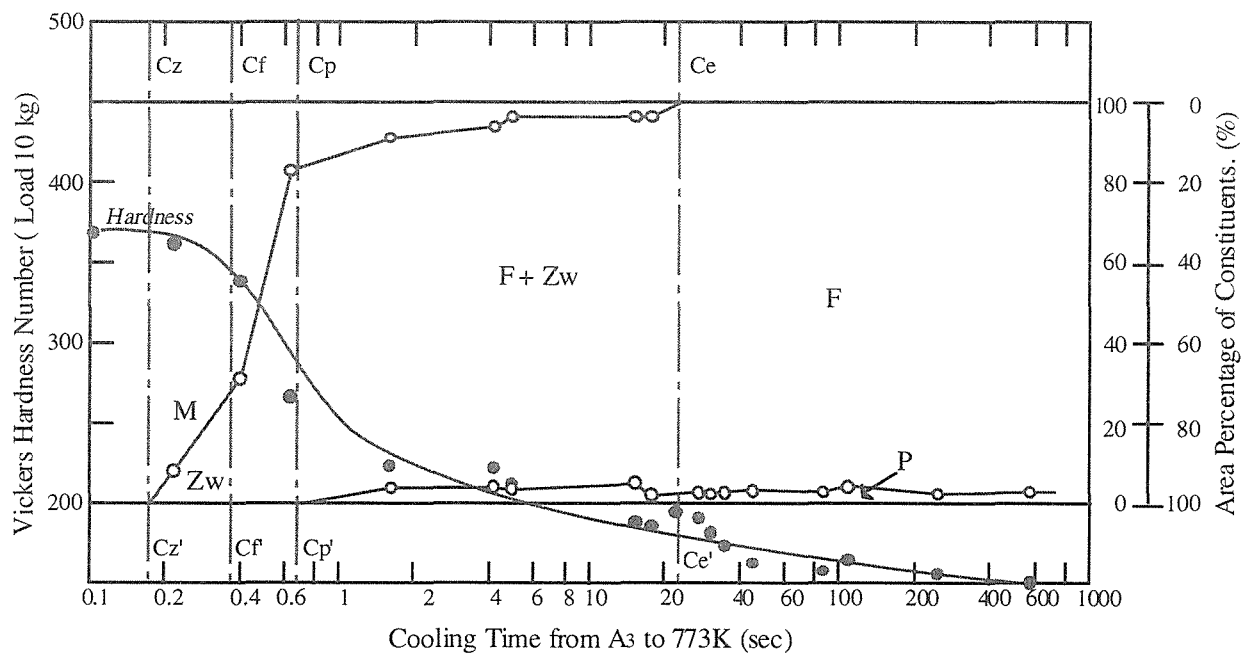
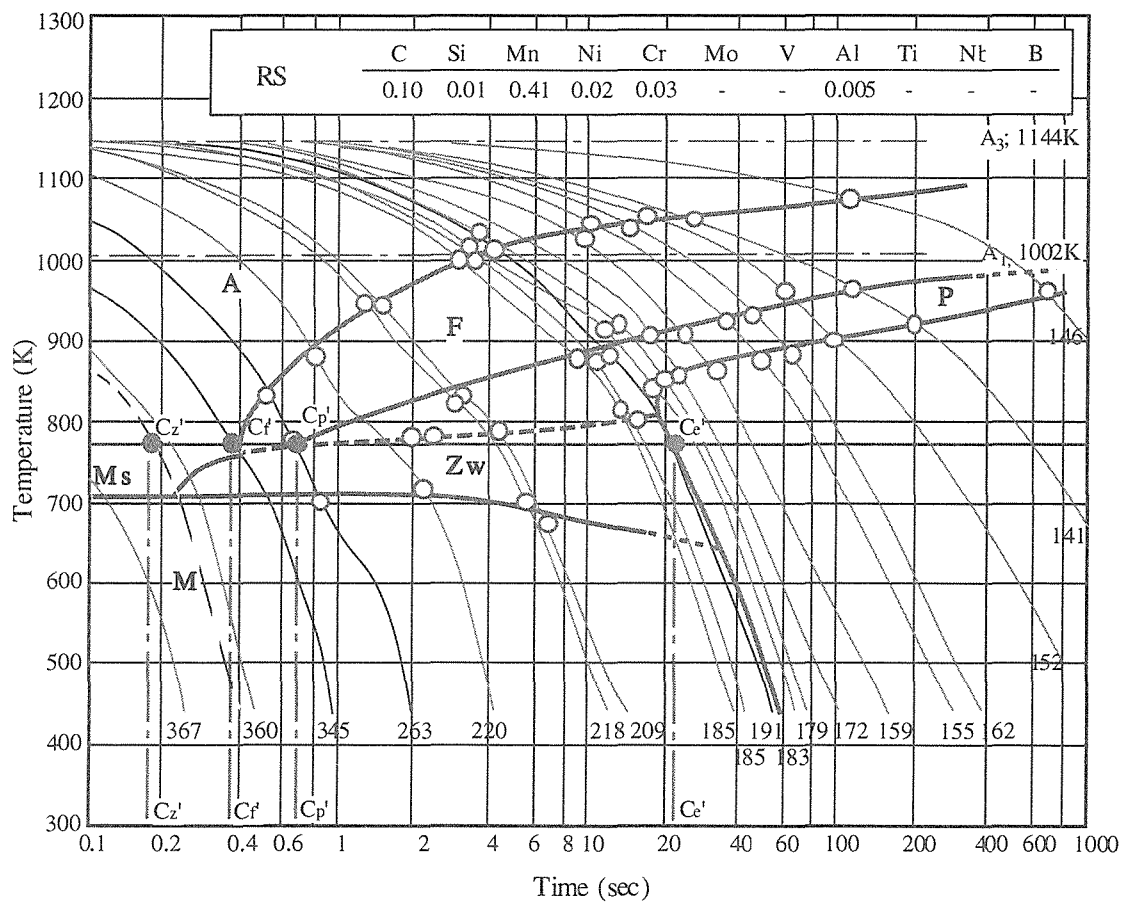


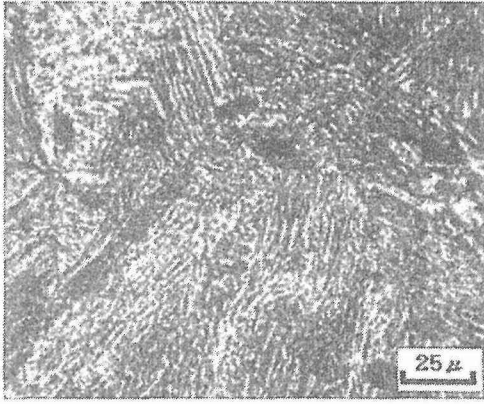
Time 380sec Hv 122

Experimental and Commercial

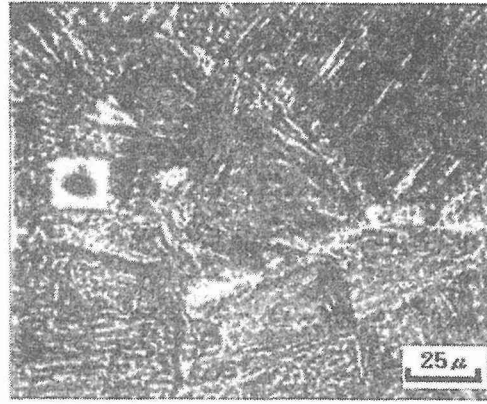
HT-50kg/mm² Class

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
RS	0.1	0.01	0.41	0.015	0.043	0.02	0.03	0.18	-	-	-	-	0.005	-	96	7
SS	0.11	0.02	0.61	0.008	0.025	0.02	0.03	0.15	-	-	-	-	0.005	-	98	8
20g	0.14	0.25	0.58	0.015	0.031	-	-	-	-	-	-	-			100	P
FH	0.14	0.09	0.96	0.018	0.026	0.06	0.07	0.18	-	-	-	-	0.054	-	102	7
SM41B	0.16	0.48	1.42	-	-	-	-	-	-	-	-	-	-	-	104	P
SM41A	0.11	0.29	1.47	-	-	-	-	-	-	-	-	0.027	0.035	-	108	P
YND33	0.09	0.24	1.15	0.011	0.007	-	-	-	-	-	-	-	-	-	112	9
KS	0.14	0.23	0.65	0.012	0.007	0.02	0.02	0.16	-	-	-	-	0.008	-	114	7
NK	0.13	0.23	1.18	0.02	0.025	0.04	0.04	0.13	-	-	-	-	0.018	-	116	7
SM50B	0.14	0.32	1.32	-	-	-	-	-	-	0.003	-	-	-	-	118	P
SM50BS1	0.15	0.28	0.97	-	-	0.02	0.01	-	-	-	-	-	-	-	120	P
YD	0.13	0.41	1.08	0.025	0.012	0.02	0.02	0.16	-	-	-	-	0.052	-	124	8
E602	0.15	0.4	1.19	-	-	0.09	-		-	-	-	-	-	-	126	9
Corten	0.09	0.54	1.34	0.096	0.03	0.44	0.96	0.32	-	-	-	-	-	-	128	10
YE	0.16	0.45	1.18	0.019	0.018	0.02	0.02	0.21	-	-	-	-	0.049	-	130	7
KT	0.15	0.42	1.21	0.016	0.02	0.06	0.04	0.14	-	-	-	-	0.051	-	132	7
E599	0.19	0.41	1.17	-	-	-	0.06	-	-	-	-	-	-	-	134	P
SM50BC1	0.13	0.44	1.44	-	-	0.18	-	-	-	-	-	0.026	0.028	-	136	P
SiMn HT50	0.22	0.12	1.08	0.024	0.027	-	-	-	-	-	0.01	-	-	-	140	9
FTW52B	0.16	0.41	1.22	0.012	0.021	0.02	-	0.08	-	-	-	-	-	-	142	10
NM	0.14	0.53	1.12	0.011	0.01	0.06	0.04	0.06	-	-	-	-	0.04	-	144	7
Welten55C	0.18	0.47	1.4	-	-	0.04	0.05	-	-	-	-	-	0.061	-	146	P
16CMnR	0.18	0.38	1.34	0.014	0.012	-	-	-	-	-	-	-	-		147	P
SM50A	0.17	0.34	1.31	-	-	-	-	-	-	-	-	-	-	-	148	P

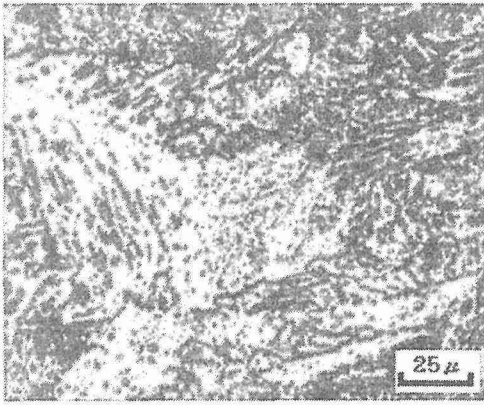




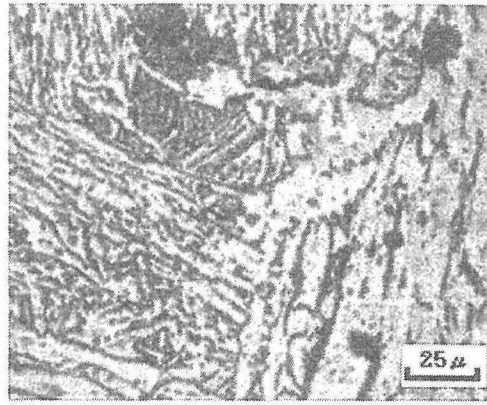
Time 0.22 Hv 360



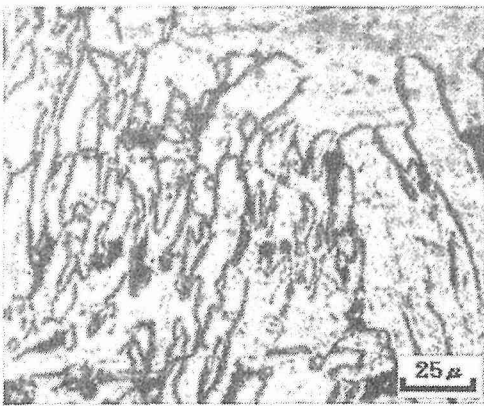
Time 0.28sec Hv 345



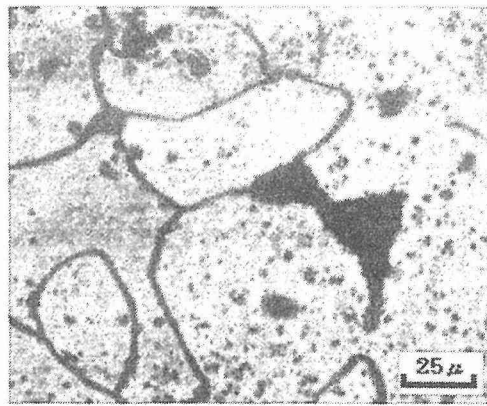
Time 0.65 Hv 263



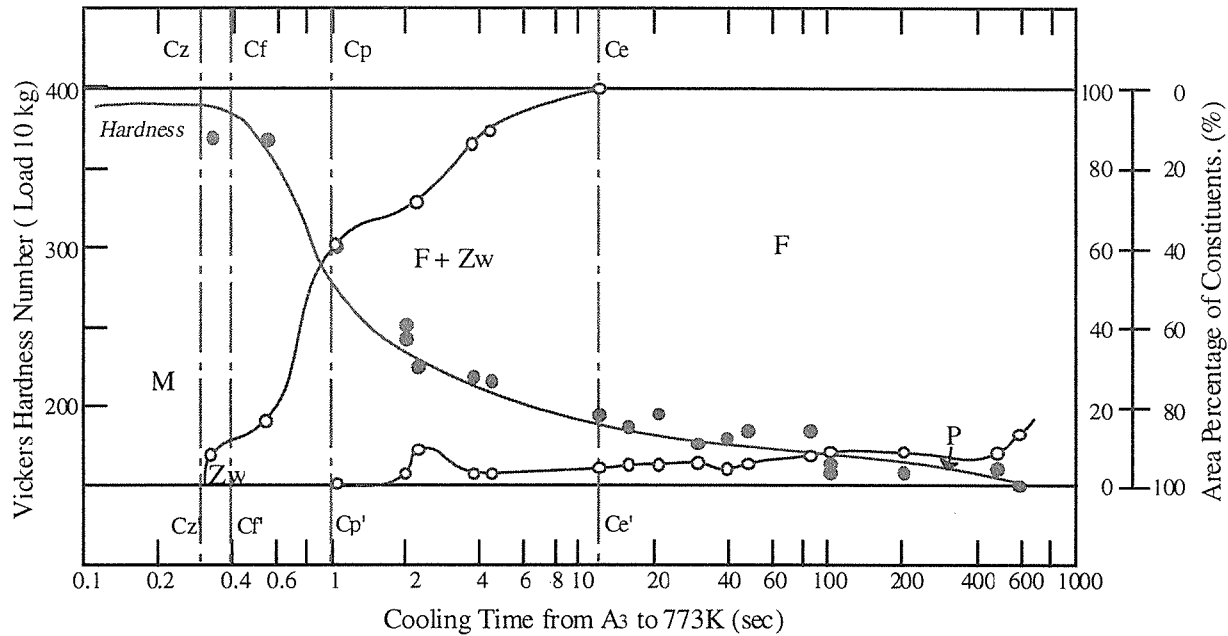
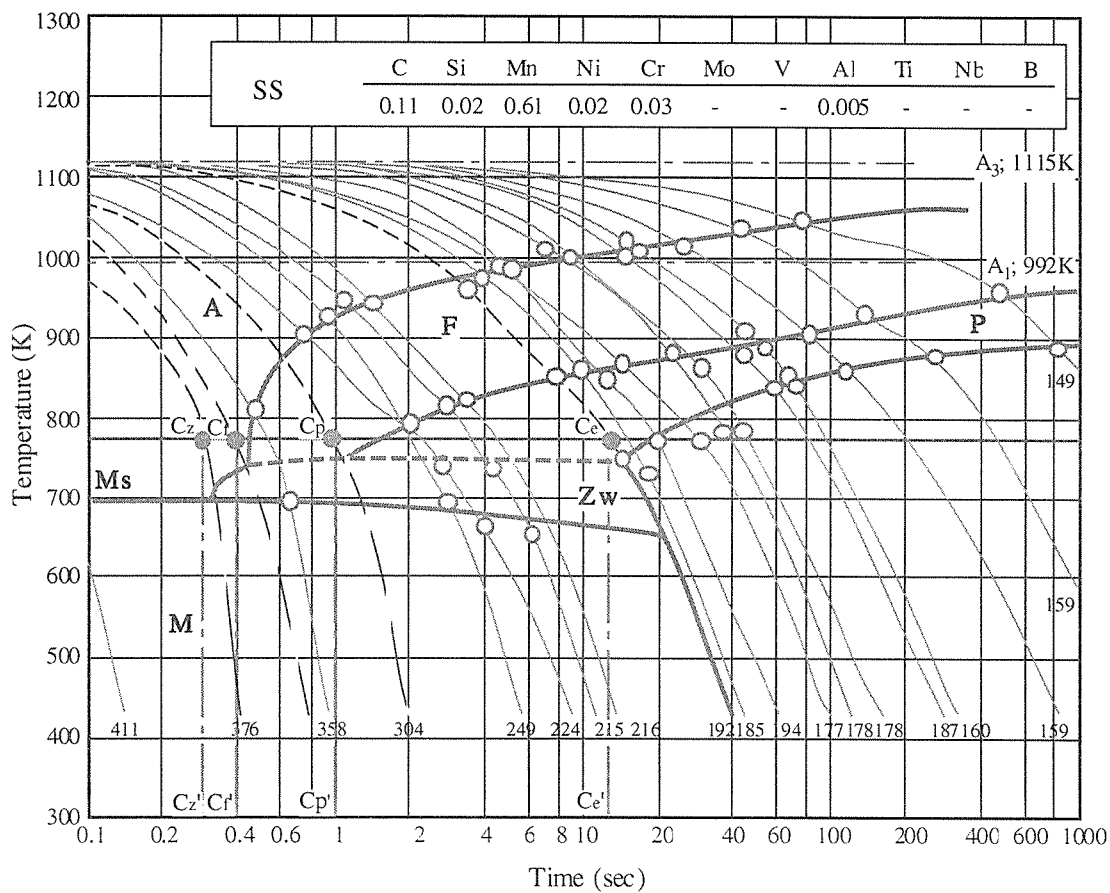
Time 17sec Hv 185

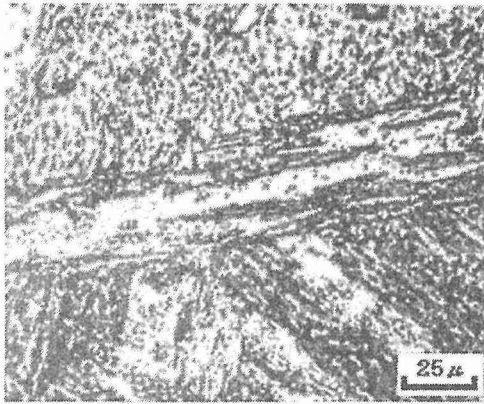


Time 85sec Hv 155

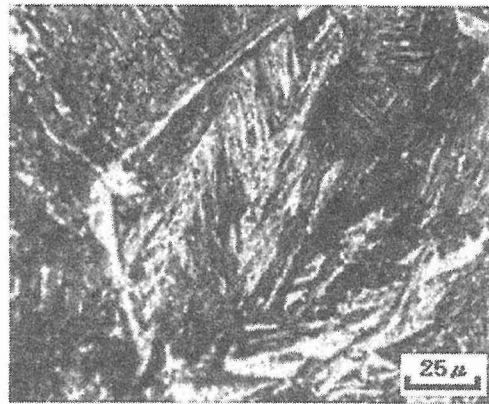


Time -1000sec Hv 146

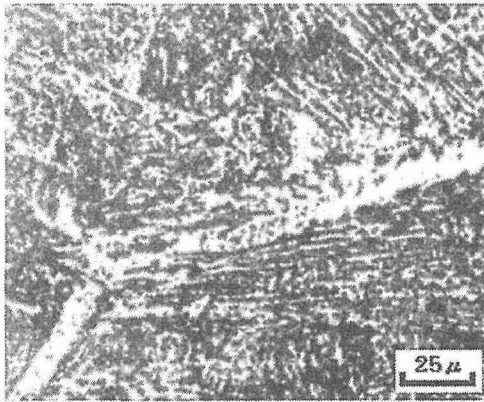




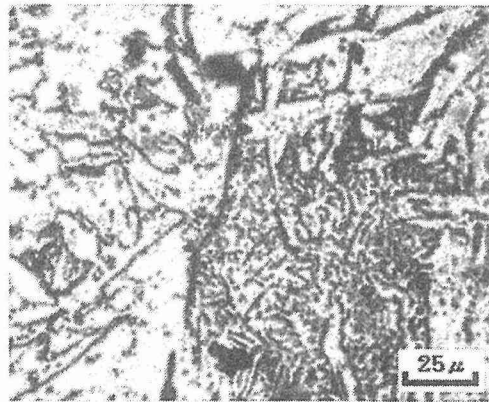
Time 0.3sec Hv 376



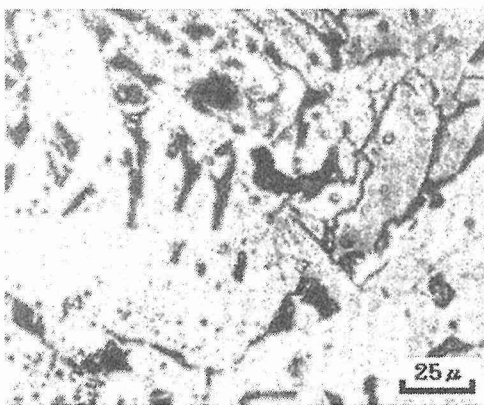
Time 0.54sec Hv 358



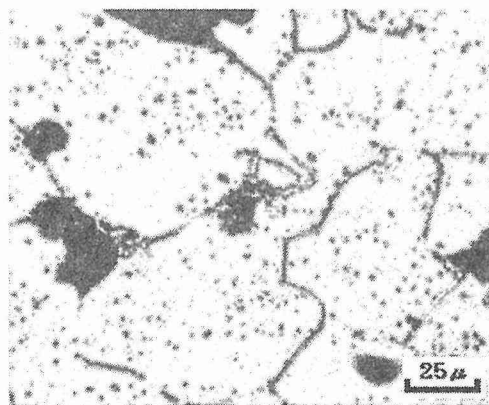
Time 2sec Hv 249



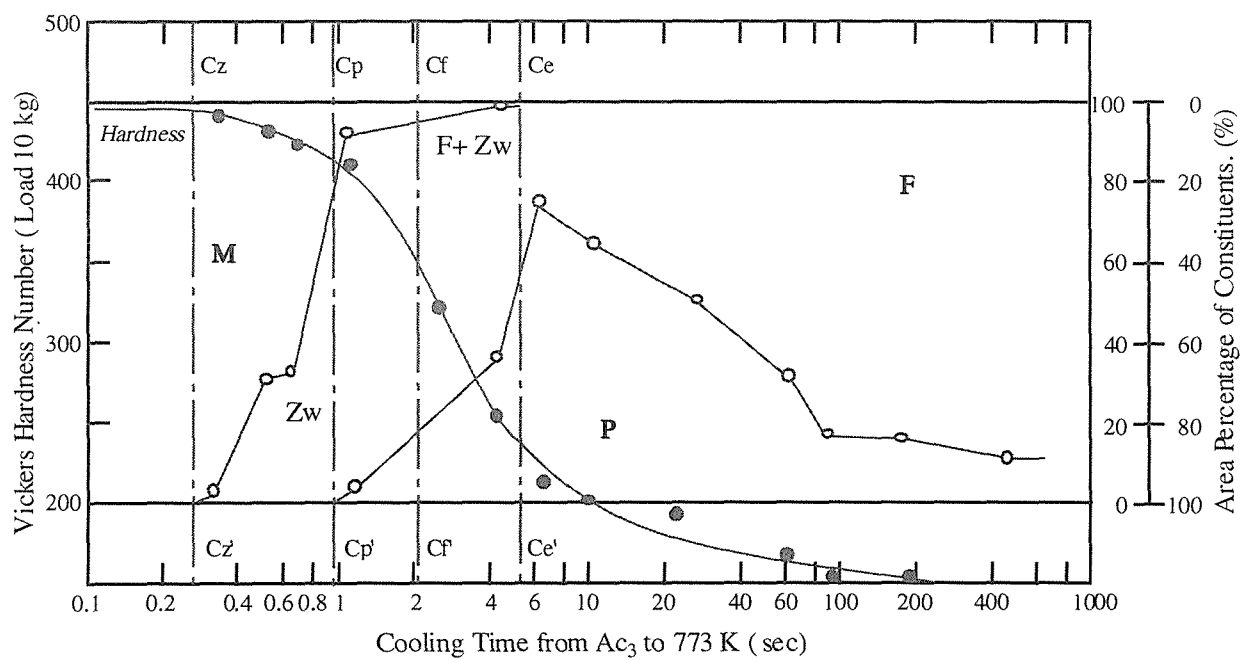
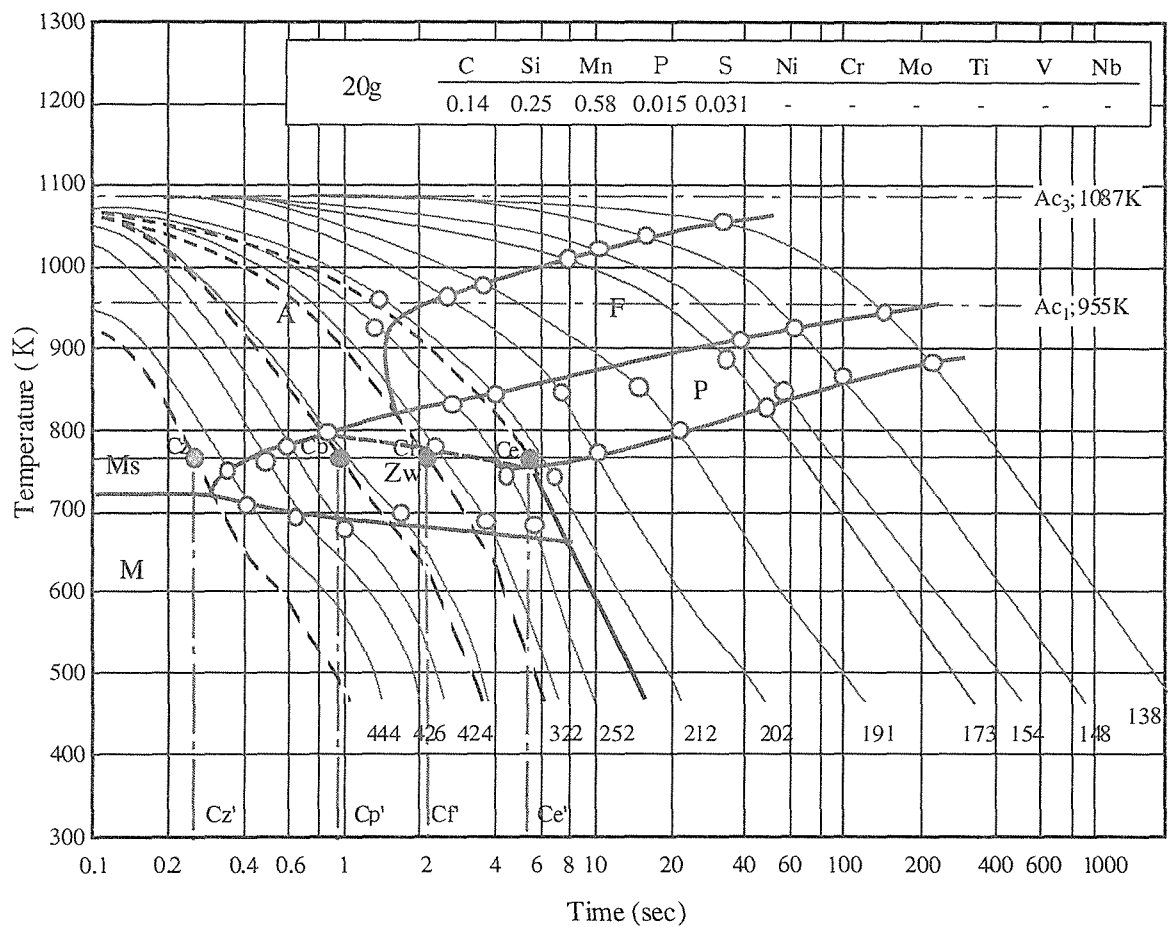
Time 20sec Hv 194

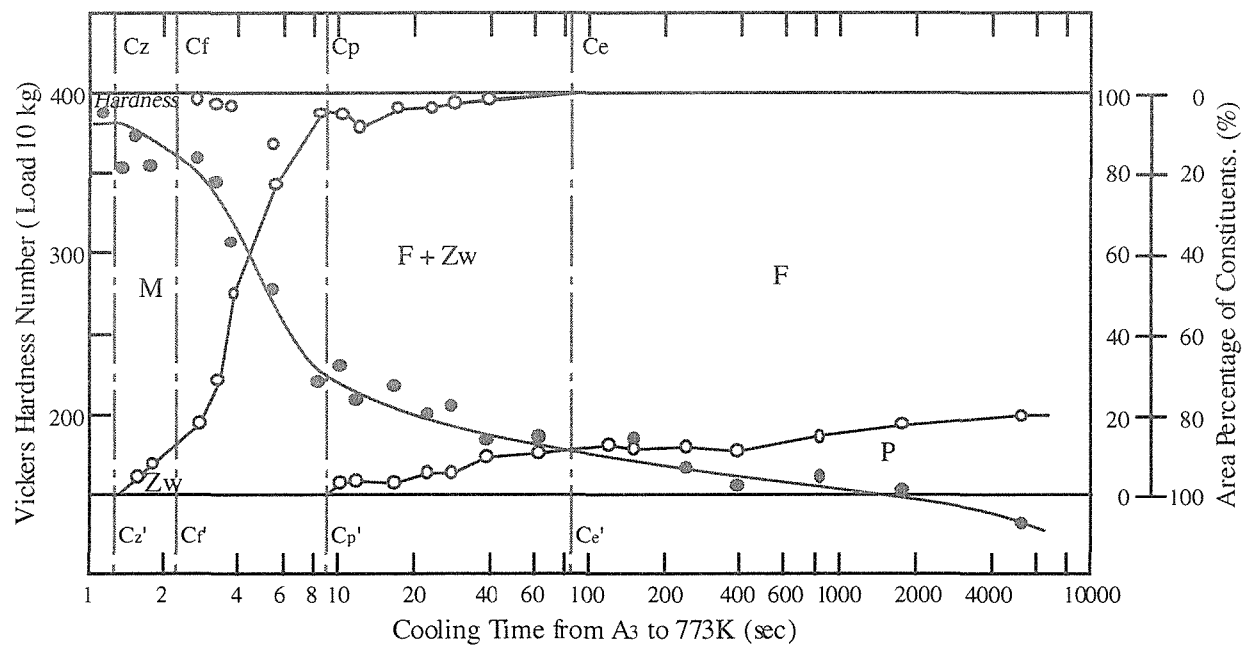
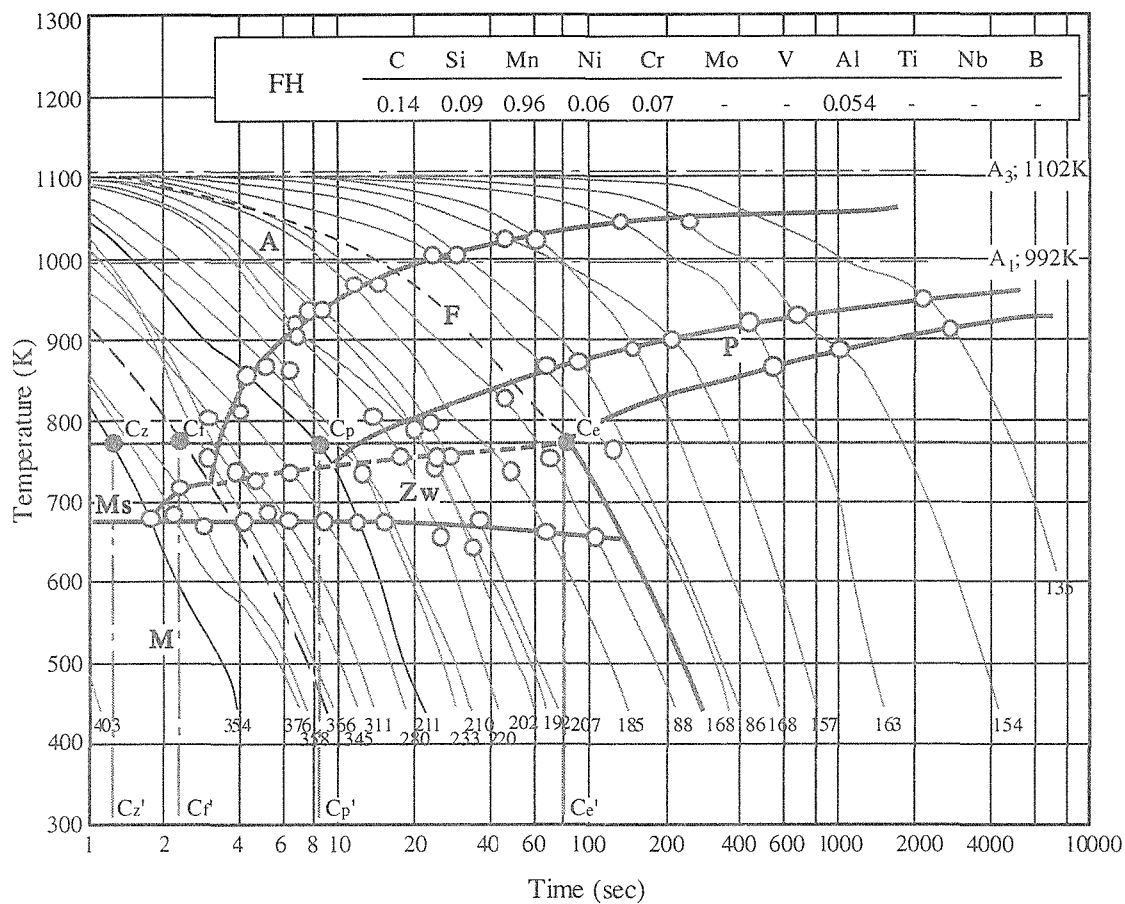


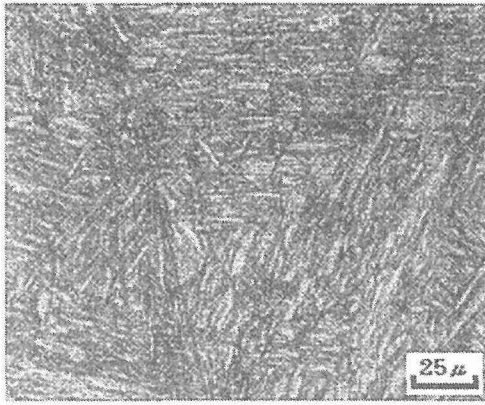
Time 50sec Hv 178



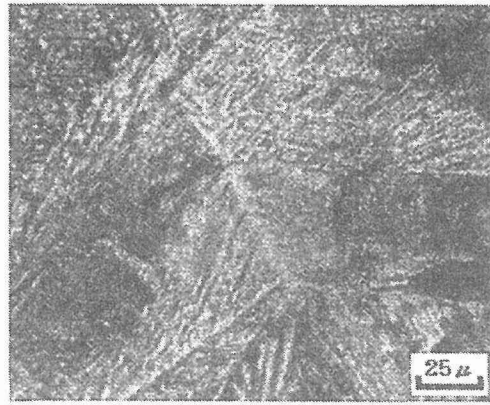
Time -1000sec Hv 149



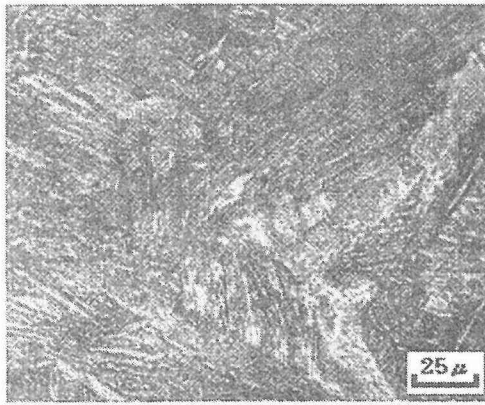




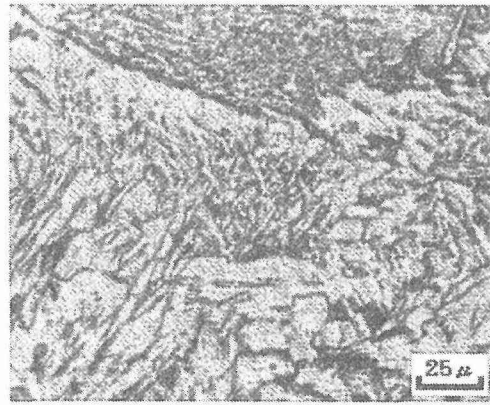
Time - Hv 421



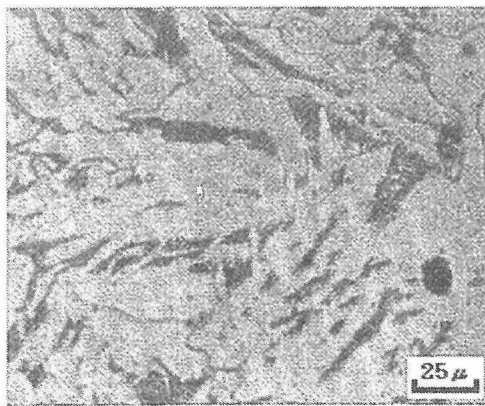
Time 1.5sec Hv 376



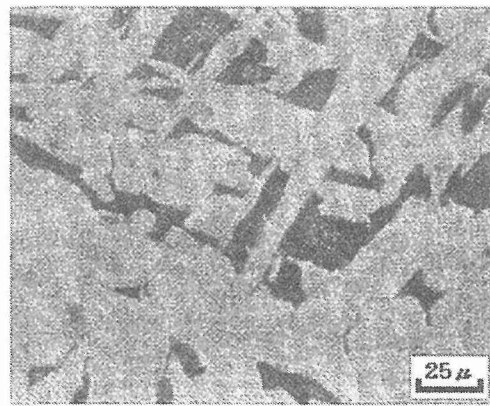
Time 3.8sec Hv 311



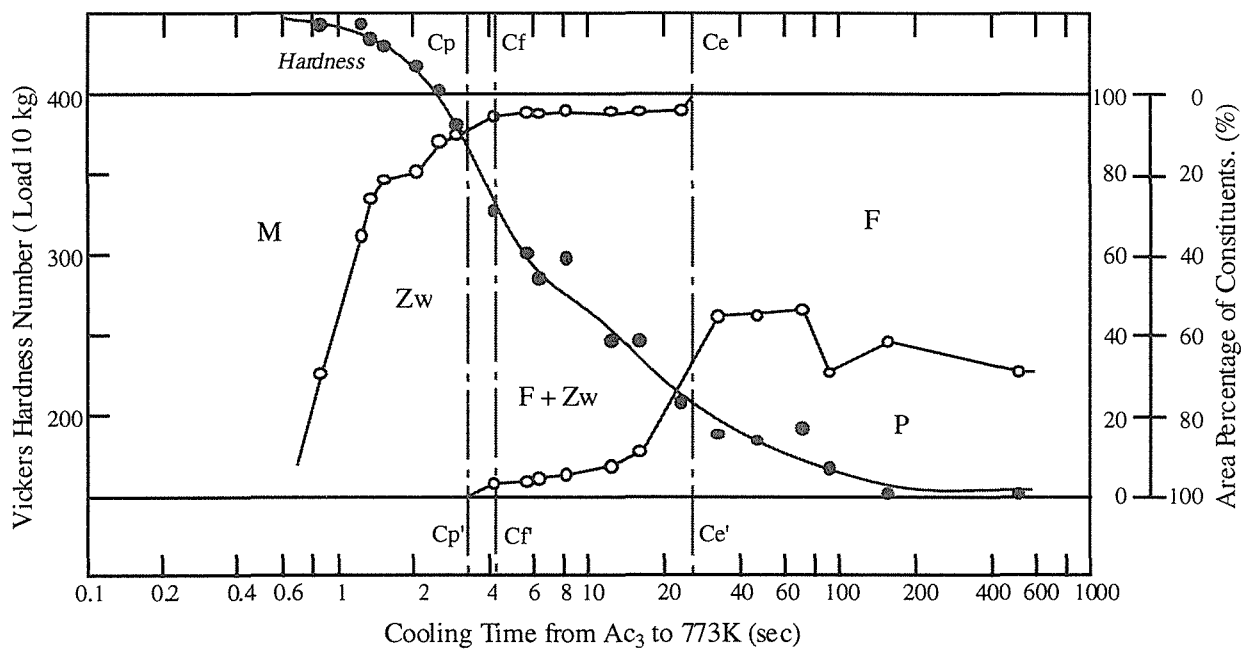
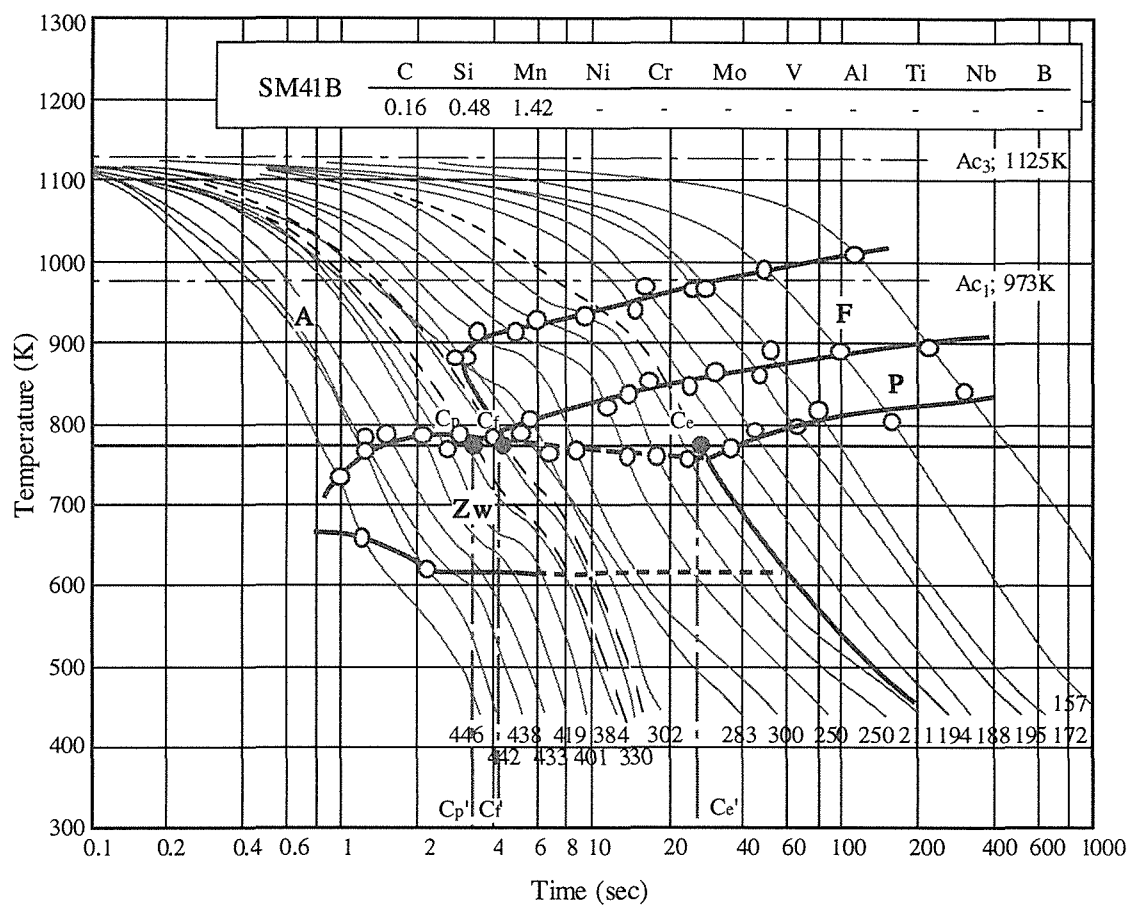
Time 30sec Hv 207

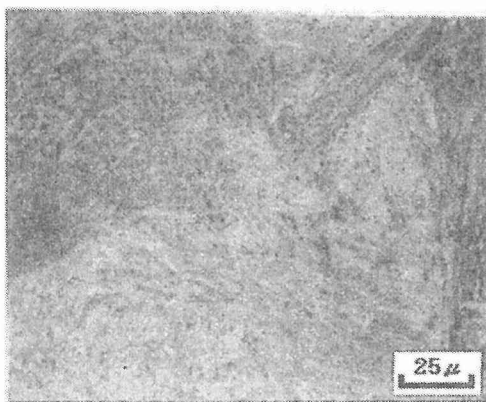


Time 120sec Hv 168

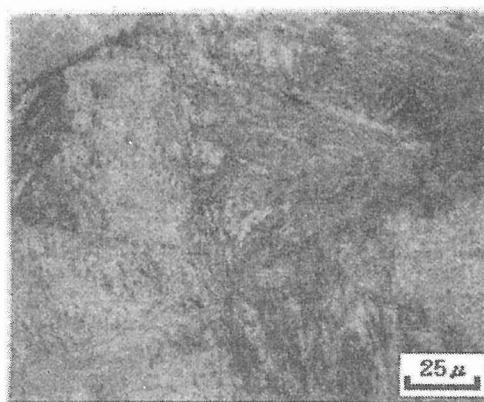


Time 380sec Hv 157

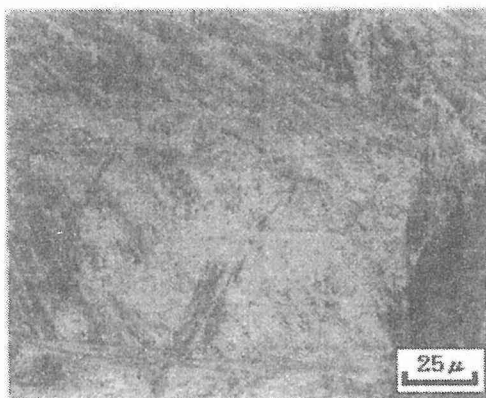




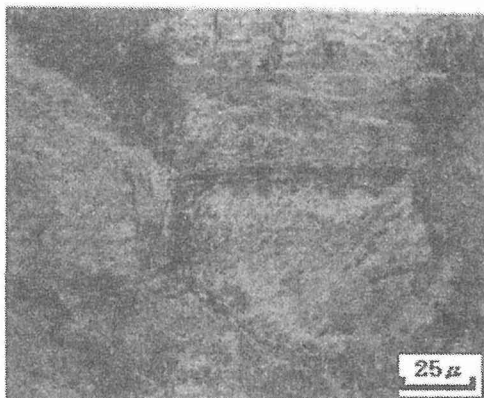
Time 0.8sec Hv 446



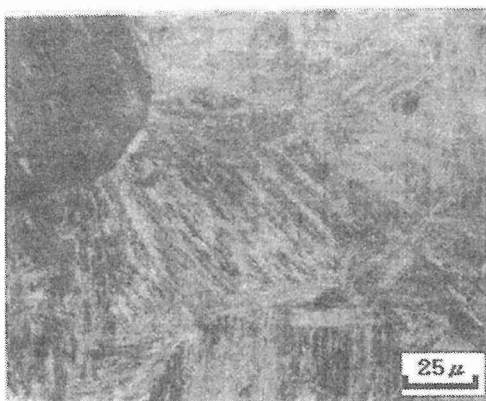
Time 1.2sec Hv 442



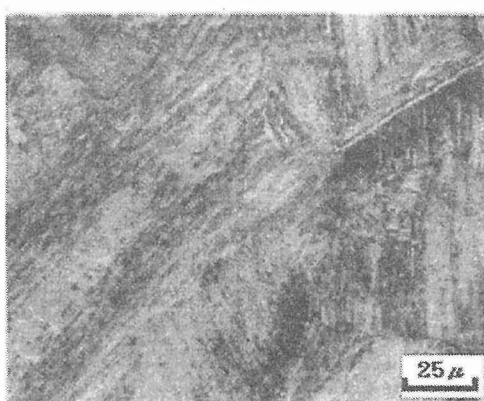
Time 1.3sec Hv 438



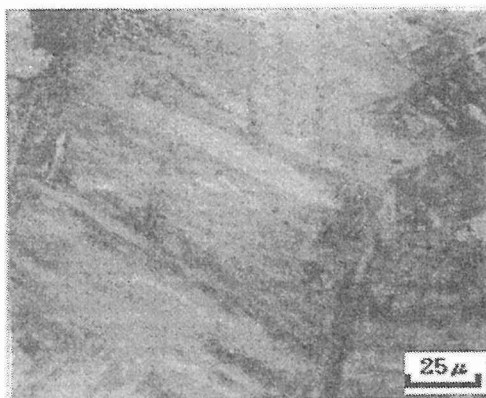
Time 1.8sec Hv 433



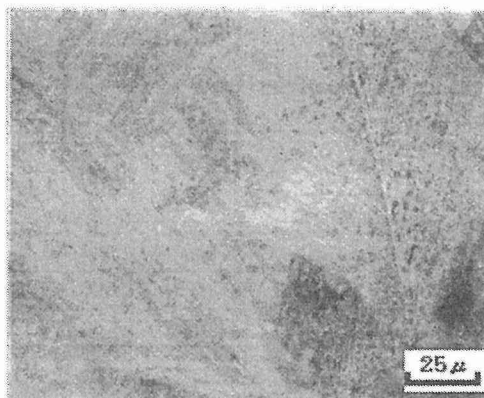
Time 2.4sec Hv 419



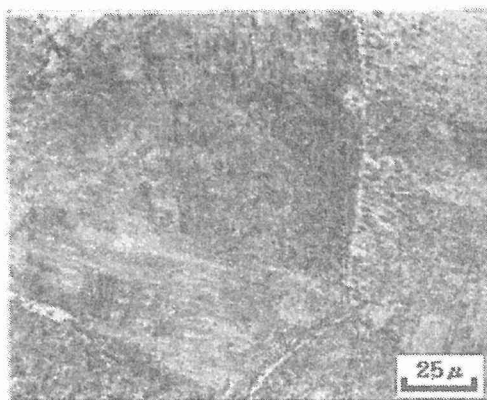
Time 2.8sec Hv 401



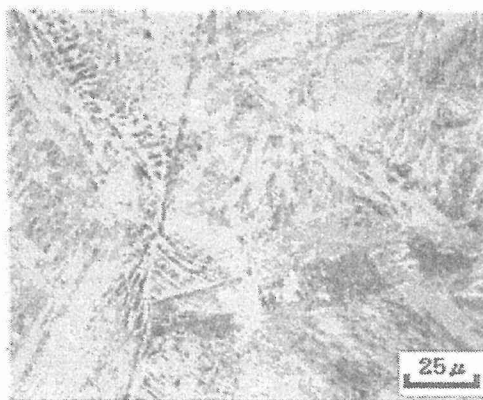
Time 3.3sec Hv 384



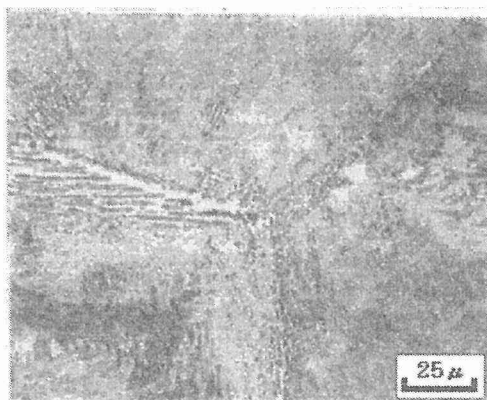
Time 4.3sec Hv 330



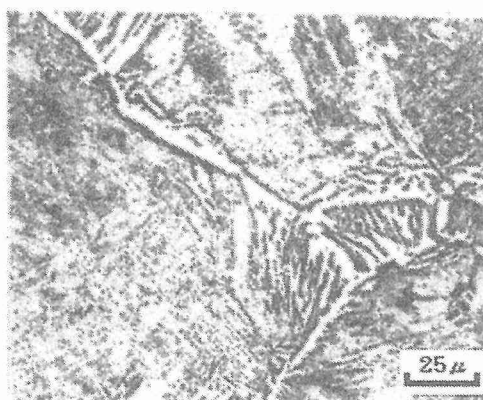
Time 5.5sec Hv 302



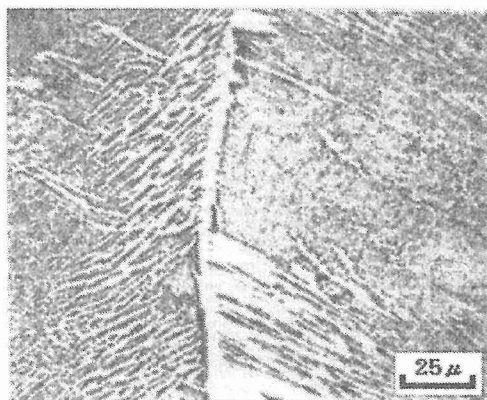
Time 6.5sec Hv 283



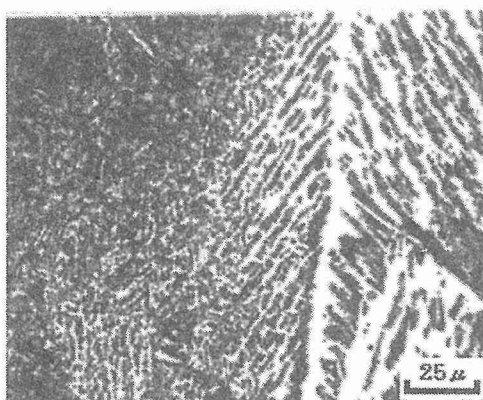
Time 8.5sec Hv 300



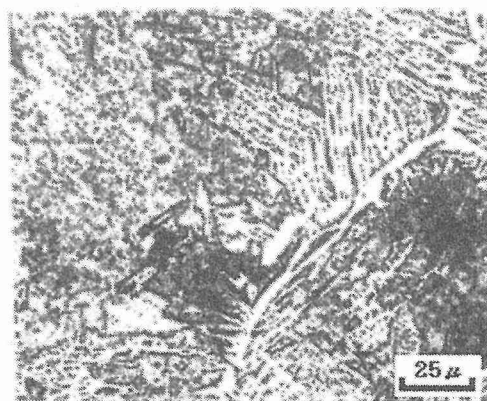
Time 14sec Hv 250



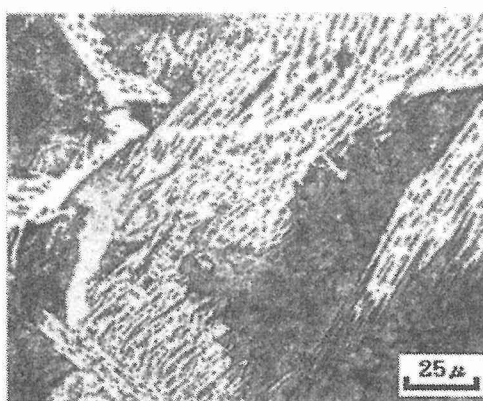
Time 17sec Hv 250



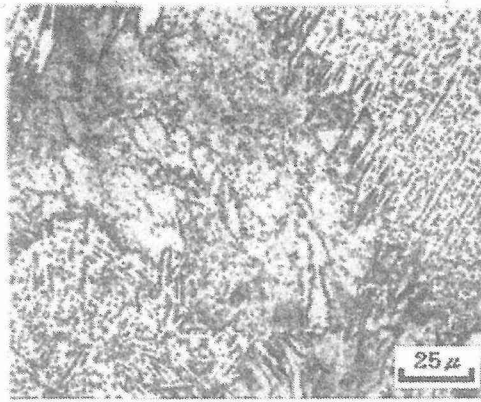
Time 24sec Hv 211



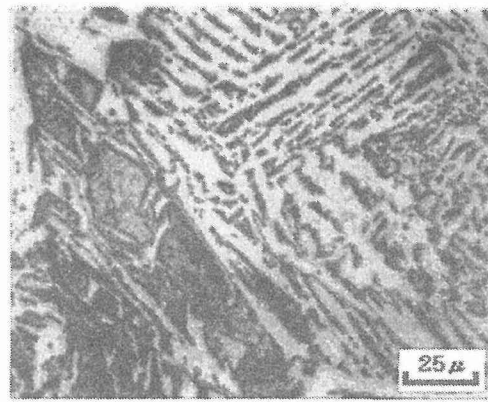
Time 38sec Hv 194



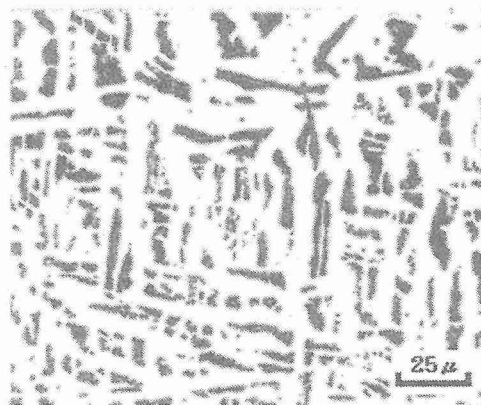
Time 48sec Hv 188



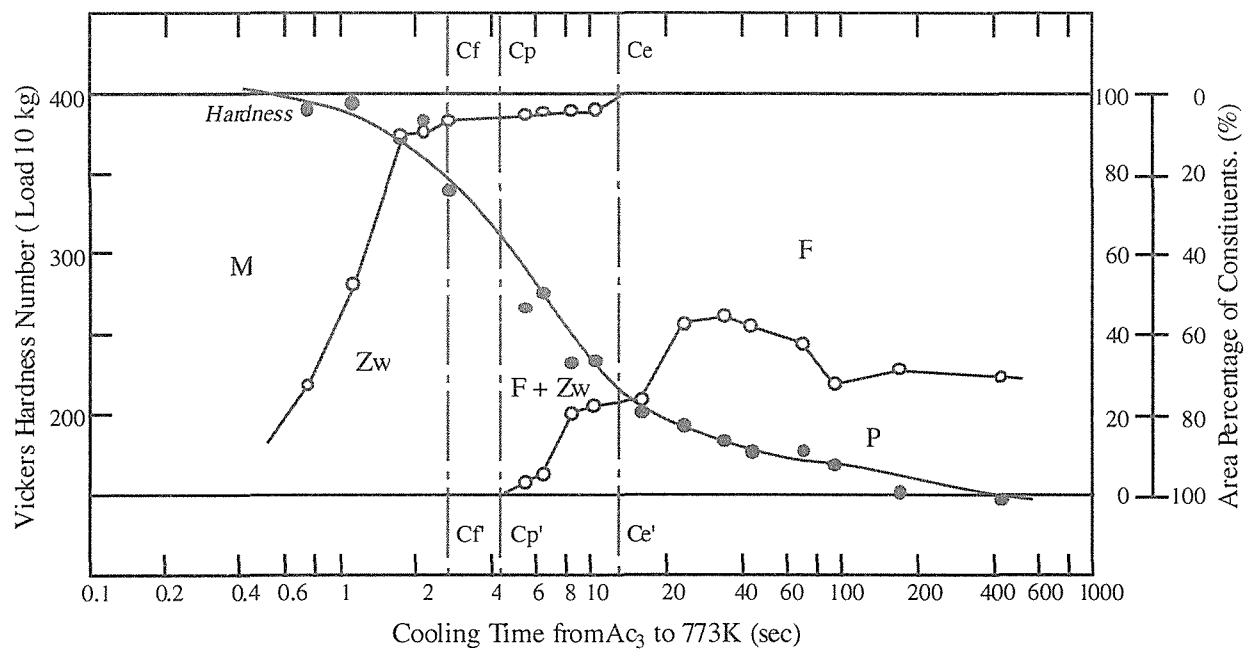
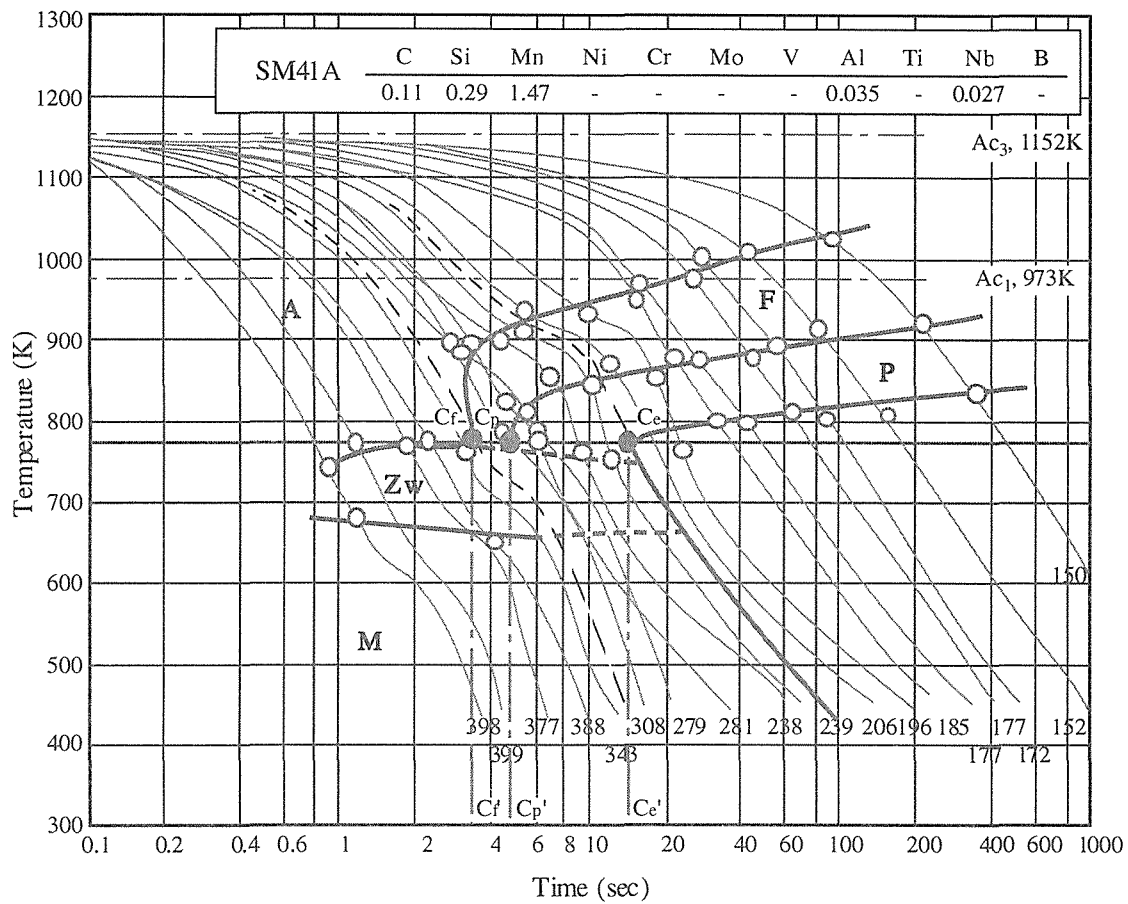
Time 78sec Hv 195

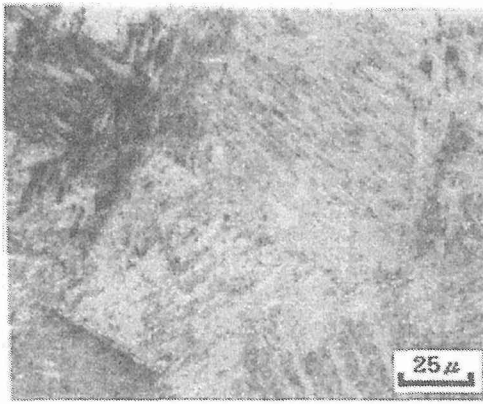


Time 100sec Hv 172

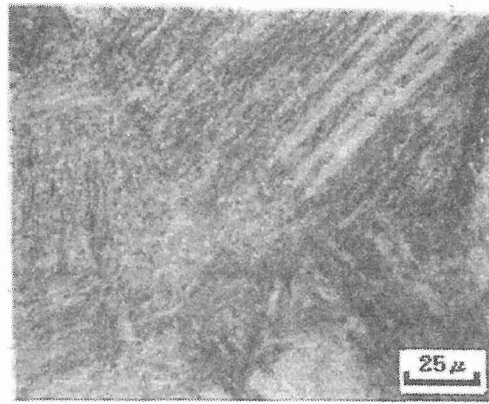


Time 180sec Hv 157

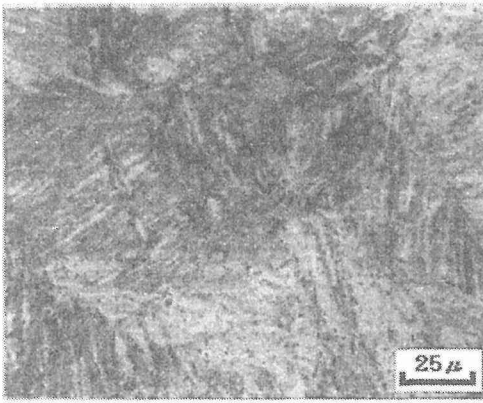




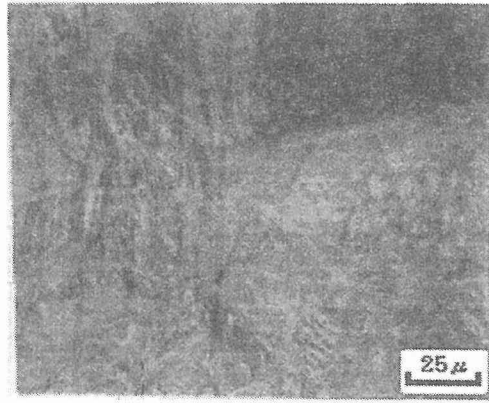
Time 0.8sec Hv 398



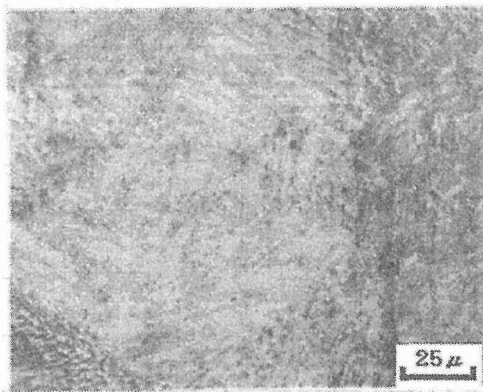
Time 1.2sec Hv 399



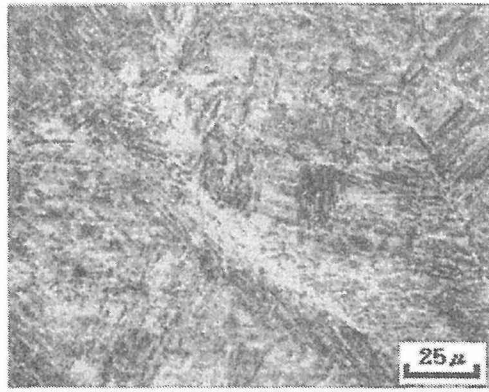
Time 1.8sec Hv 377



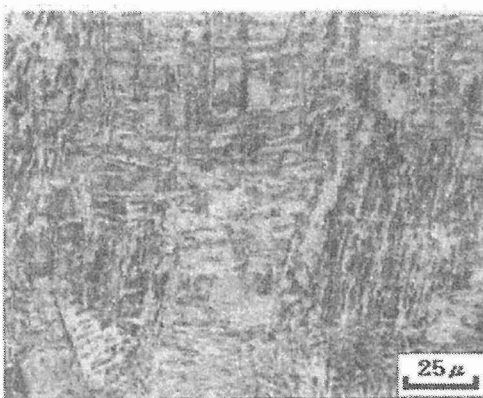
Time 2.5sec Hv 388



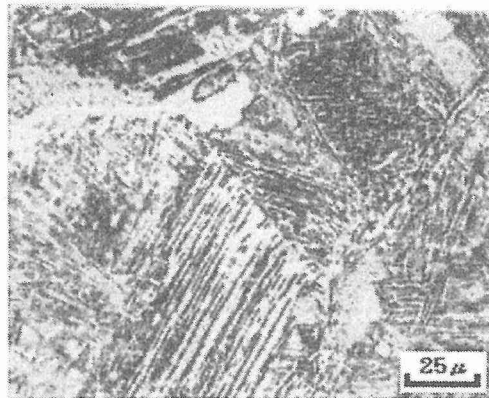
Time 3.3sec Hv 343



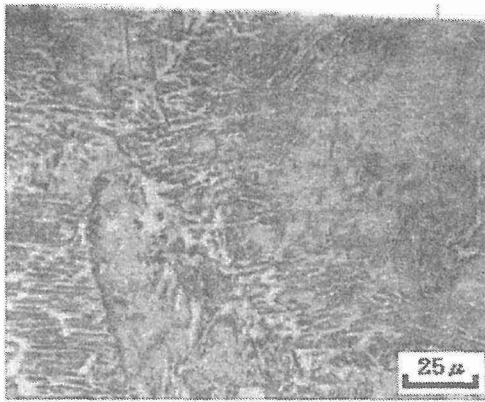
Time 5sec Hv 308



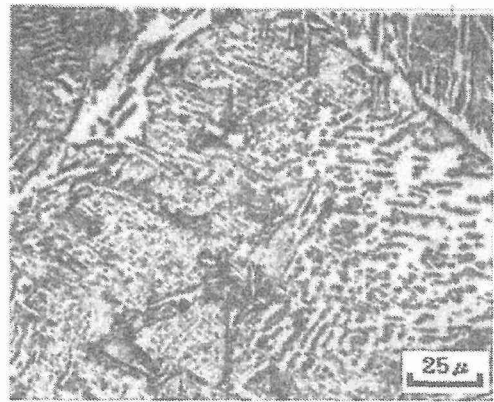
Time 6sec Hv 279



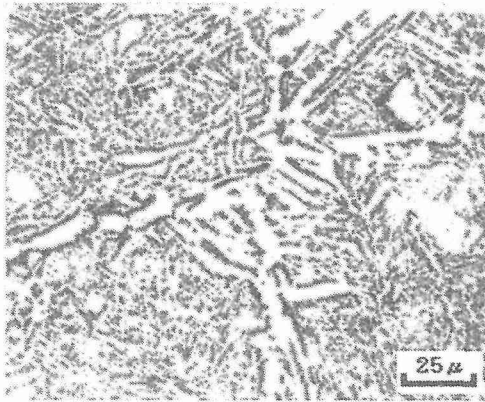
Time 6.8sec Hv 281



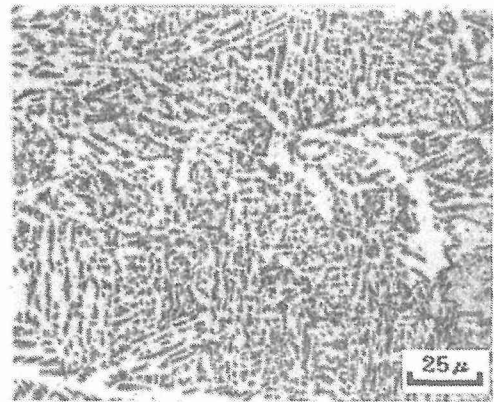
Time 9sec Hv 238



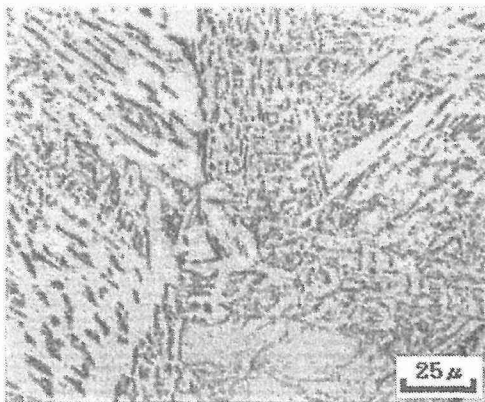
Time 12sec Hv 239



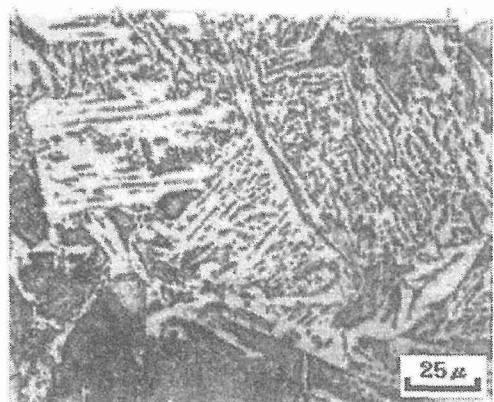
Time 18sec Hv 206



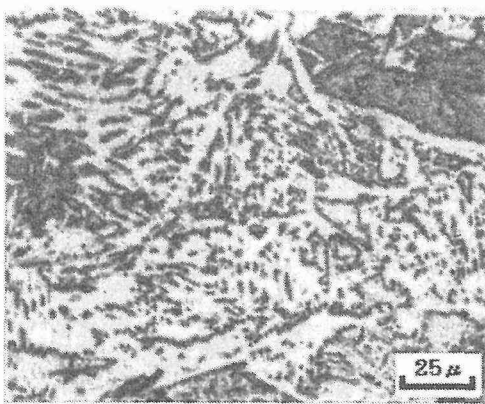
Time 25sec Hv 196



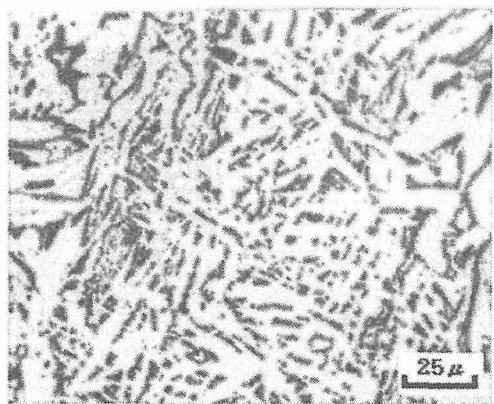
Time 36sec Hv 185



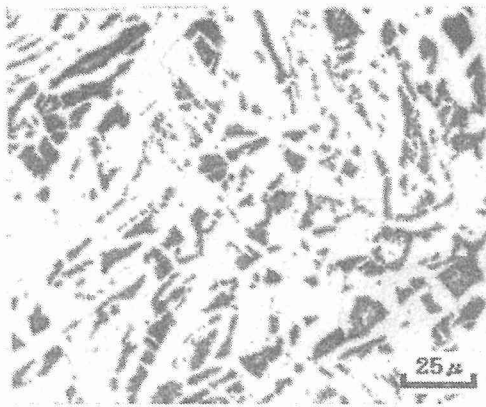
Time 48sec Hv 177



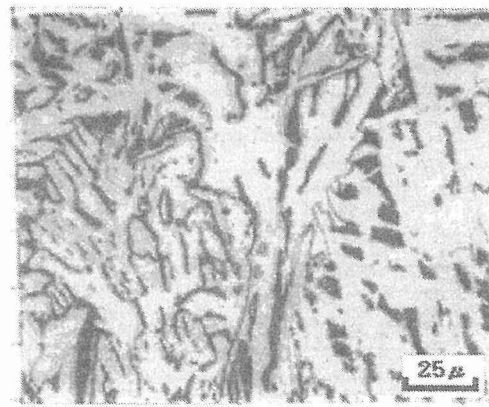
Time 78sec Hv 177



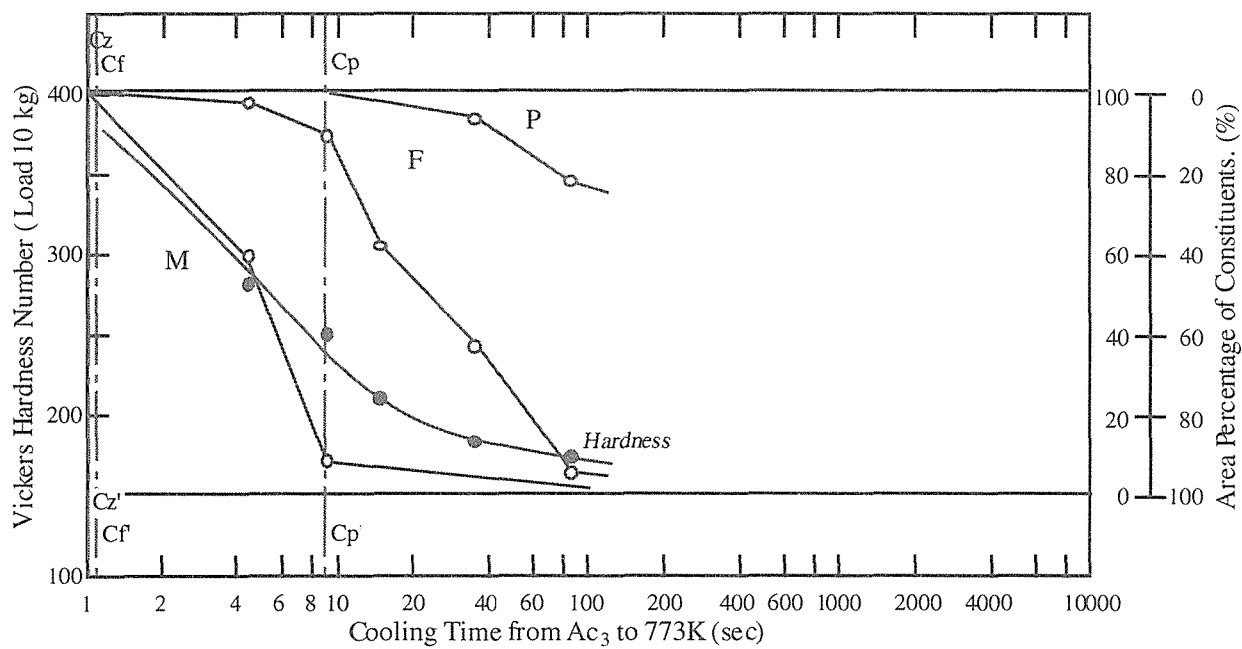
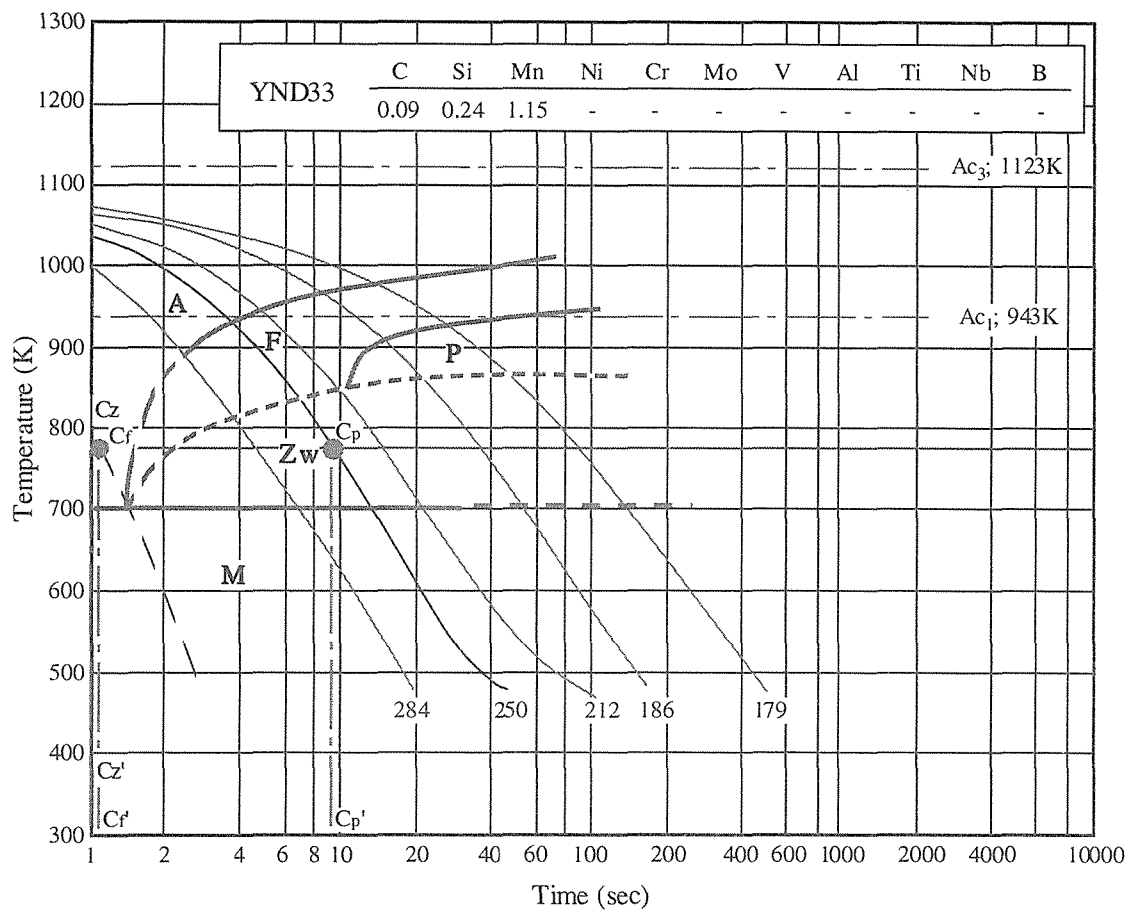
Time 110sec Hv 172

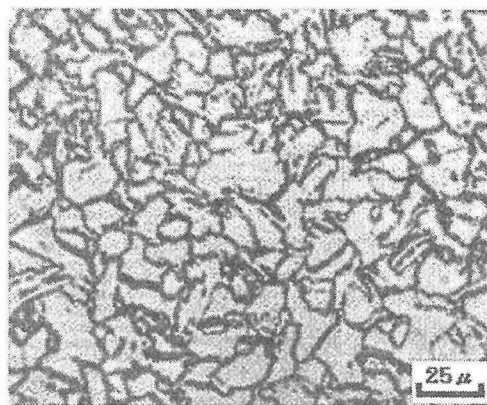


Time 180sec Hv 152

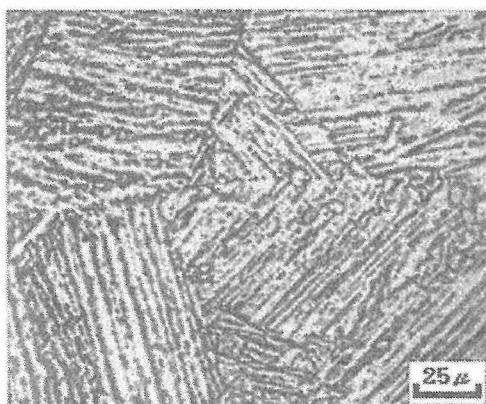


Time 460sec Hv 150

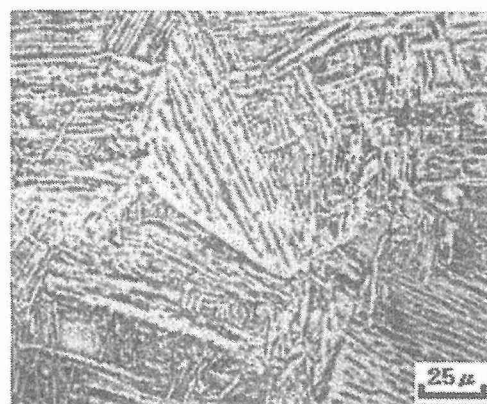




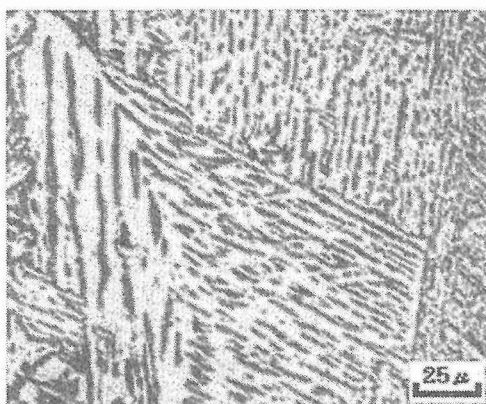
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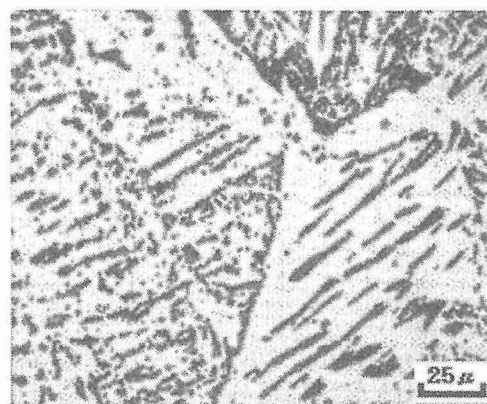
Time 4.6sec Hv 284



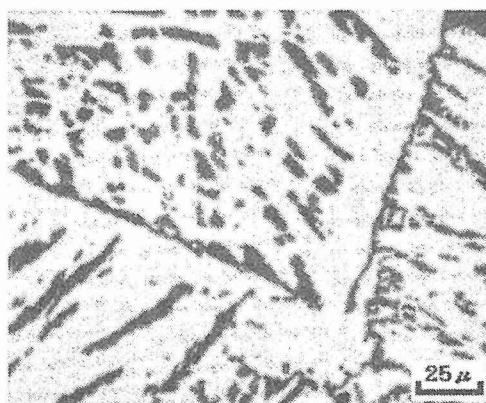
Time 9.4sec Hv 250



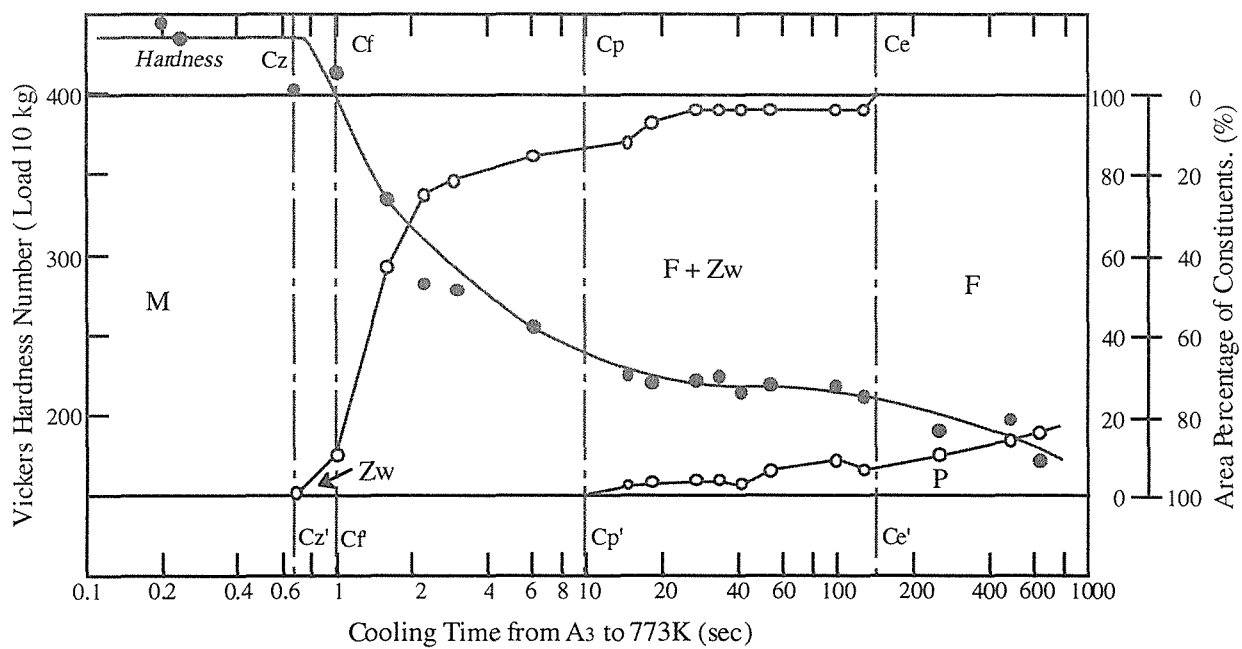
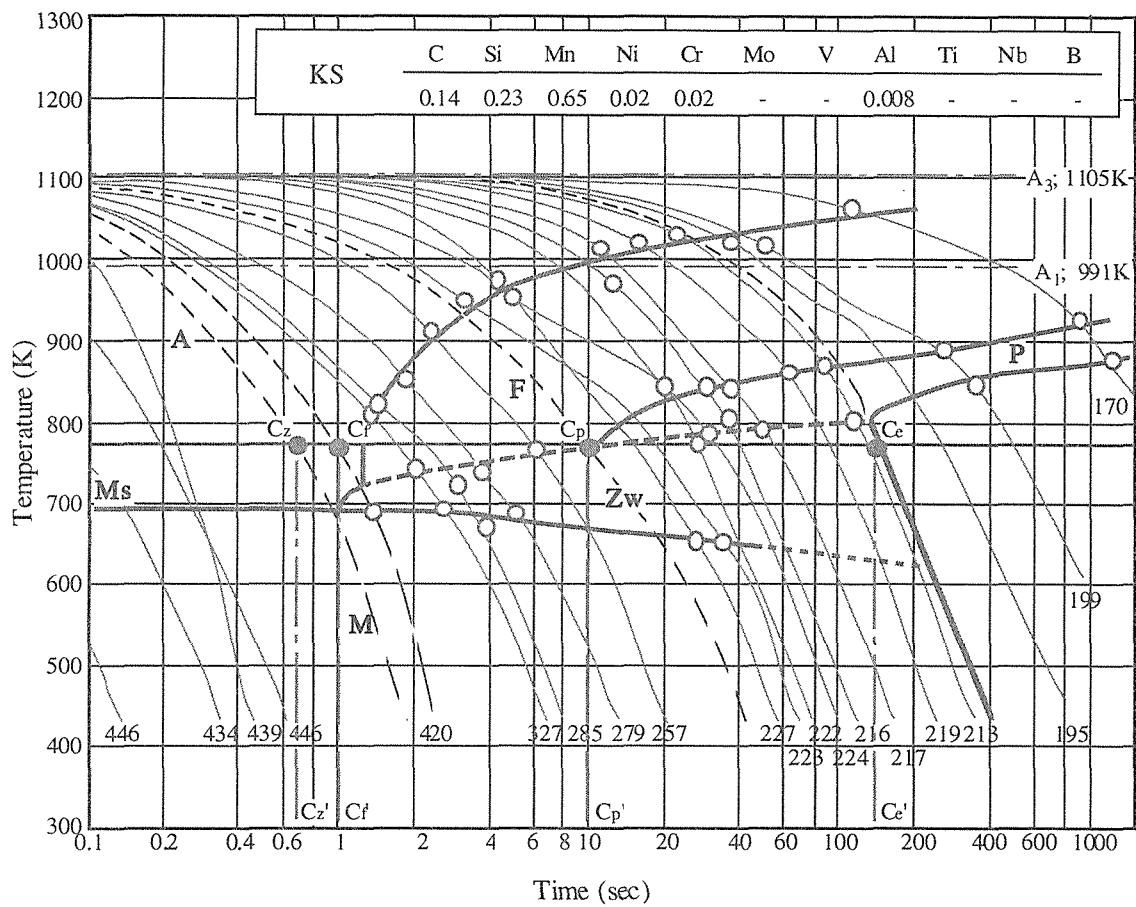
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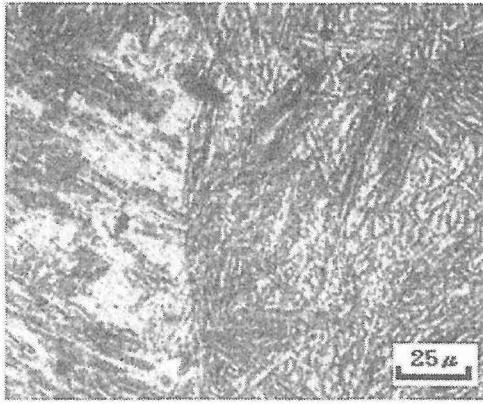


Time 36sec Hv 186

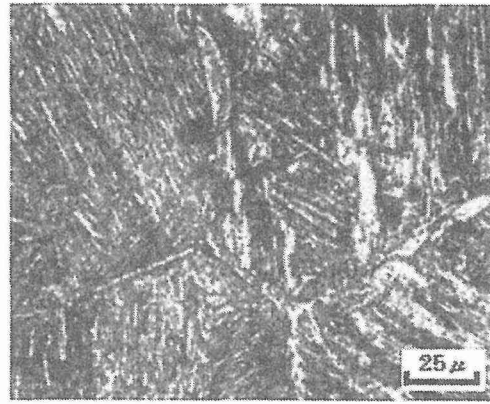


Time 90sec Hv 179

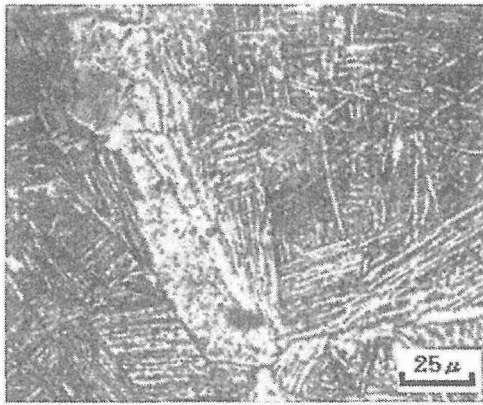




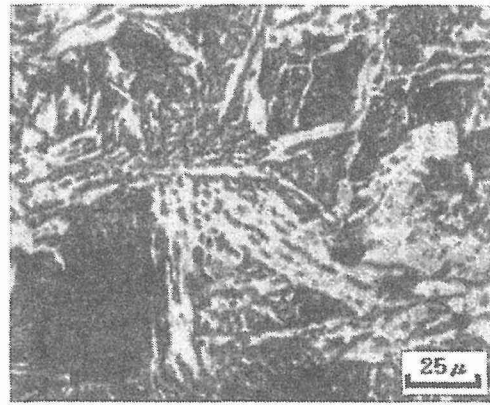
Time 0.22sec Hv 439



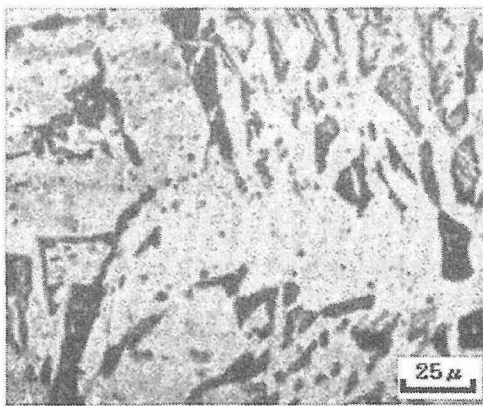
Time 0.9sec Hv 420



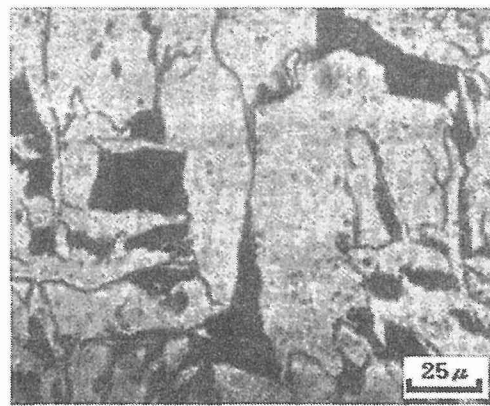
Time 1.6sec Hv 327



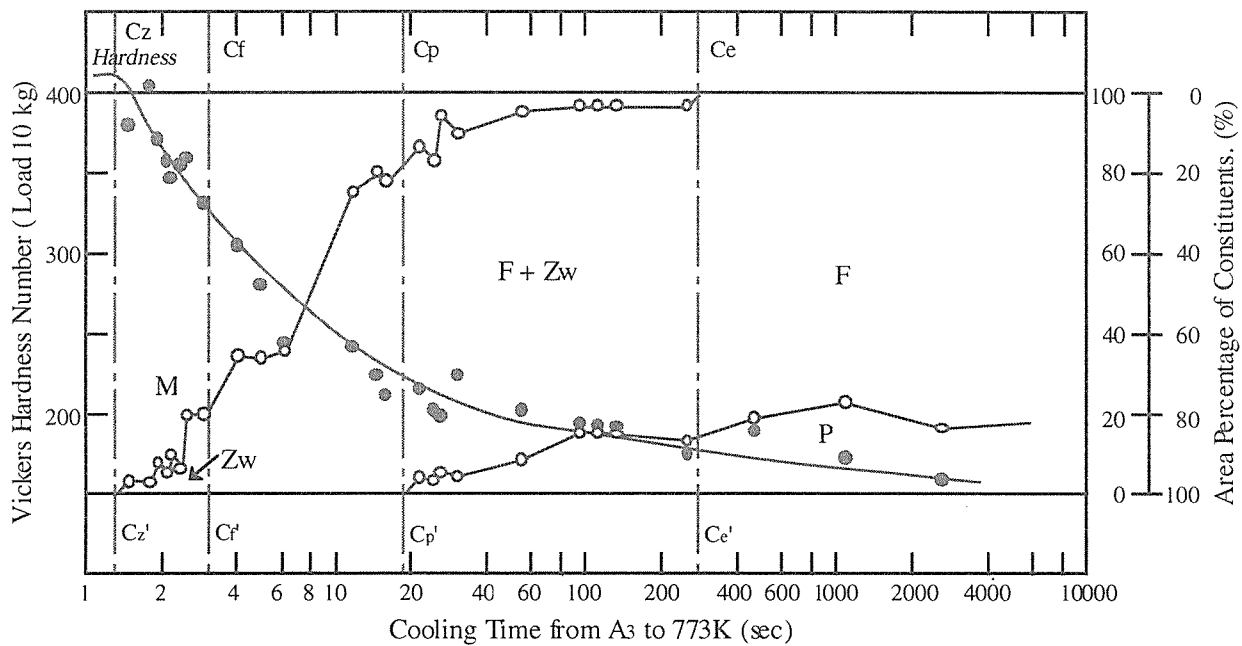
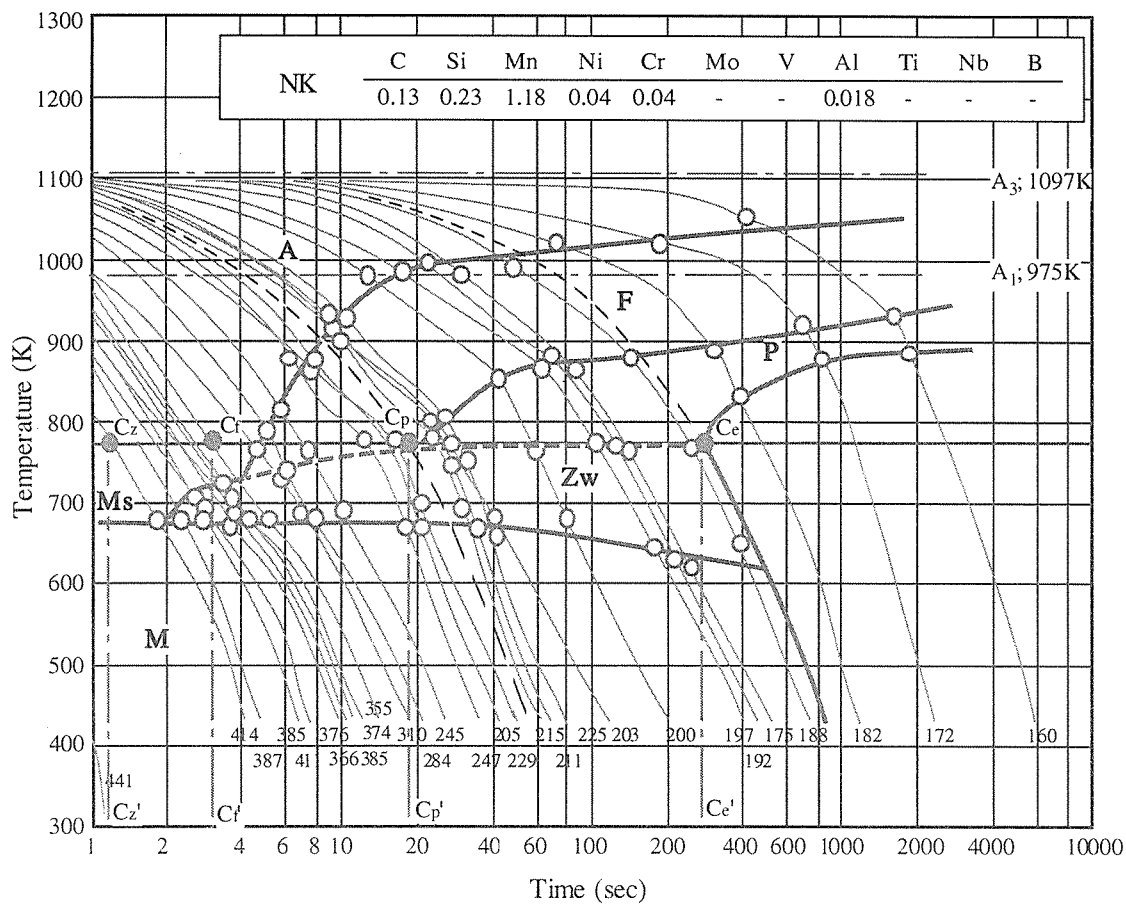
Time 18sec Hv 223

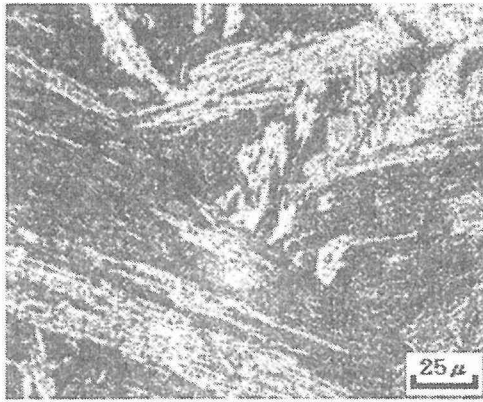


Time 90sec Hv 219

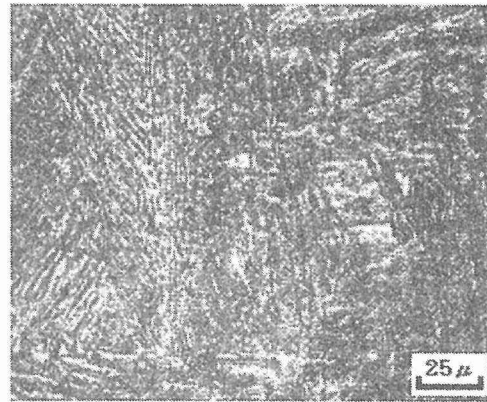


Time 250sec Hv 195

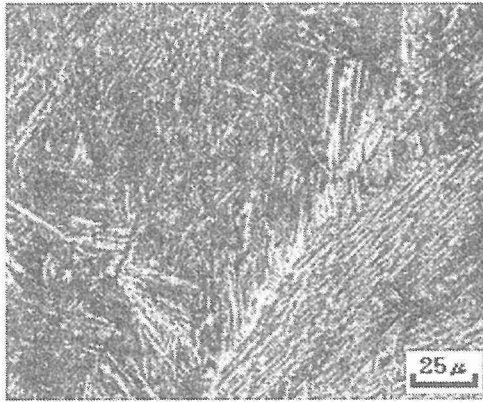




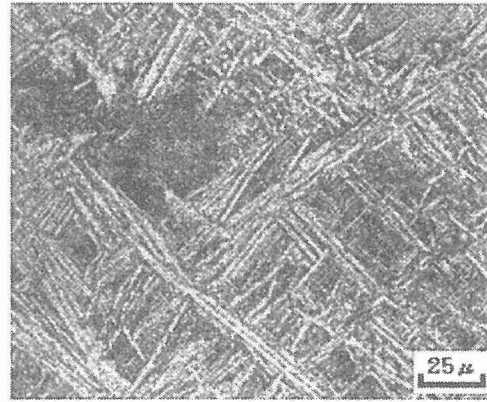
Time - Hv 441



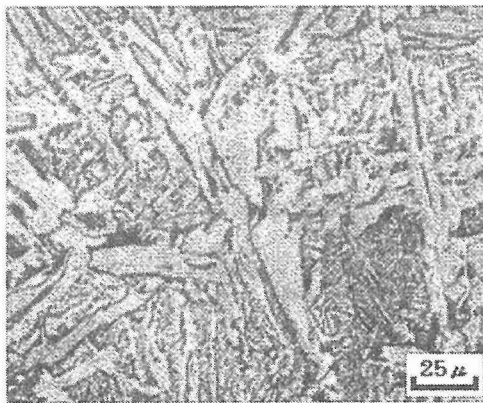
Time 4sec Hv 366



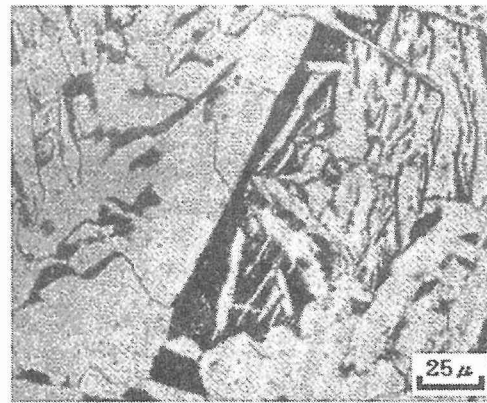
Time 5sec Hv 284



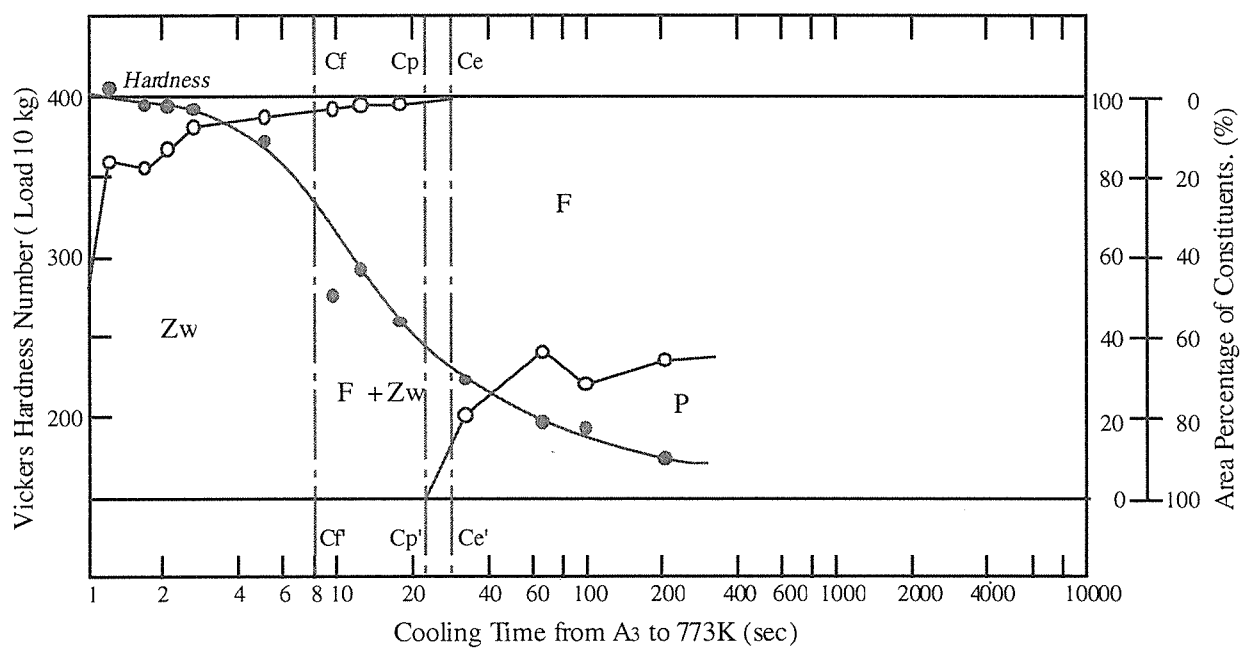
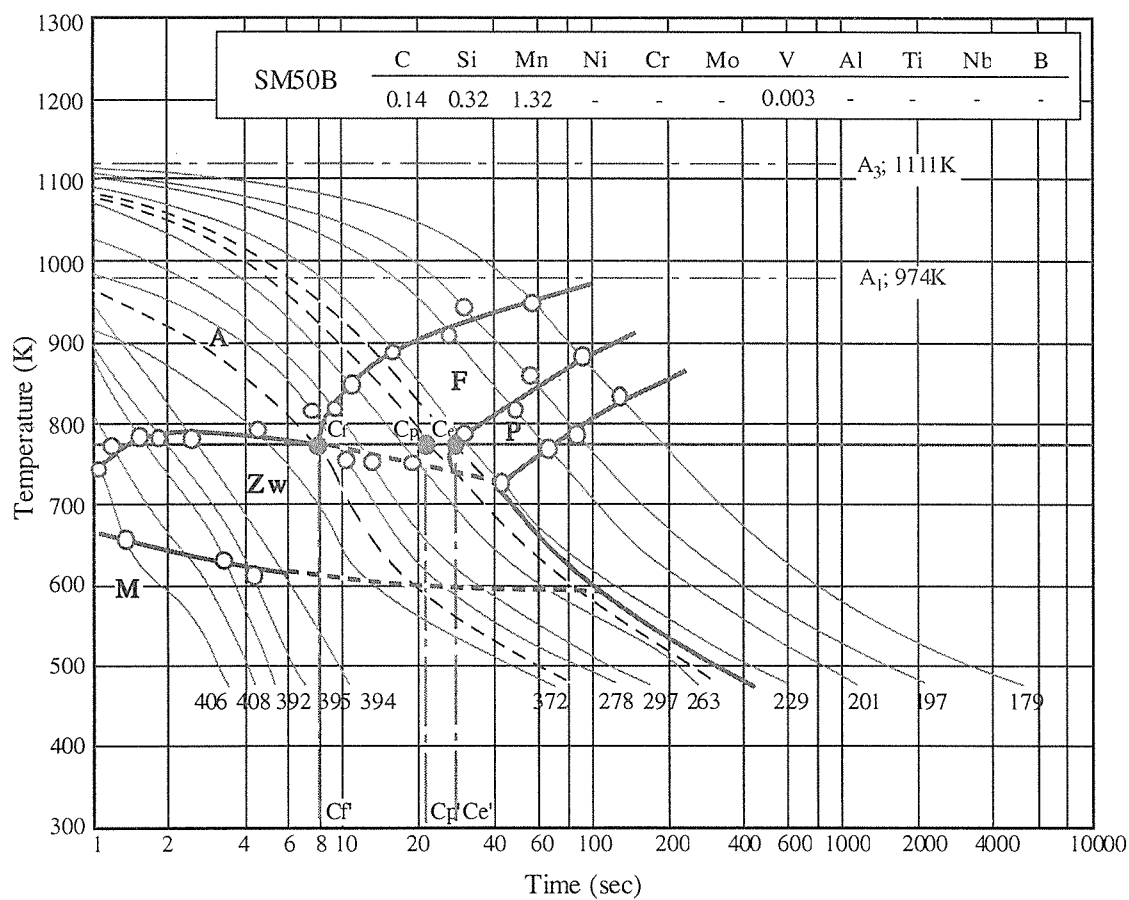
Time 12sec Hv 247

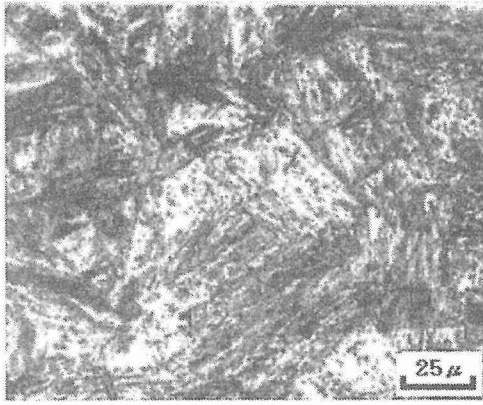


Time 59sec Hv 200

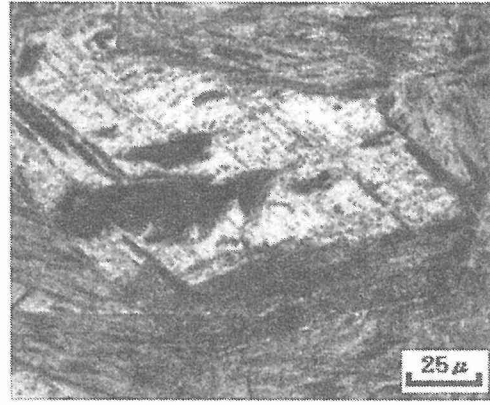


Time 300sec Hv 188

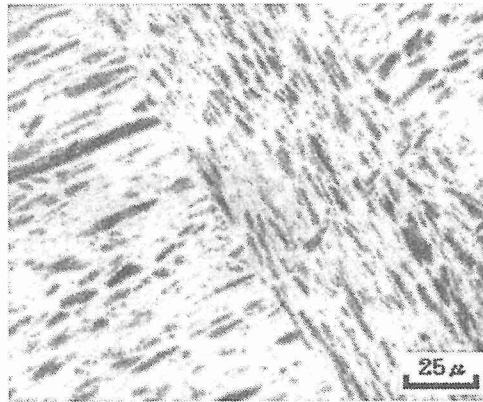




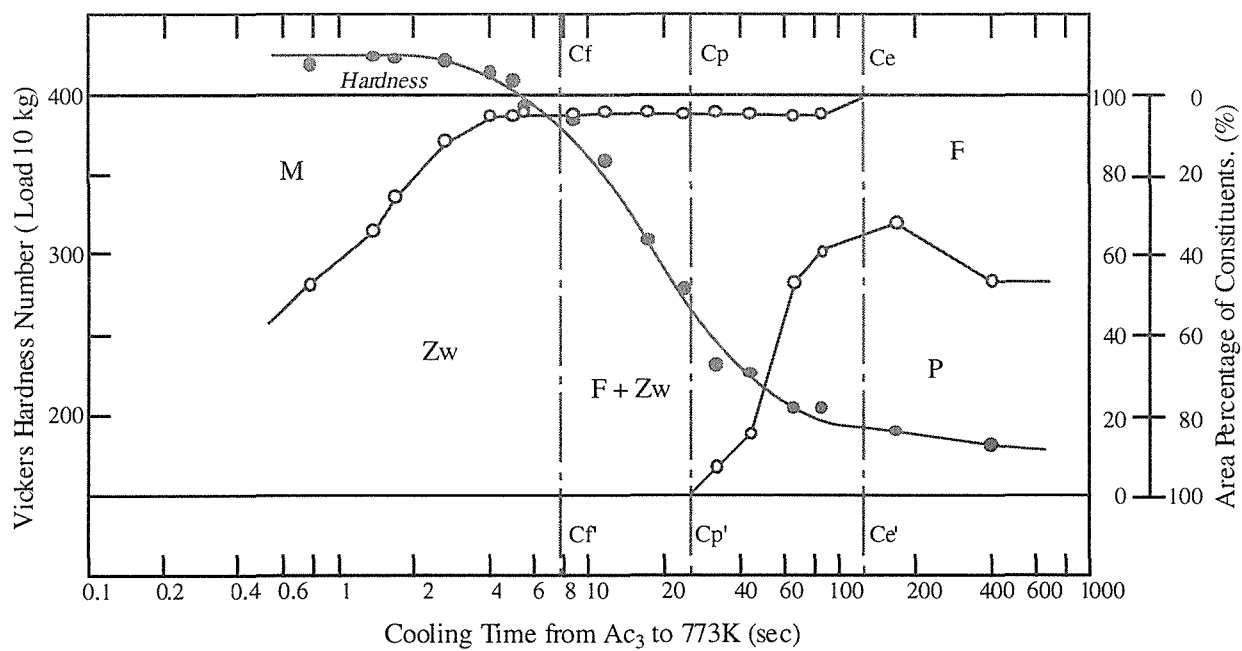
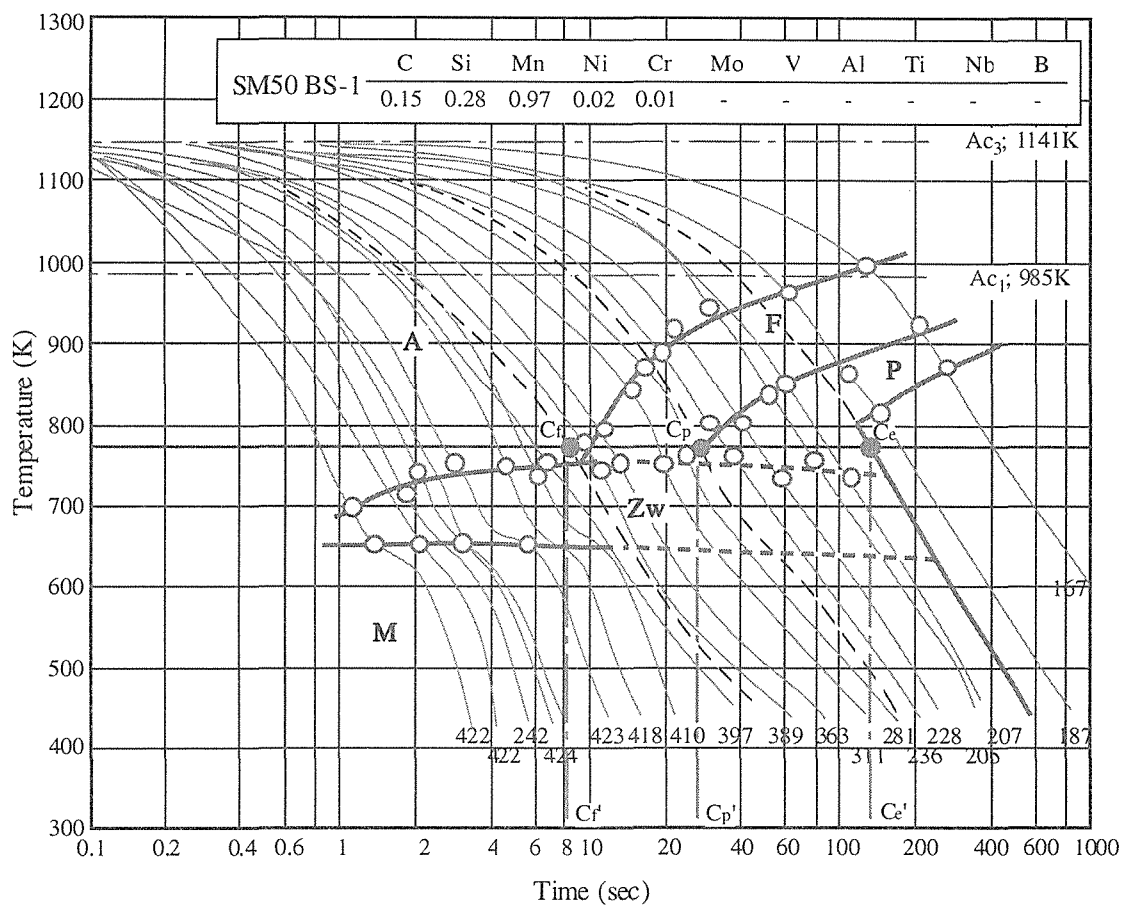
Time 15sec Hv 297

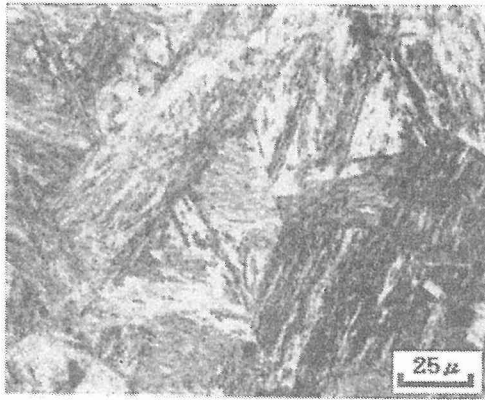


Time 20sec Hv 263

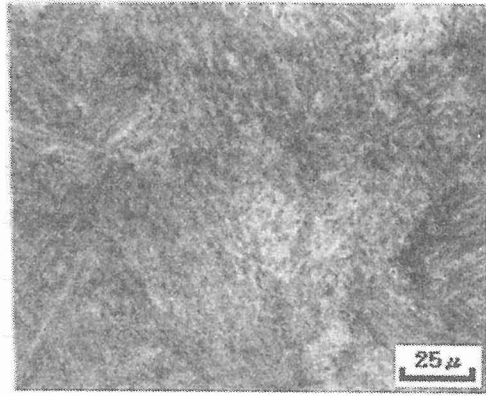


Time 25sec Hv 229

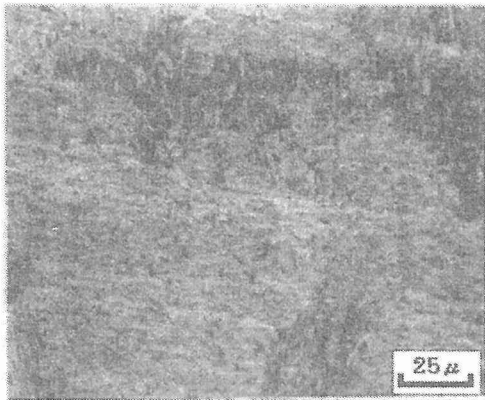




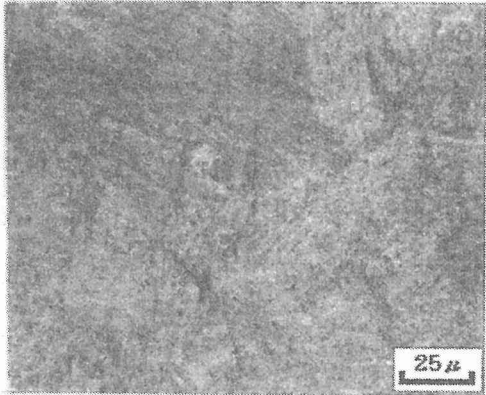
Time 0.8sec Hv 422



Time 1.2sec Hv 422



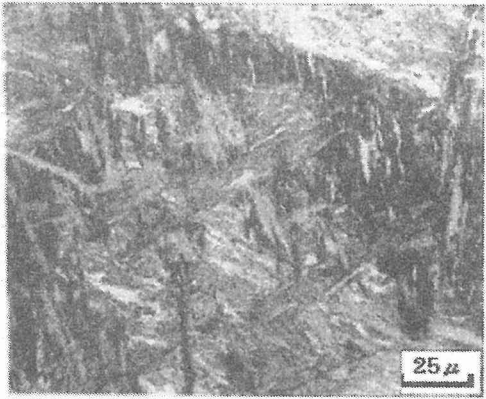
Time 1.4sec Hv 424



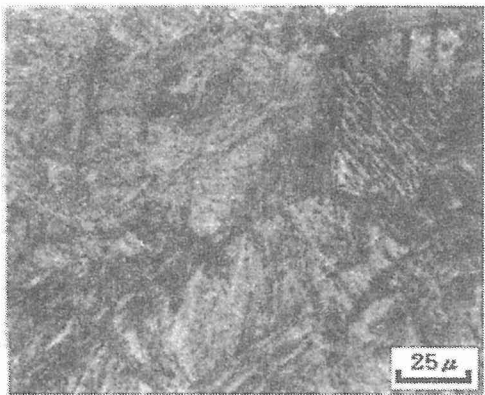
Time 2.8sec Hv 423



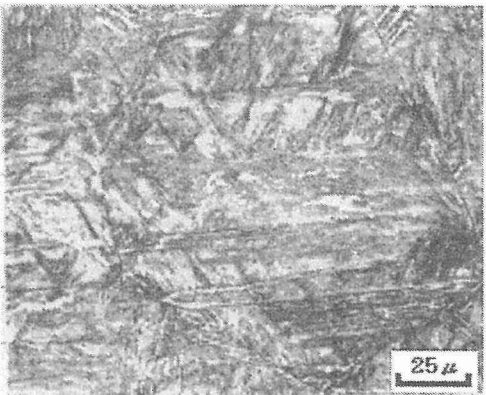
Time 4.4sec Hv 418



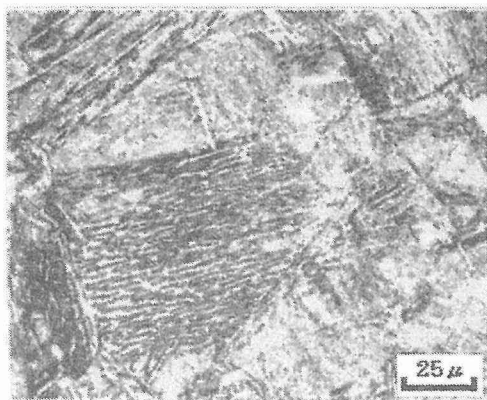
Time 5.3sec Hv 410



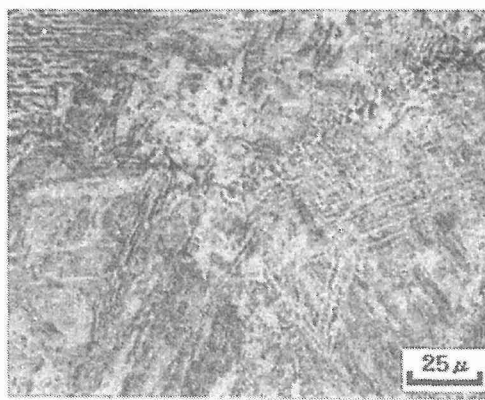
Time 6sec Hv 397



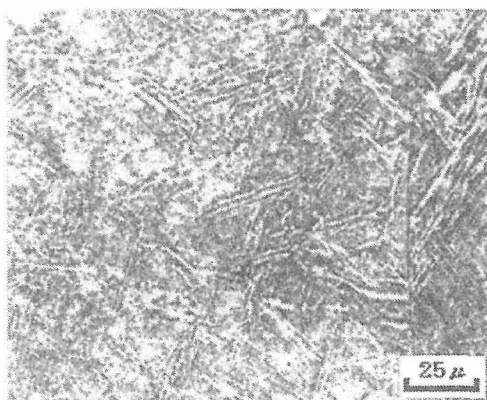
Time 10sec Hv 389



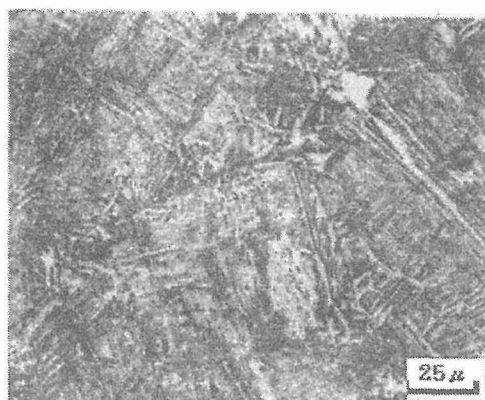
Time 12sec Hv 363



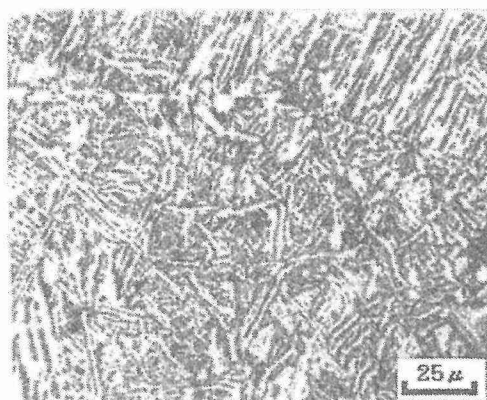
Time 19sec Hv 311



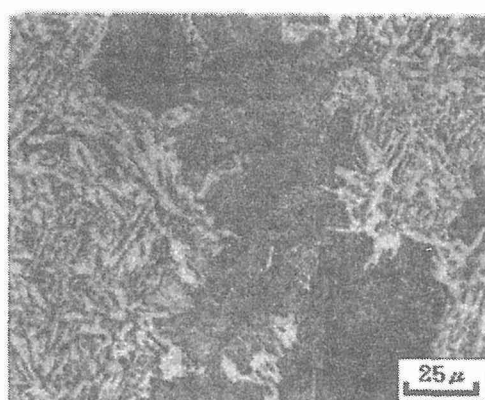
Time 25sec Hv 281



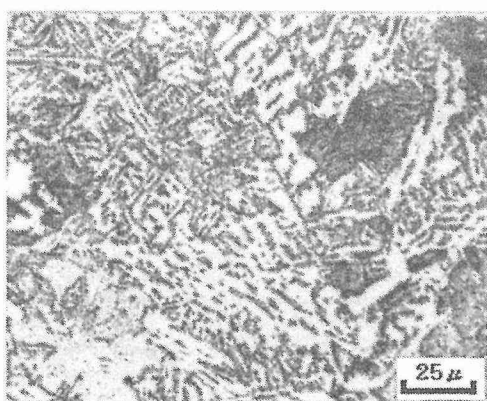
Time 35 Hv 236



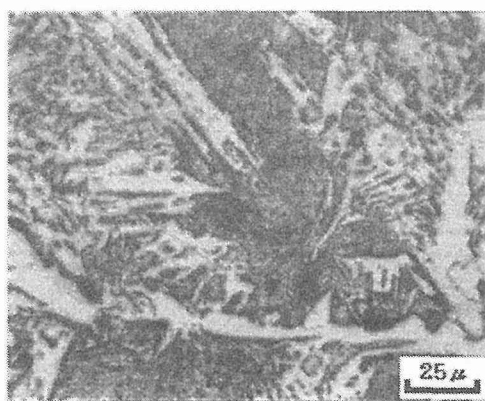
Time 48sec Hv 228



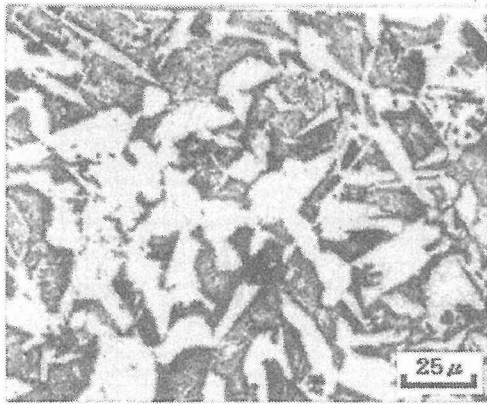
Time 70sec Hv 205



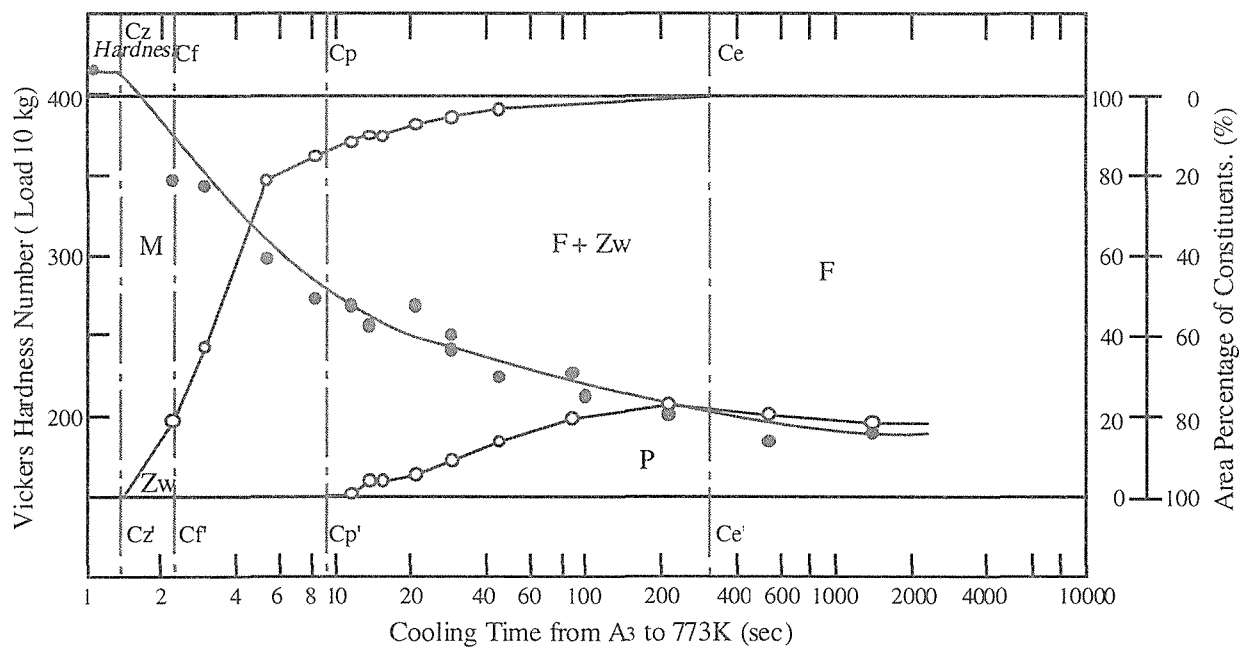
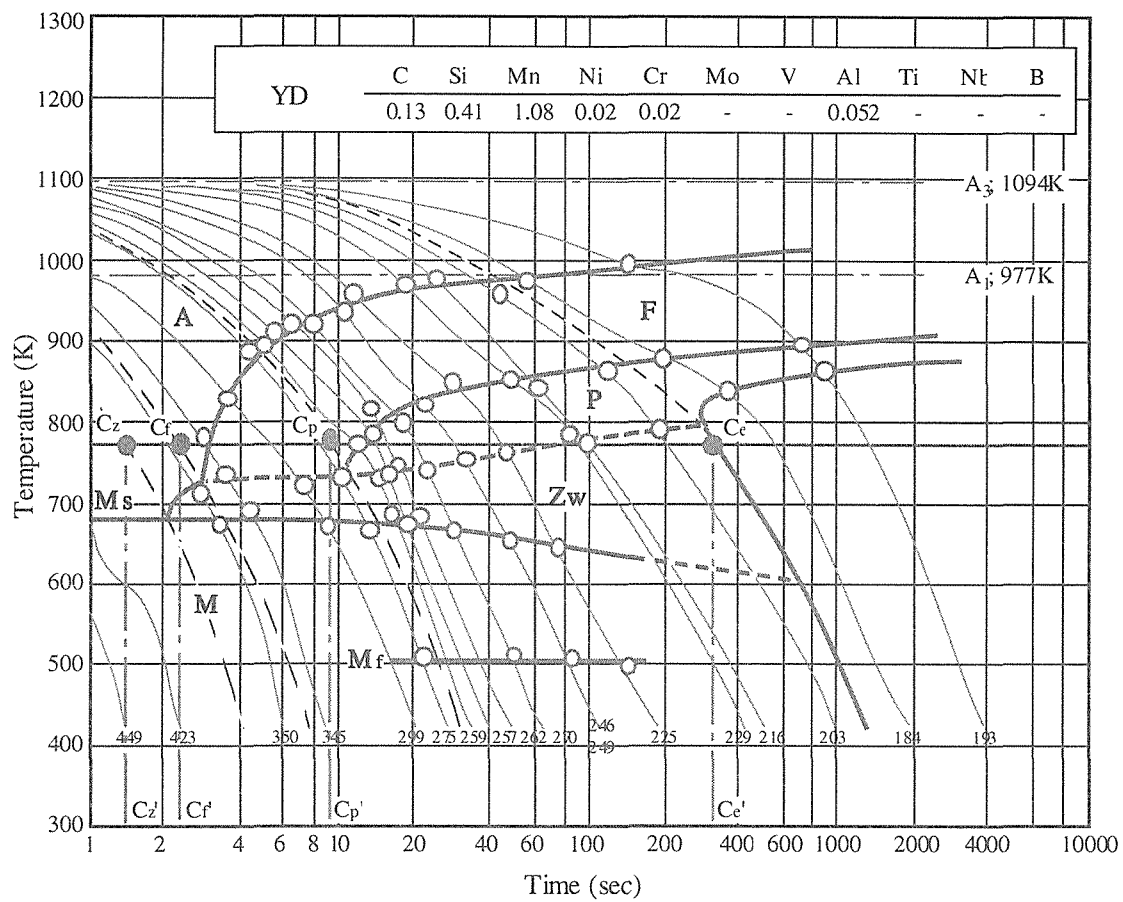
Time 90sec Hv 207

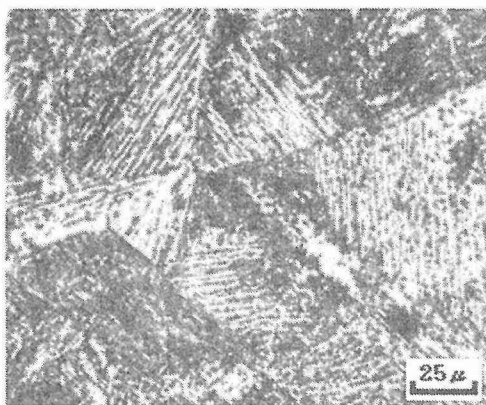


Time 180sec Hv 187

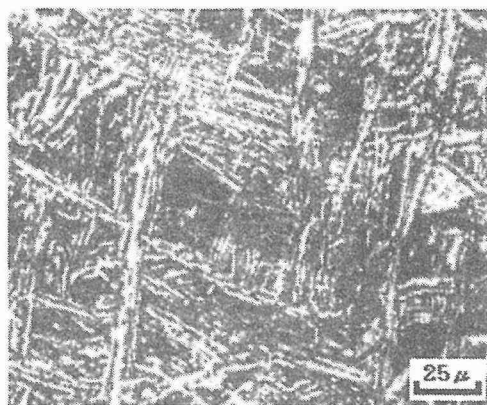


Time 400sec Hv 167

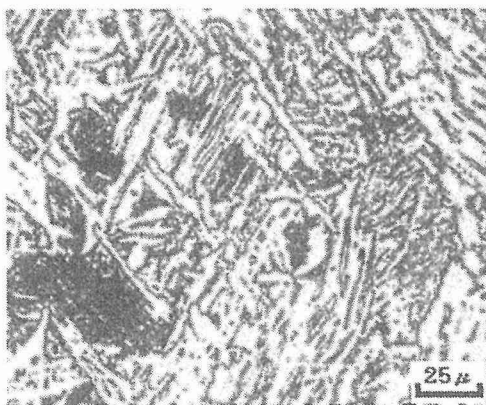




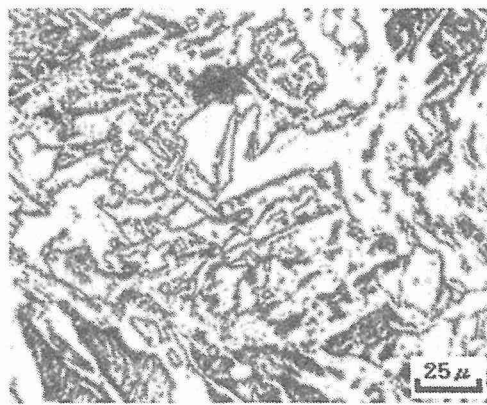
Time 3sec Hv 345



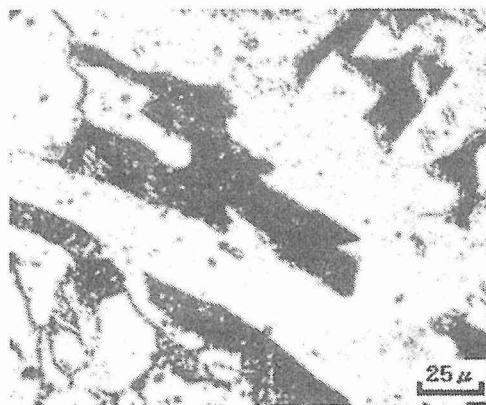
Time 5.5sec Hv 299



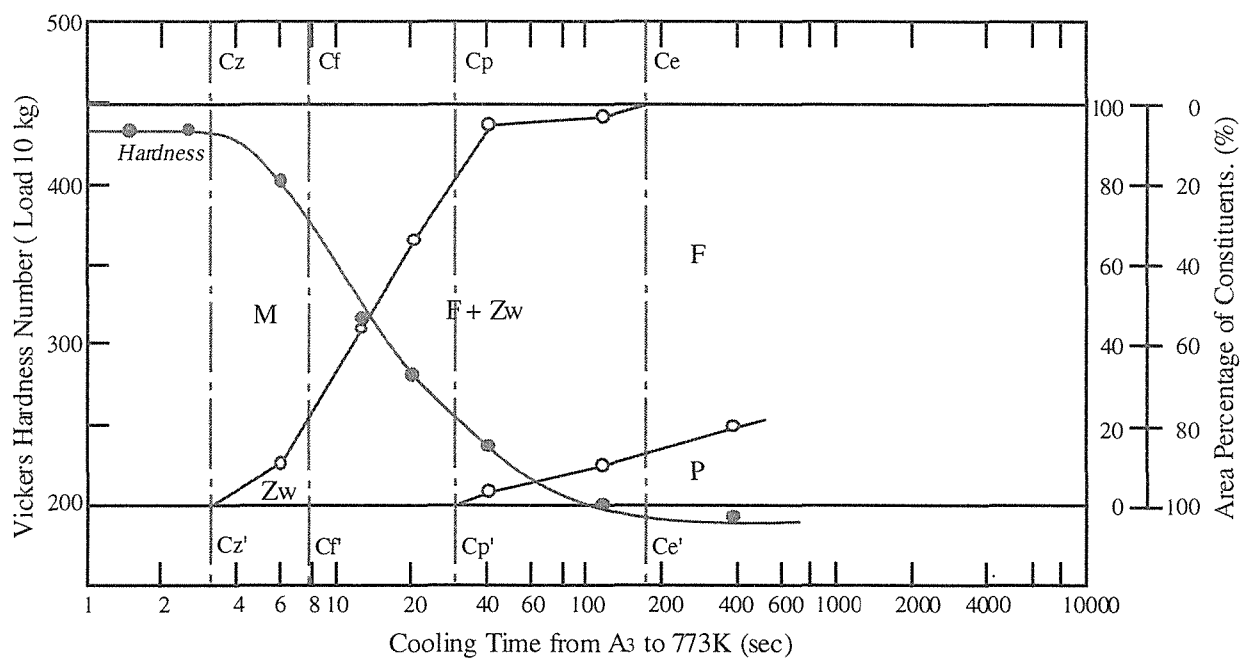
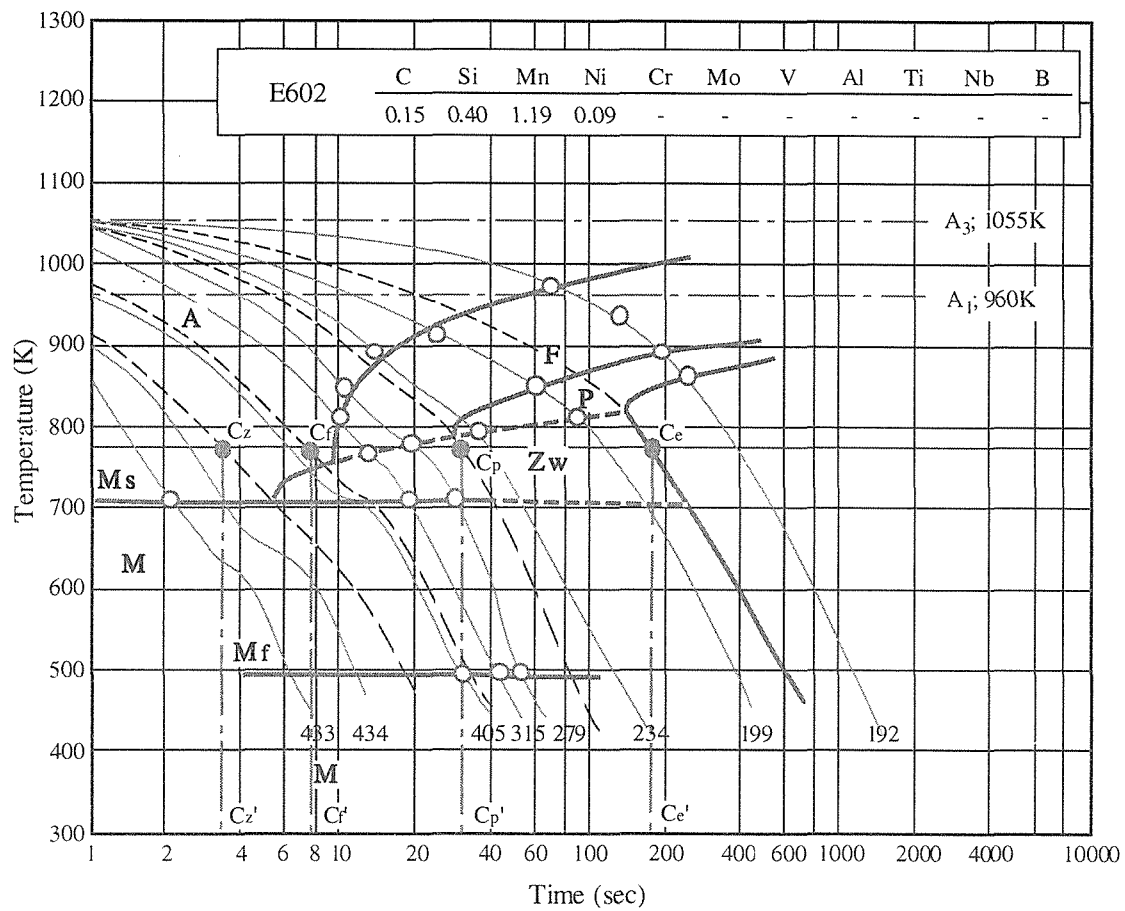
Time 30sec Hv 246

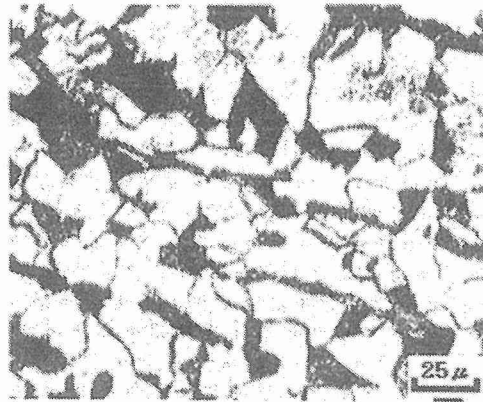


Time 100sec Hv 216



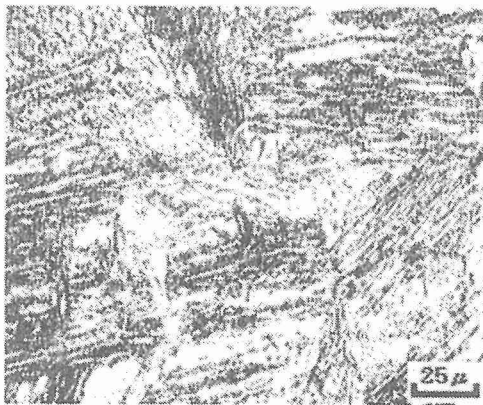
Time 560sec Hv 184





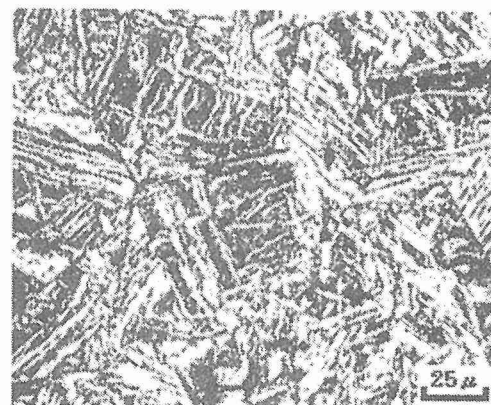
Base

Hv -



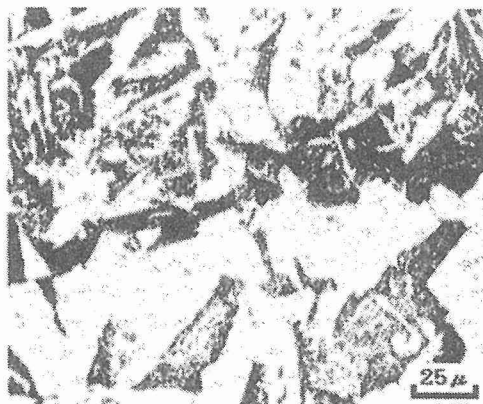
Time 1.6sec

Hv 433



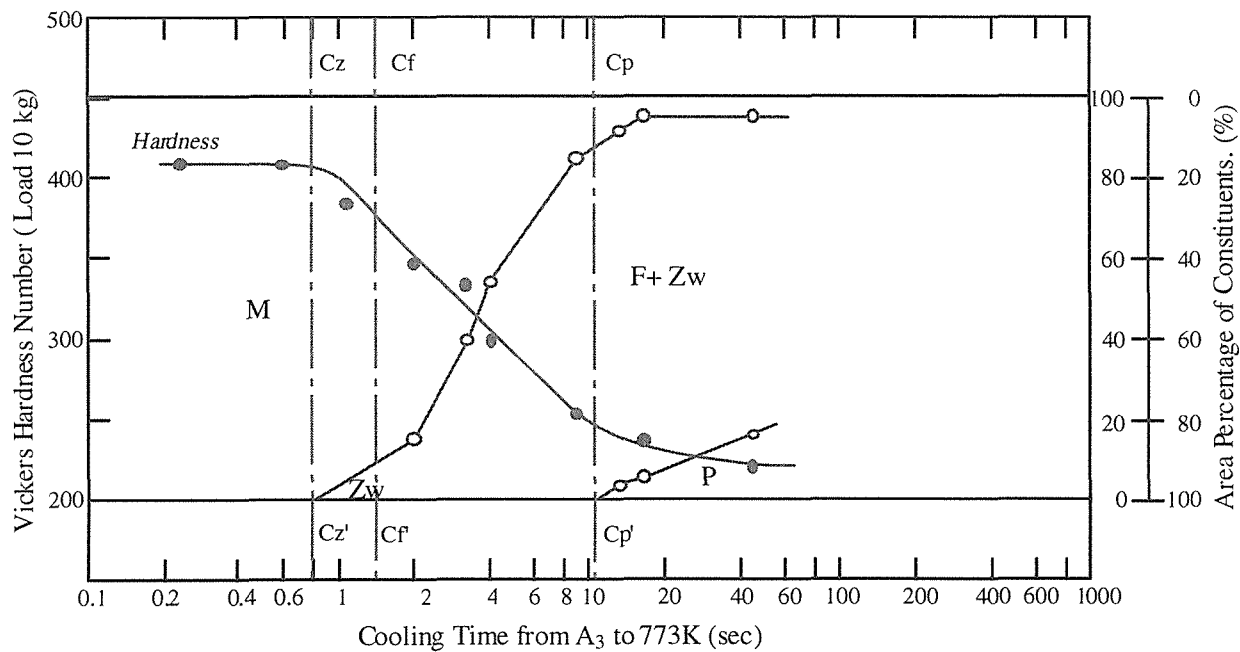
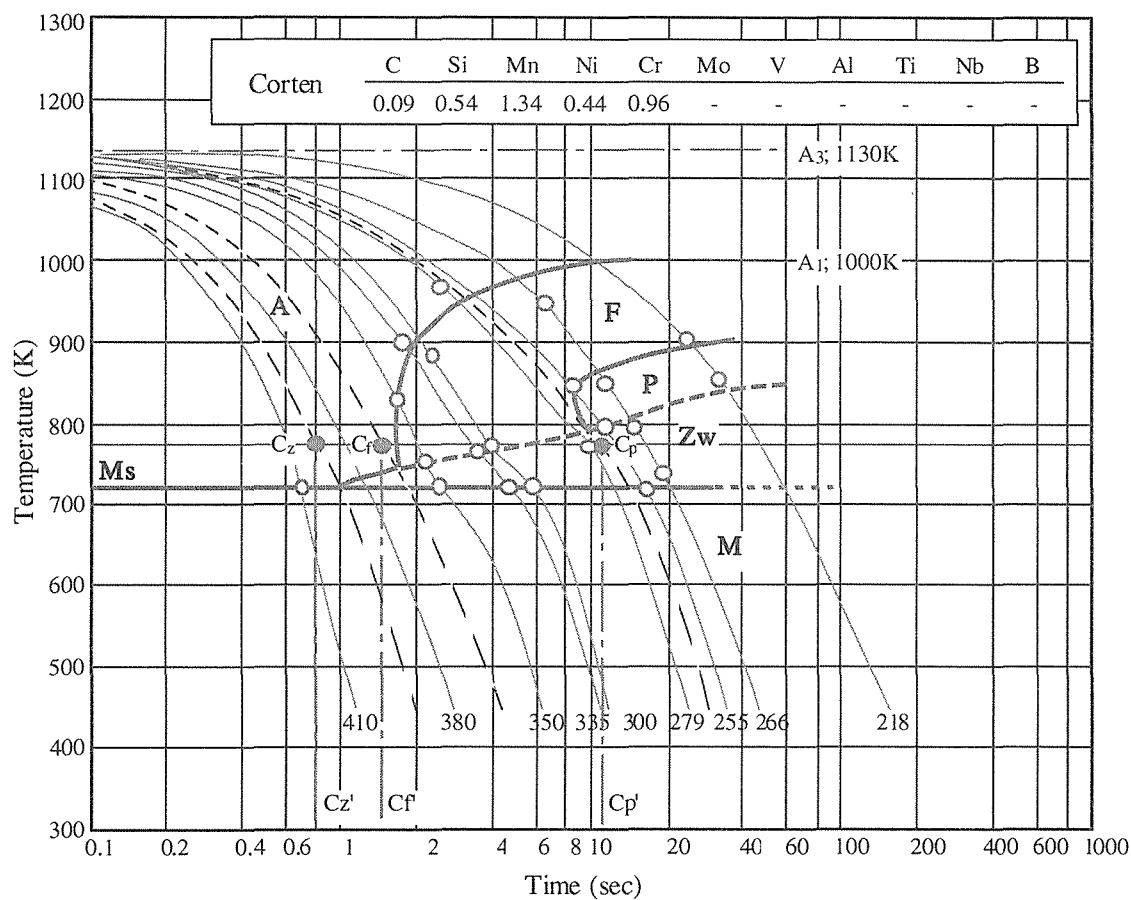
Time 20sec

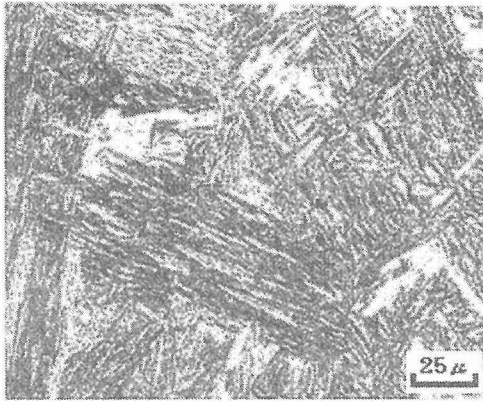
Hv 279



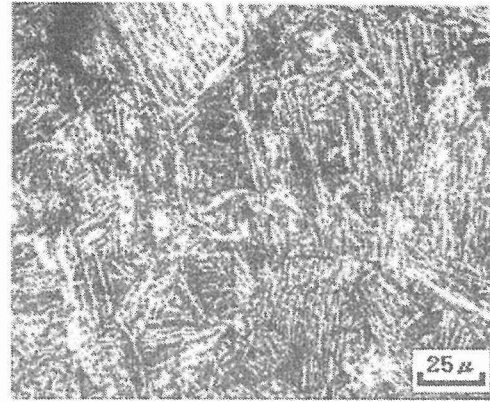
Time 400sec

Hv 192

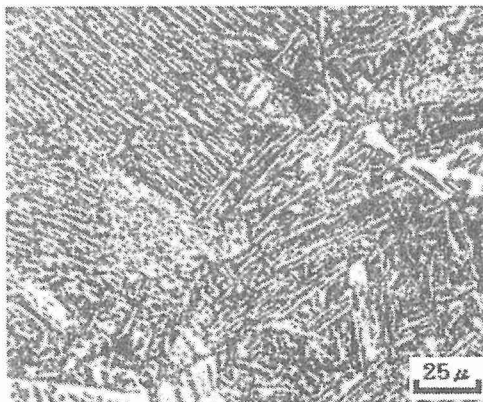




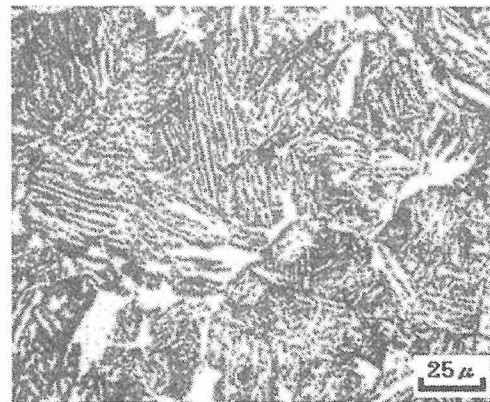
Time 0.7sec Hv 410



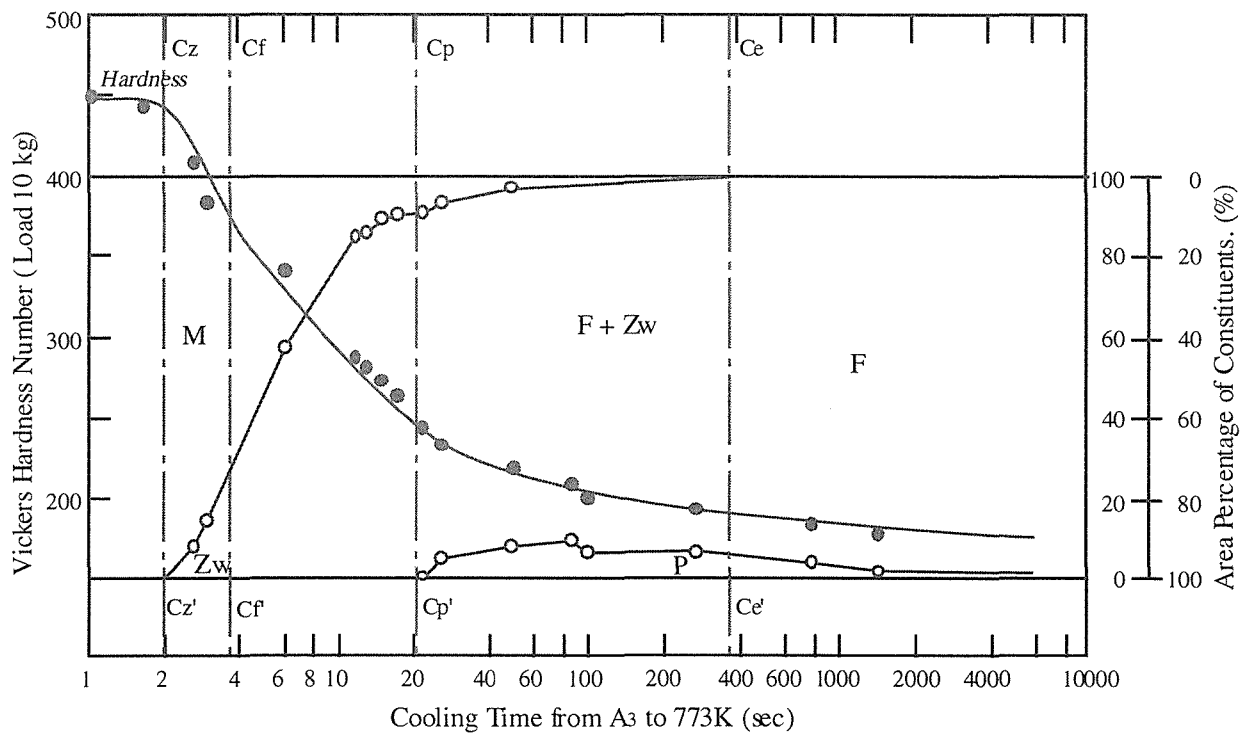
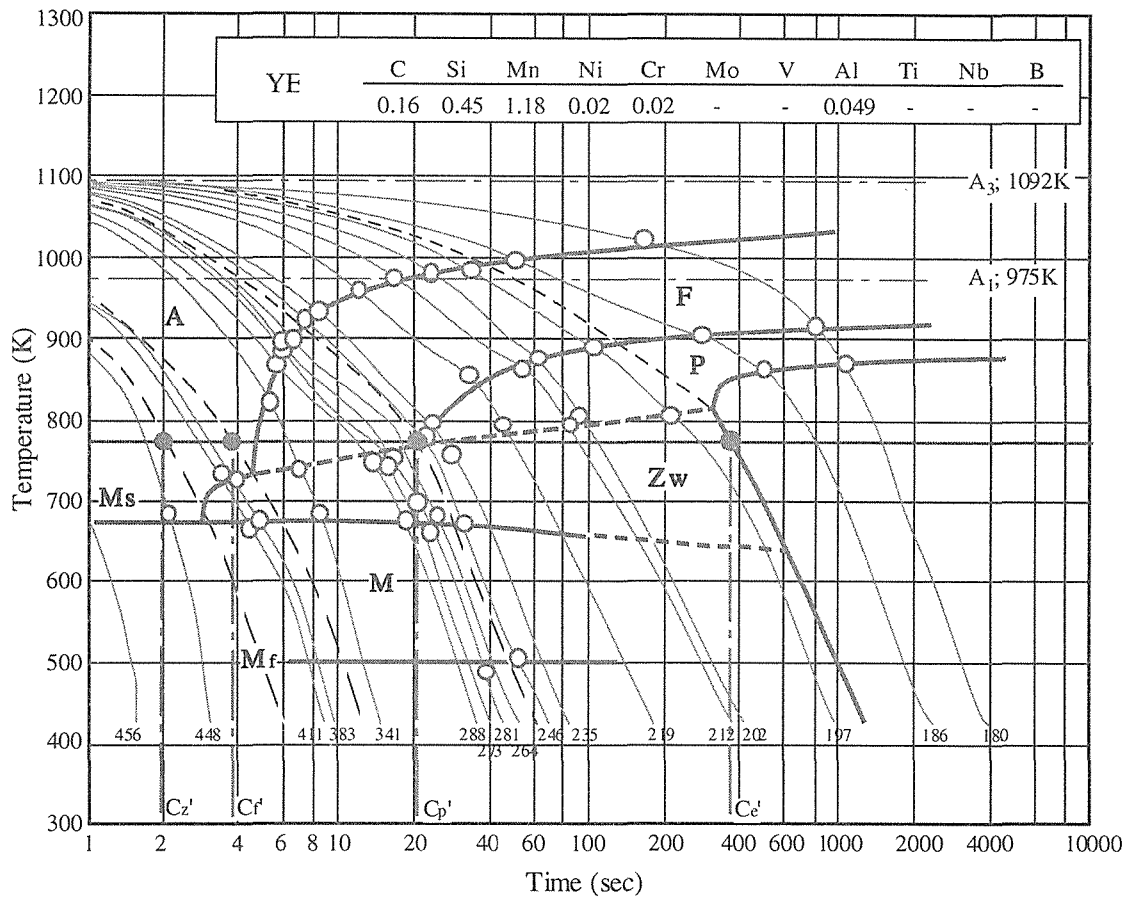
Time 3.5sec Hv 335

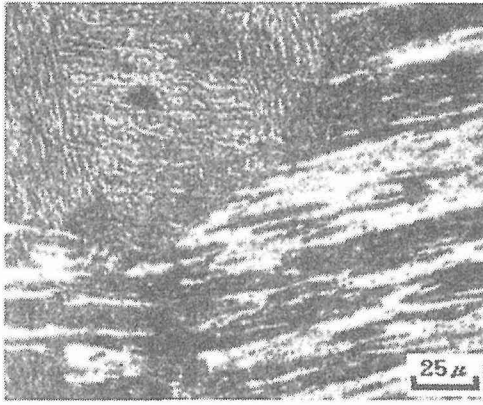


Time 10sec Hv 279

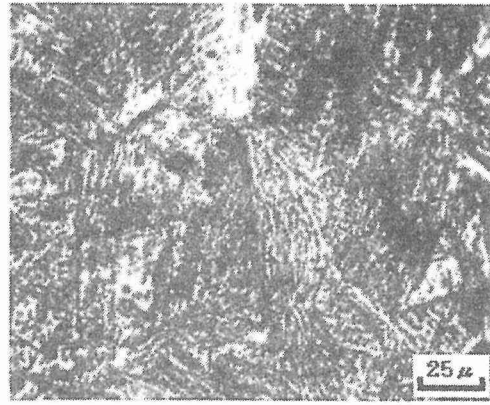


Time 16sec Hv 266

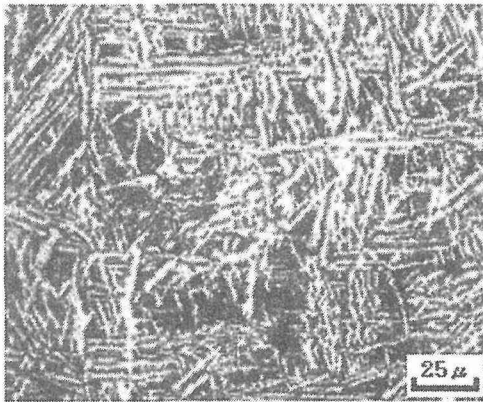




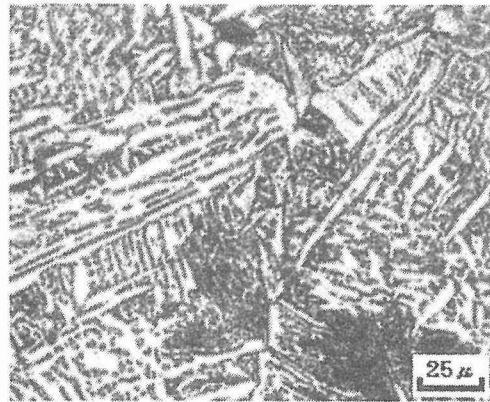
Time - Hv 464



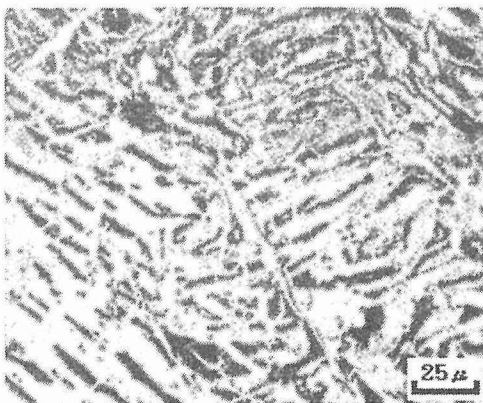
Time 3sec Hv 411



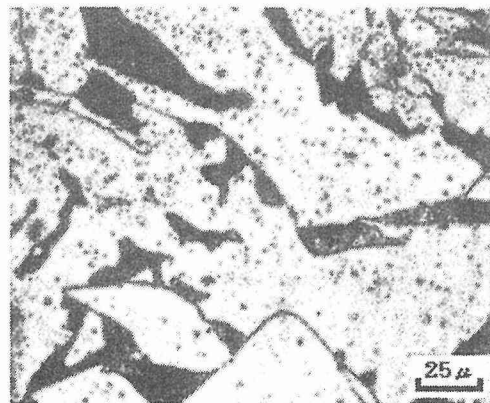
Time 15sec Hv 273



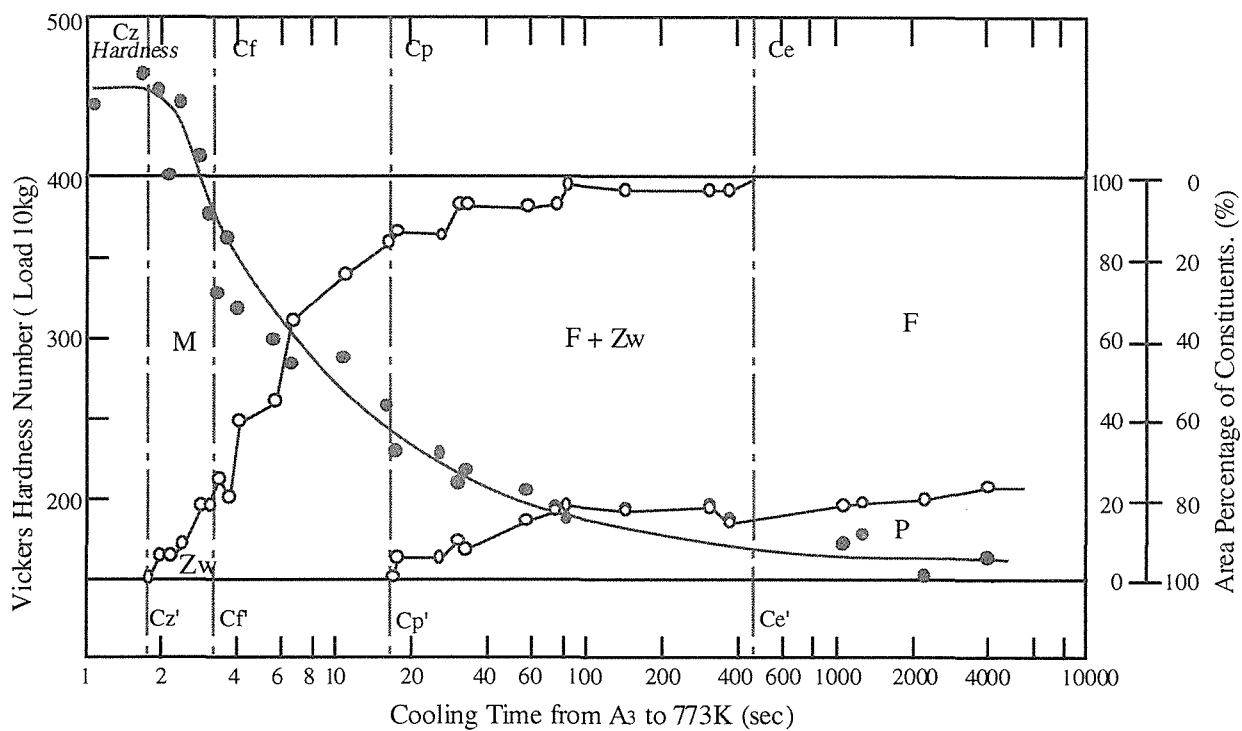
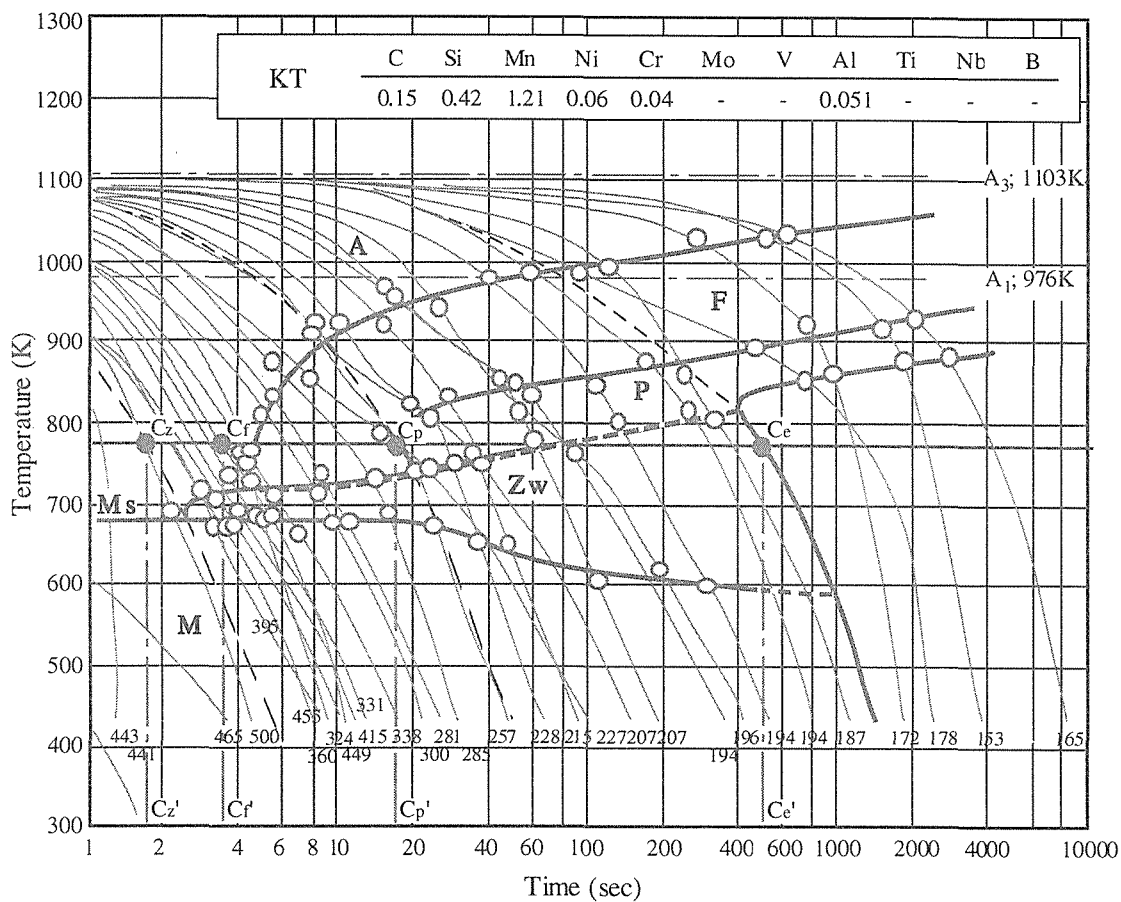
Time 25sec Hv 235

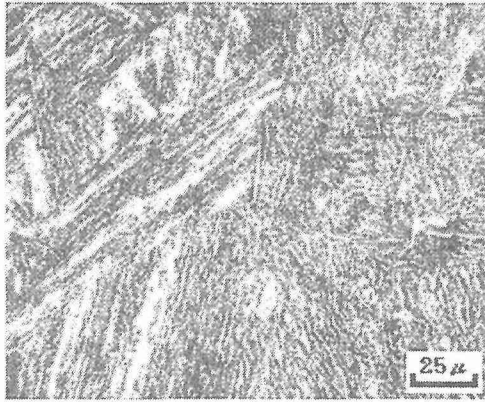


Time 110sec Hv 202

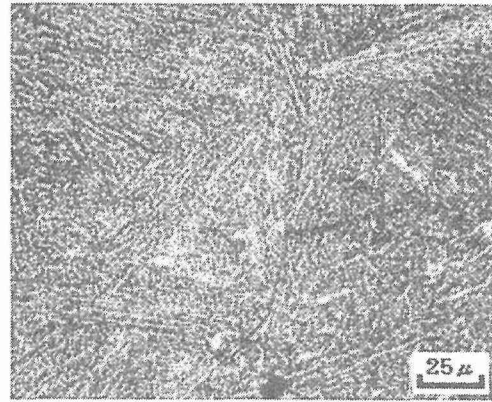


Time 800sec Hv 186

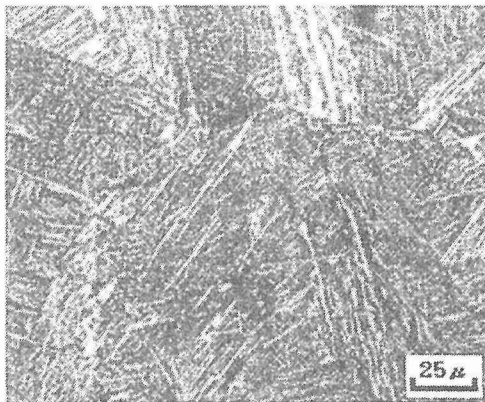




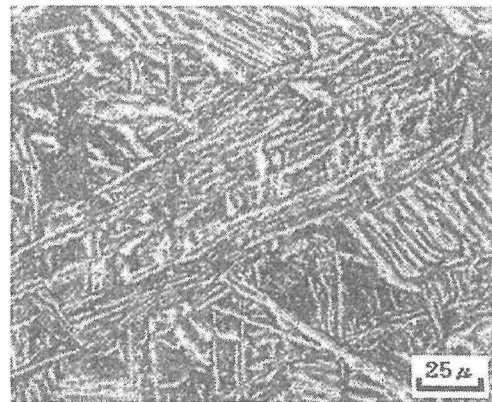
Time - Hv 519



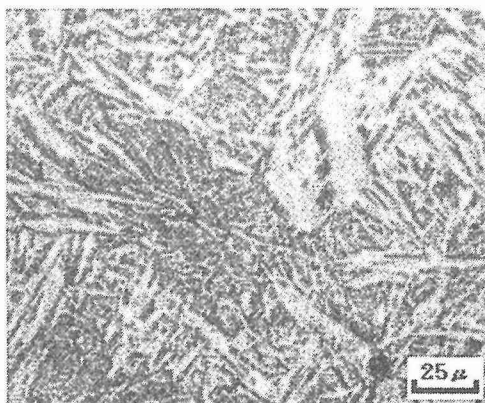
Time 2.2sec Hv 449



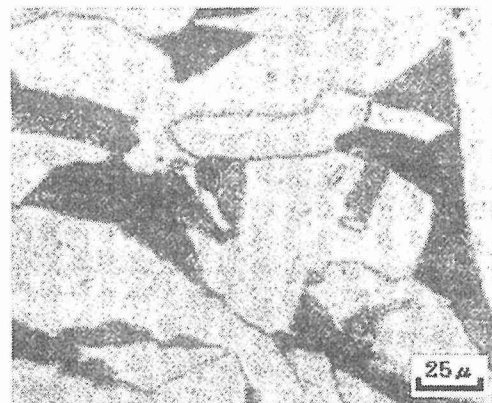
Time 3.8sec Hv 338



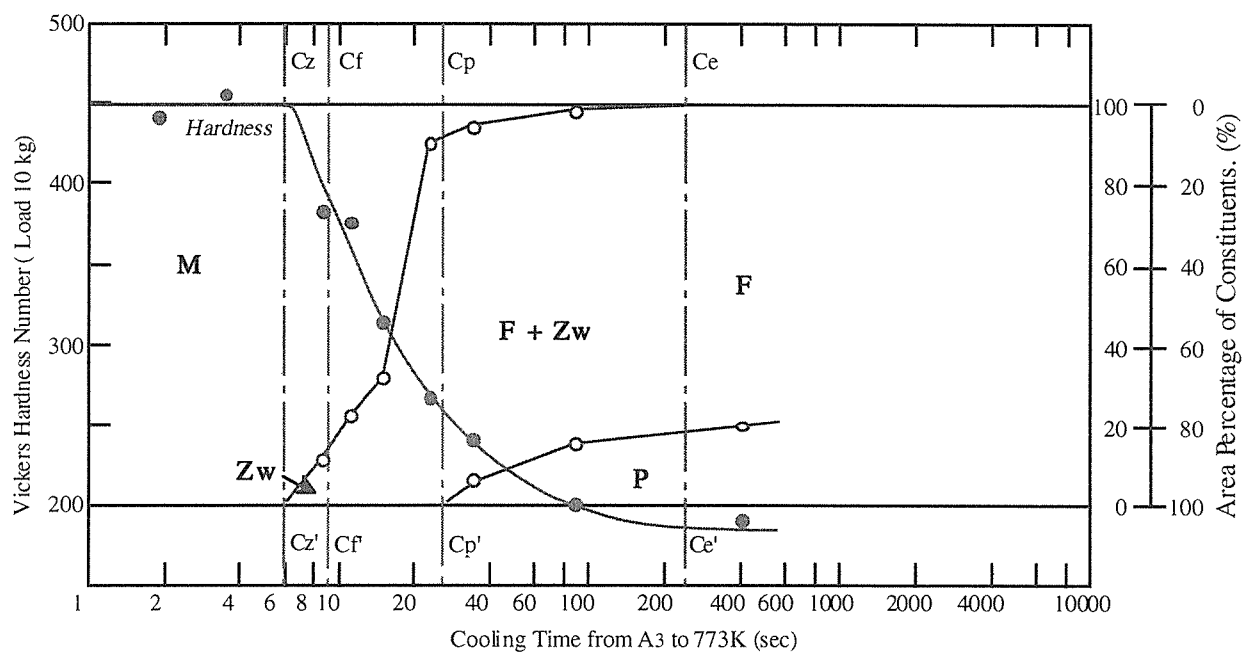
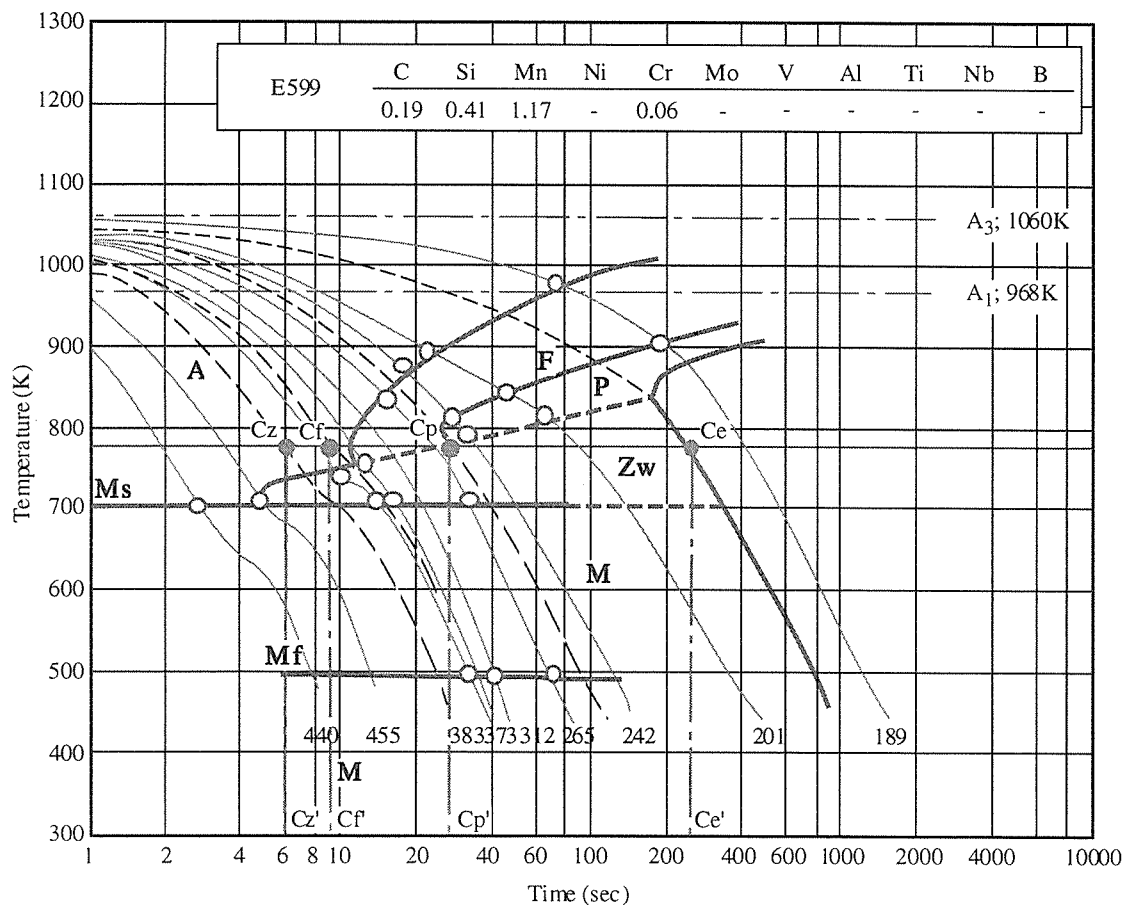
Time 28sec Hv 257

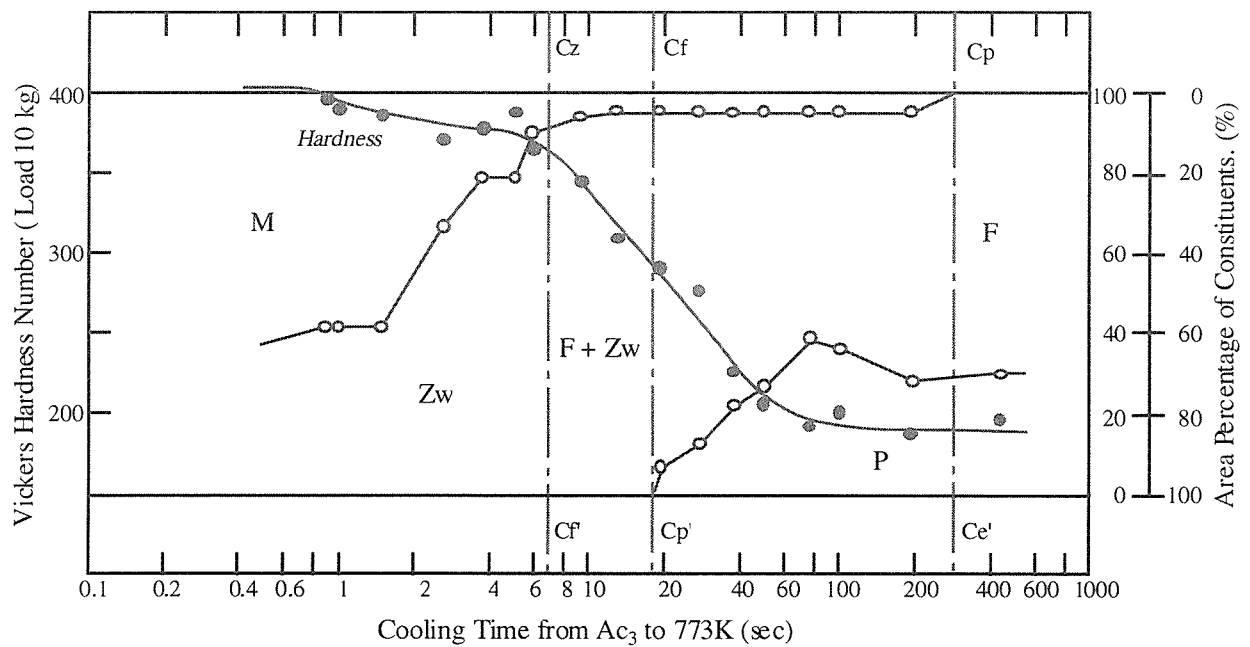
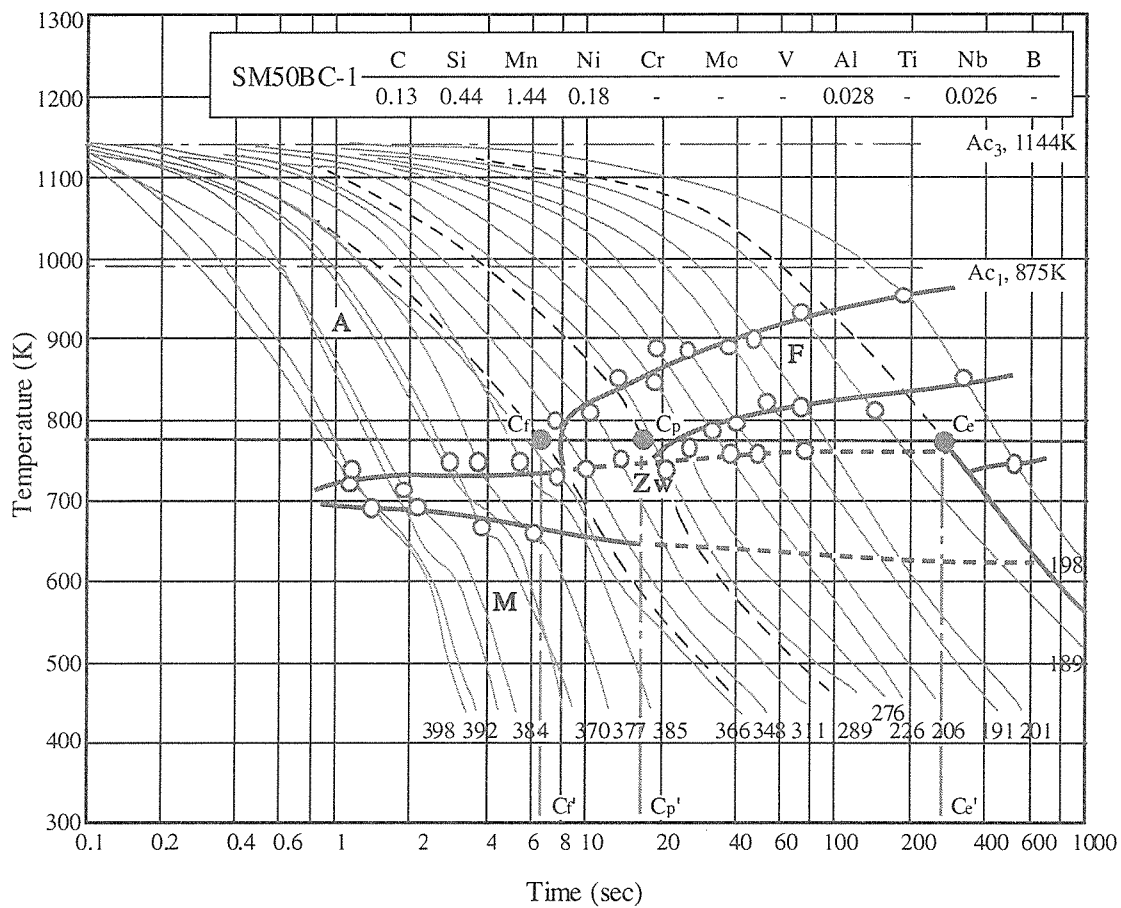


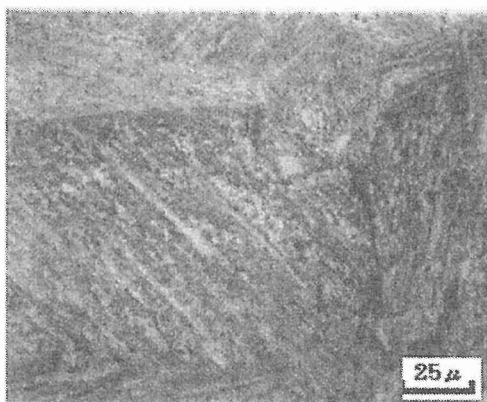
Time 18sec Hv 215



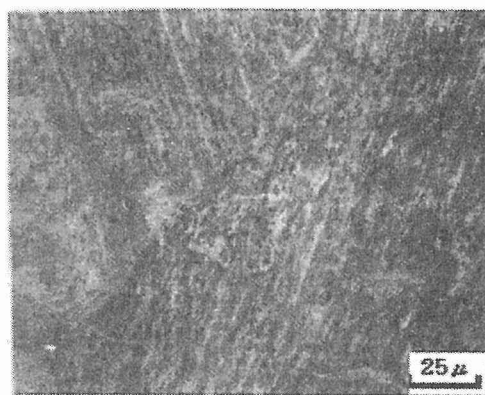
Time 2200sec Hv 153



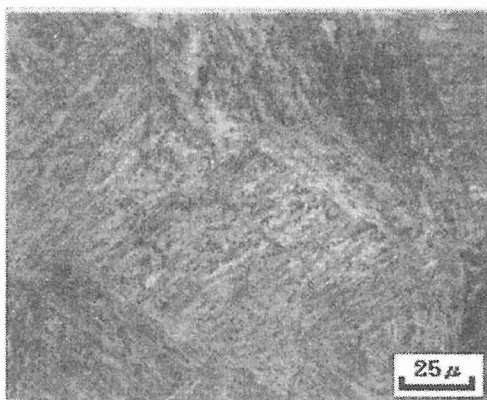




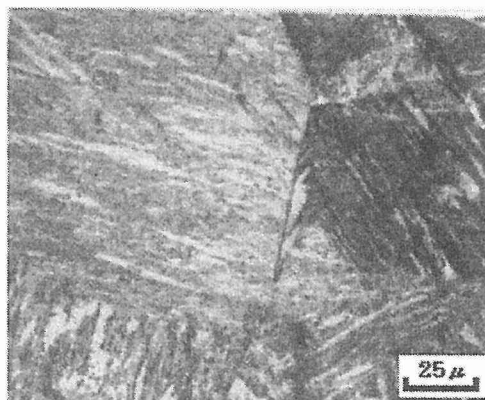
Time 0.9sec Hv 398



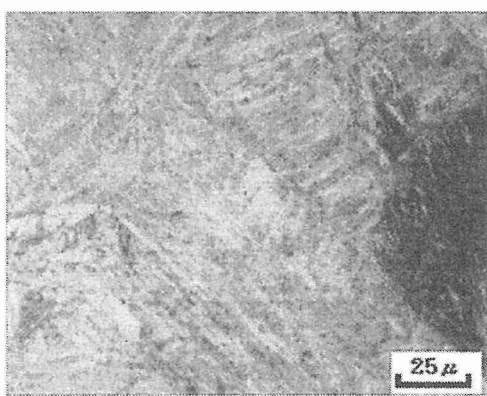
Time 1sec Hv 392



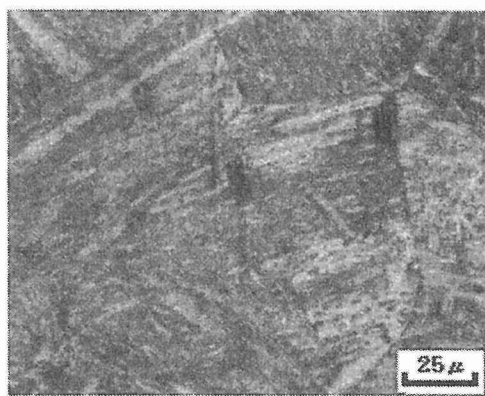
Time 1.5sec Hv 384



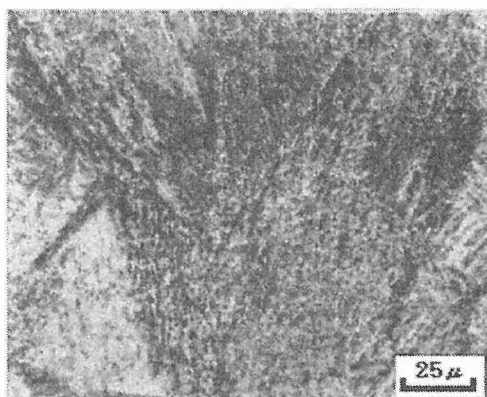
Time 2.8sec Hv 370



Time 3.4sec Hv 377



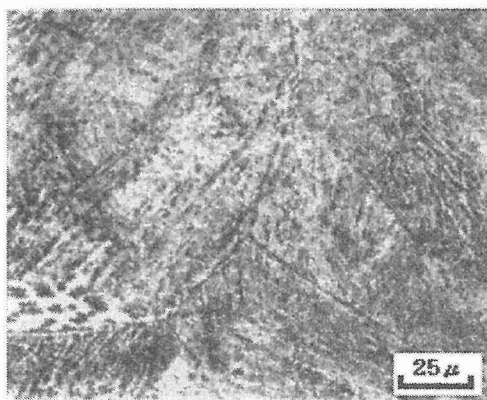
Time 5sec Hv 385



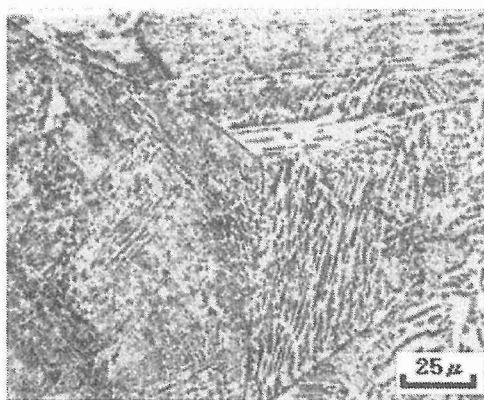
Time 6sec Hv 366



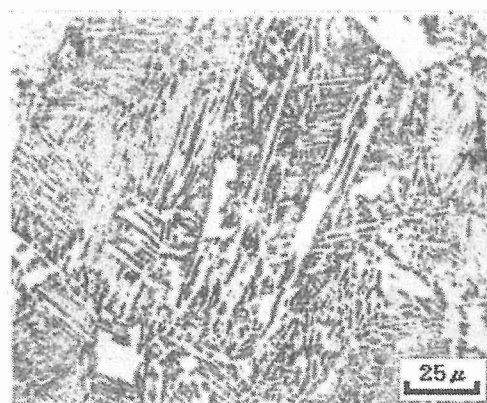
Time 9sec Hv 348



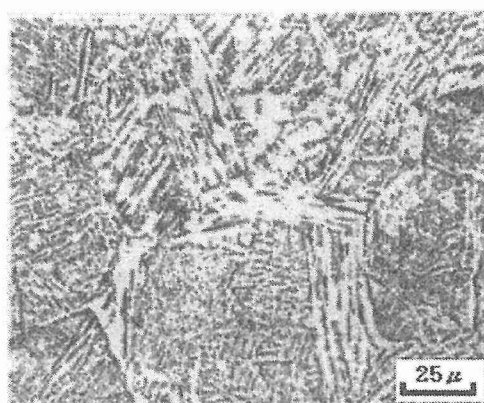
Time 13sec Hv 311



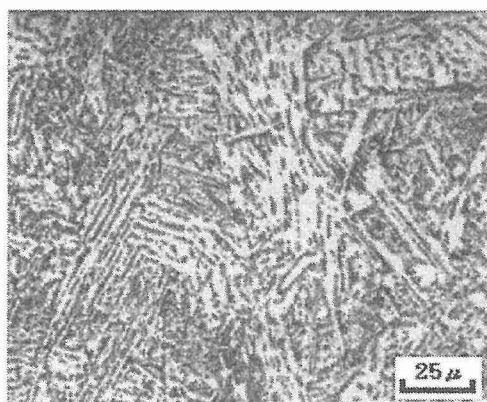
Time 19sec Hv 289



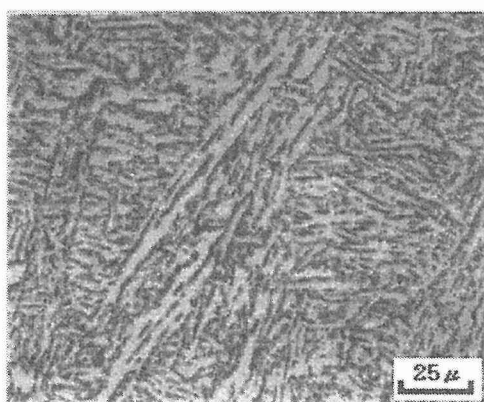
Time 27sec Hv 276



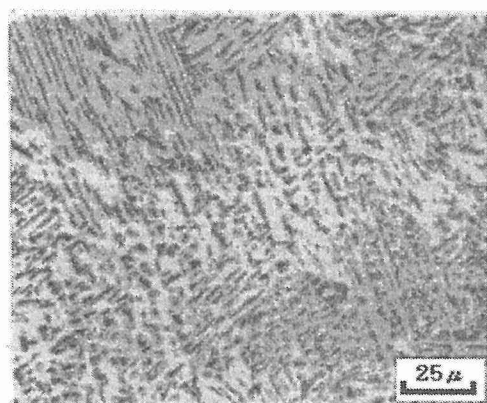
Time 36sec Hv 226



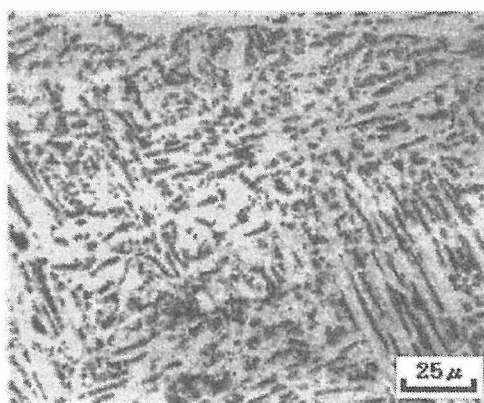
Time 47sec Hv 206



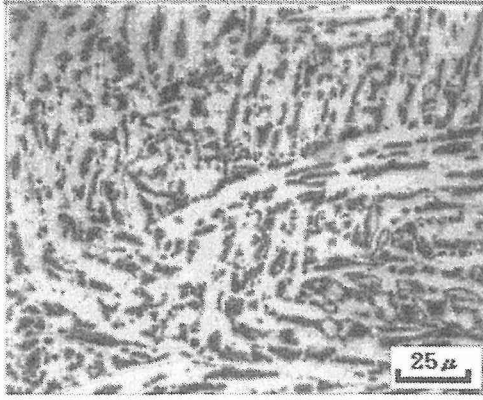
Time 70sec Hv 191



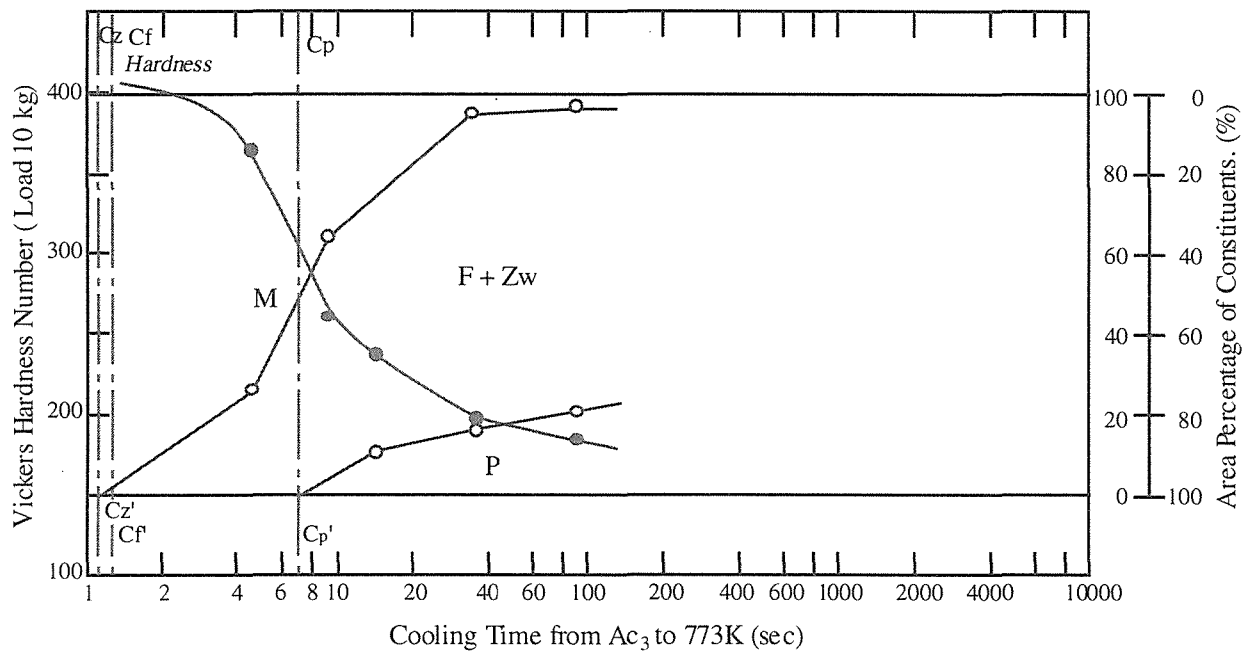
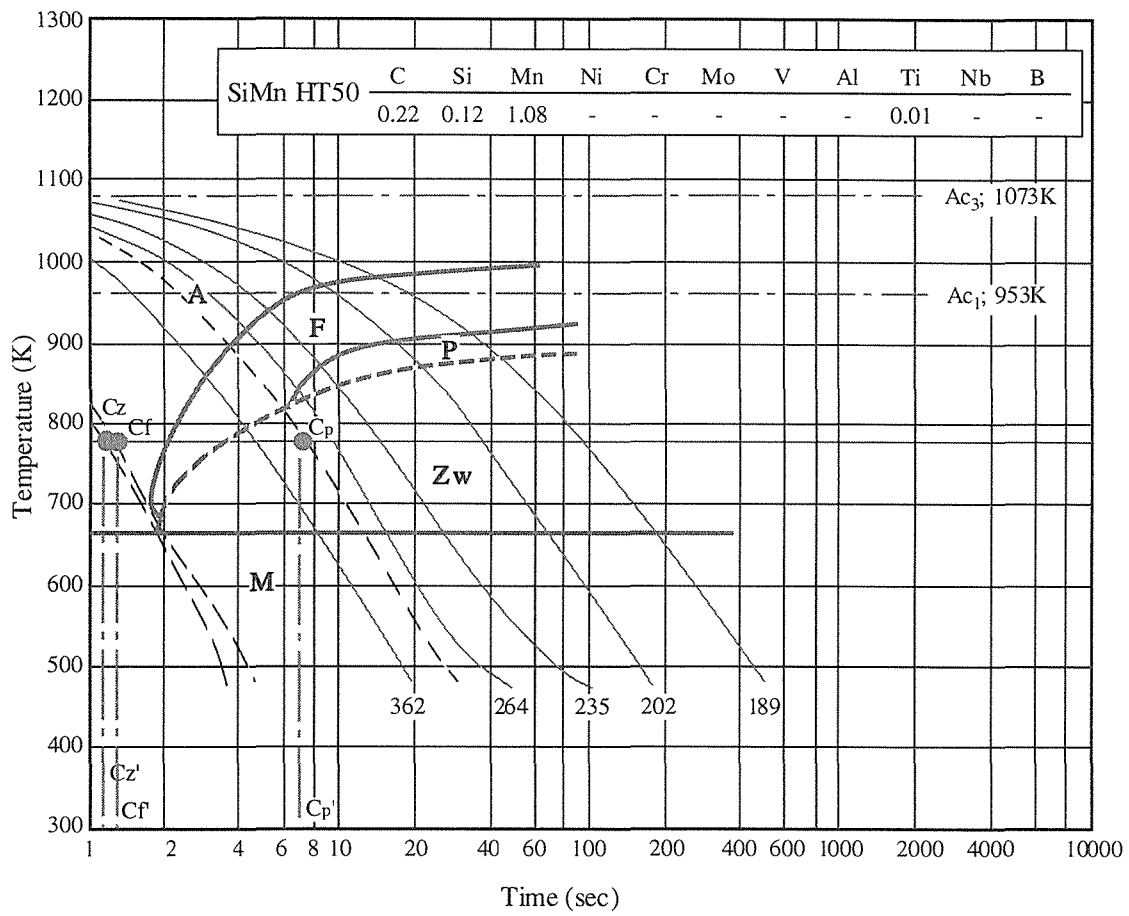
Time 90sec Hv 201

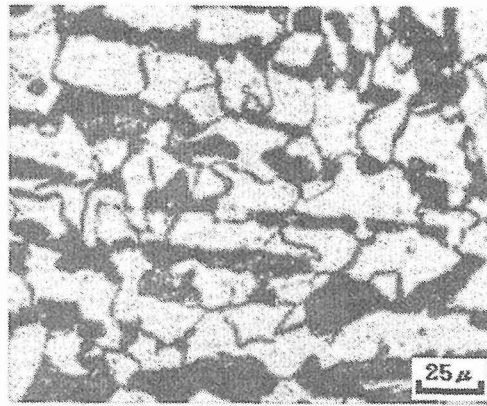


Time 180sec Hv 189

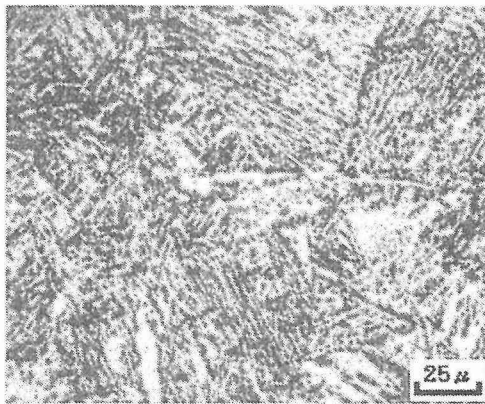


Time 480sec Hv 198

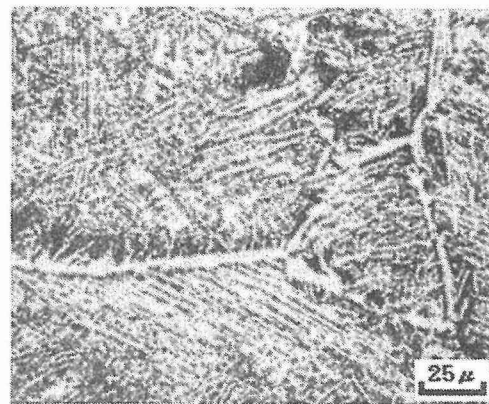




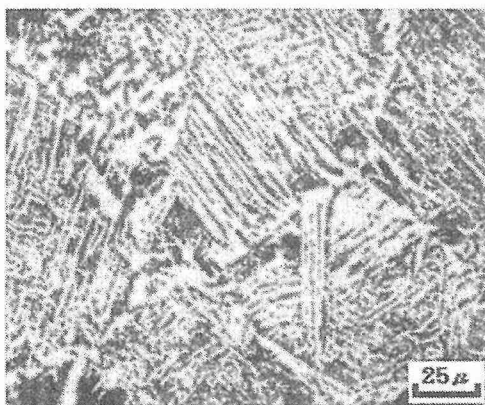
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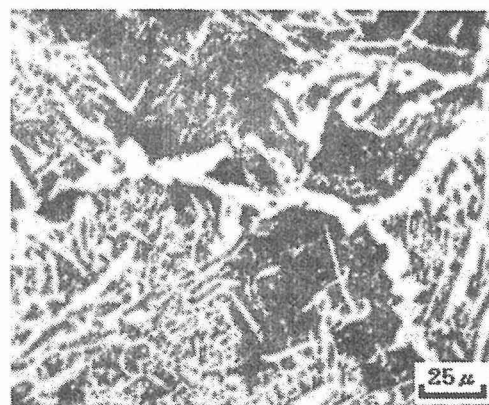
Time 4.6sec Hv 362



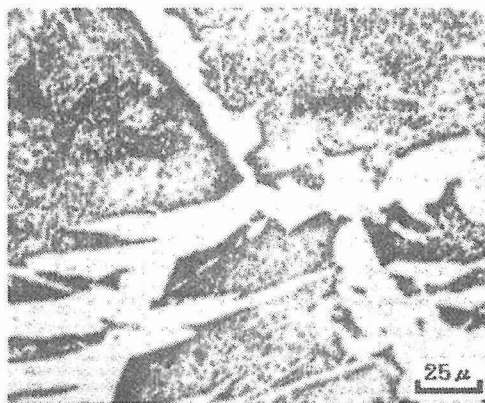
Time 9.4sec Hv 264



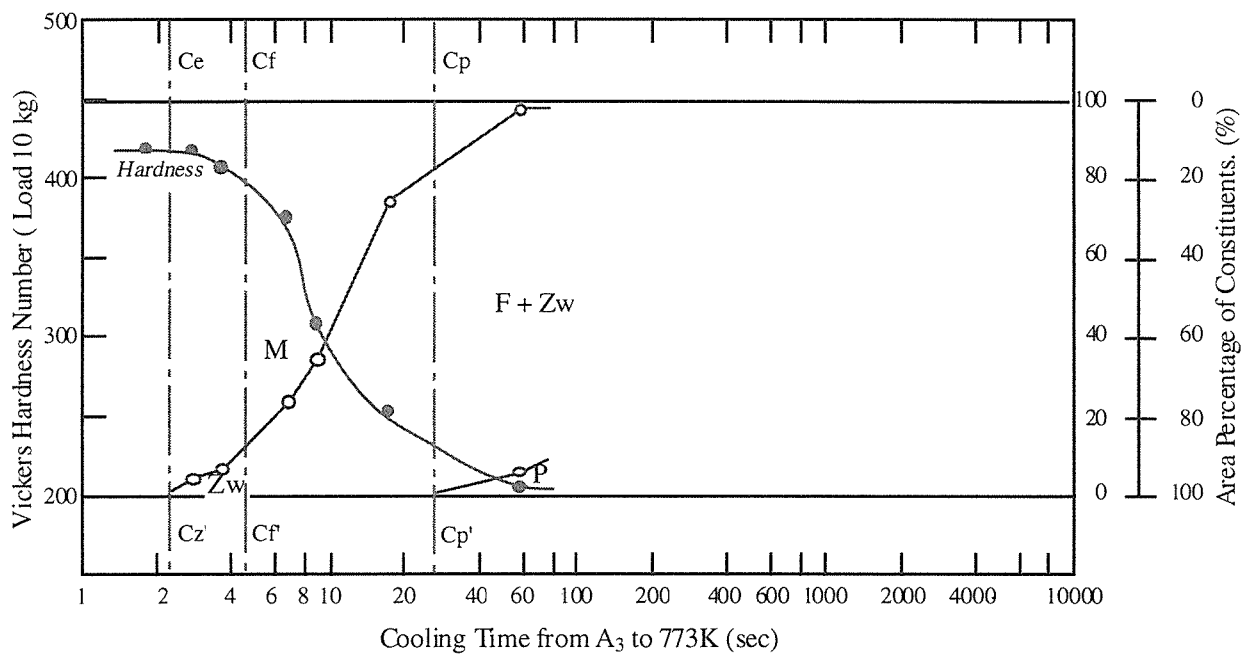
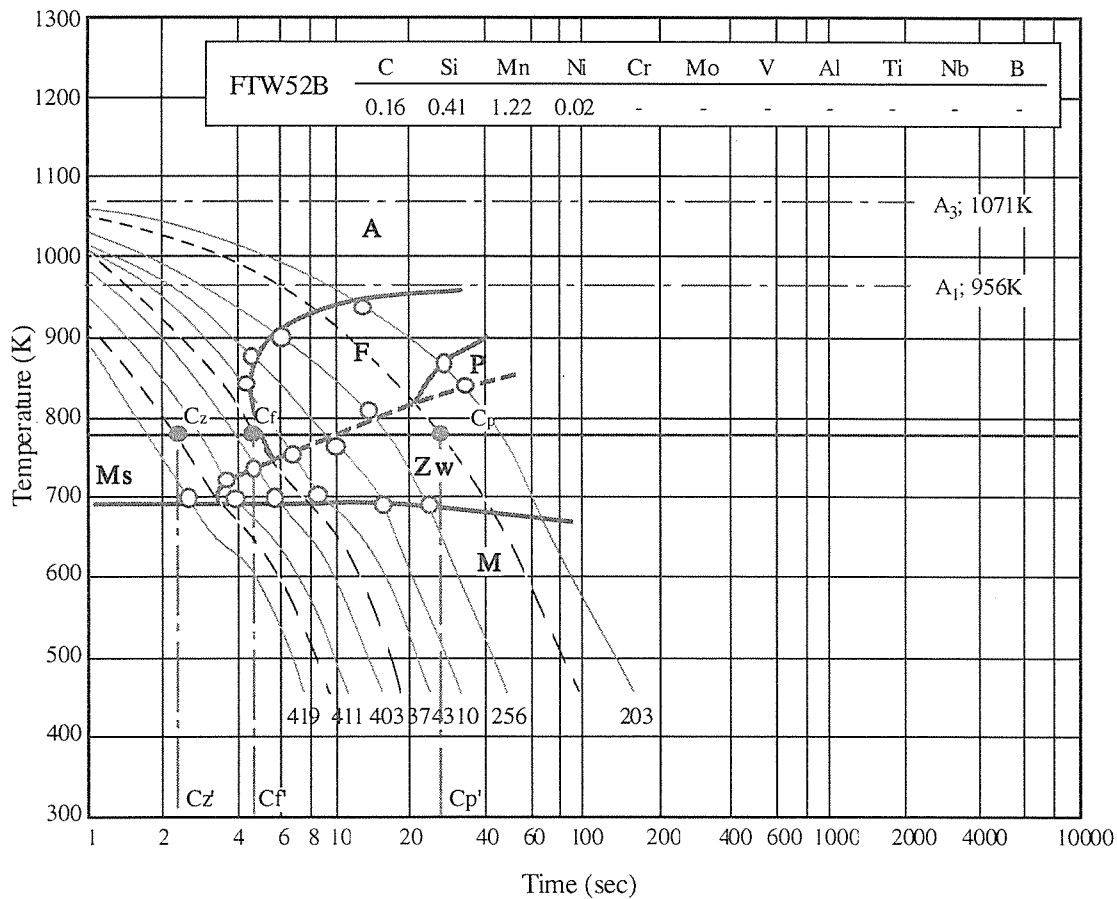
Time 15sec Hv 235

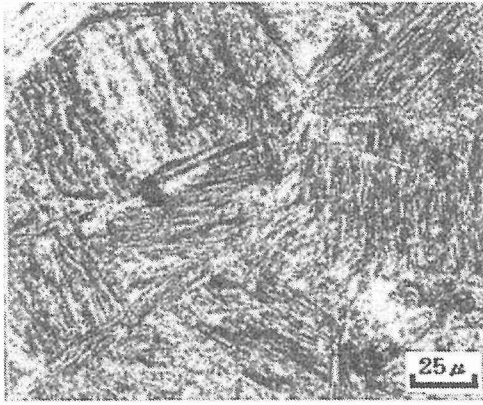


Time 36sec Hv 202

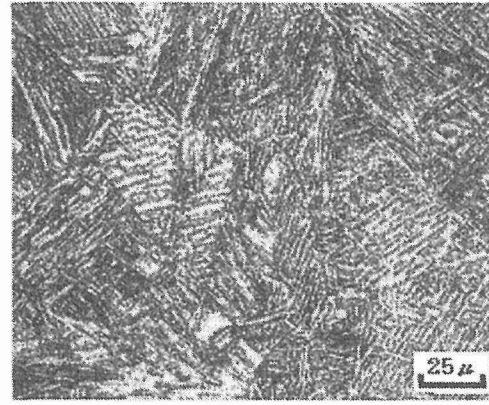


Time 90sec Hv 189

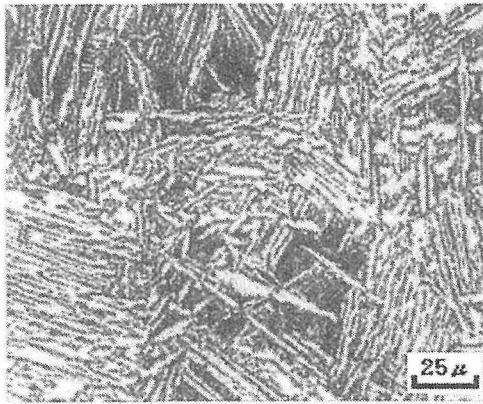




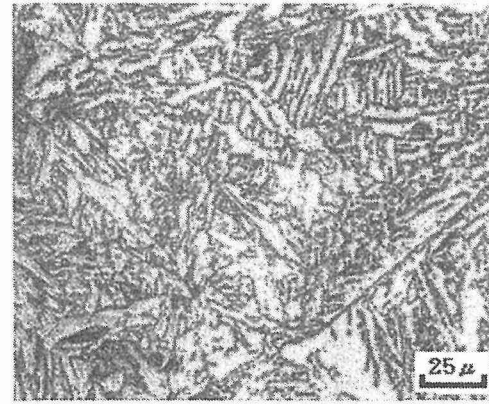
Time 1.8sec Hv 419



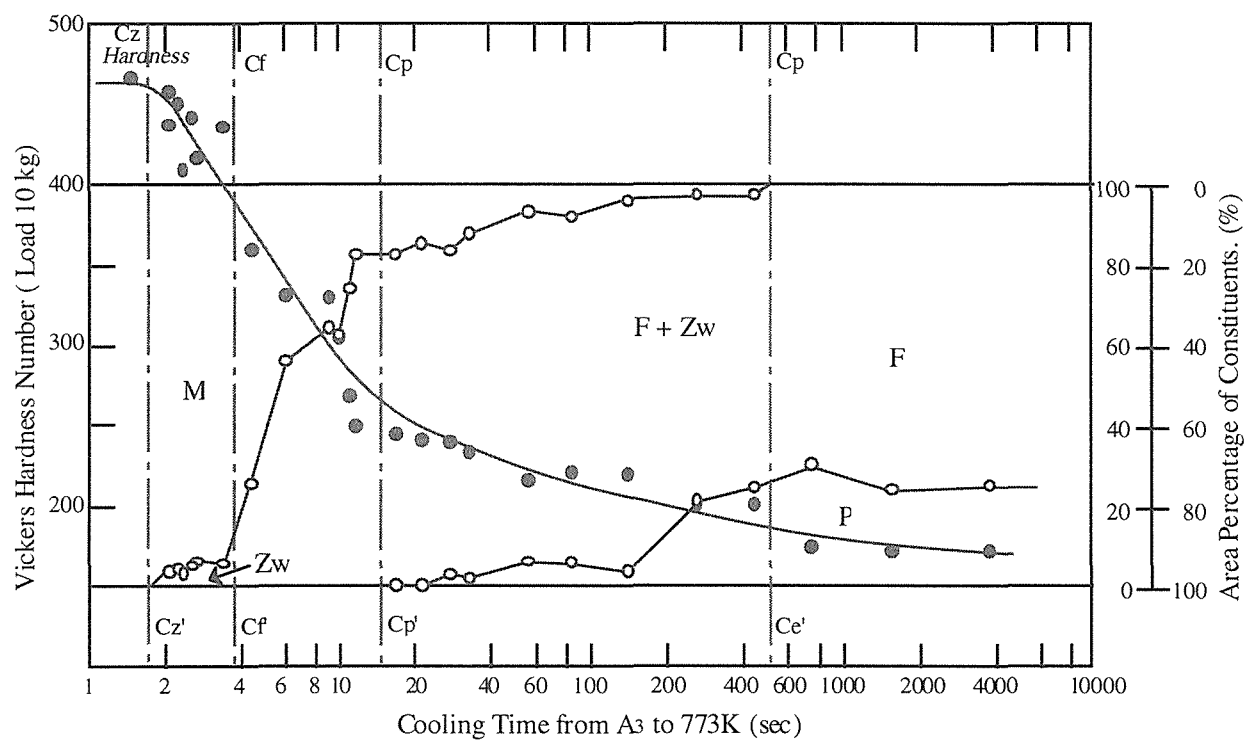
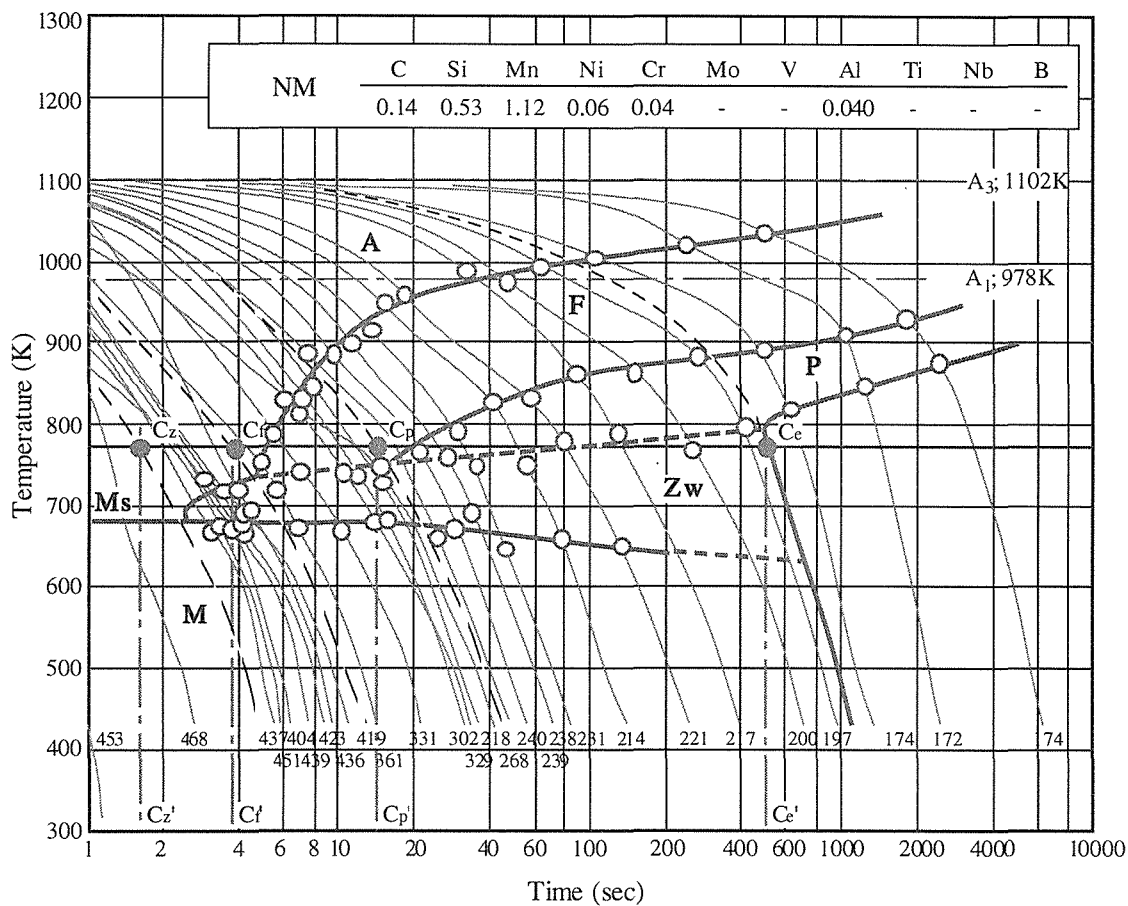
Time 9sec Hv 310

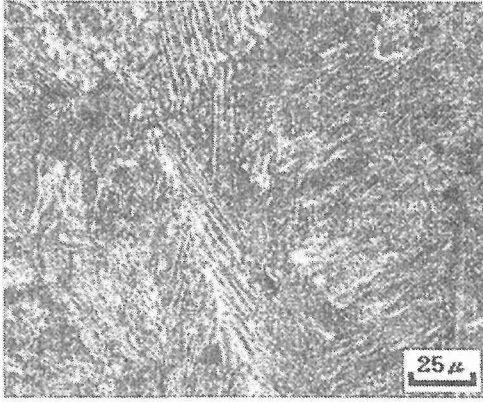


Time 17sec Hv 256

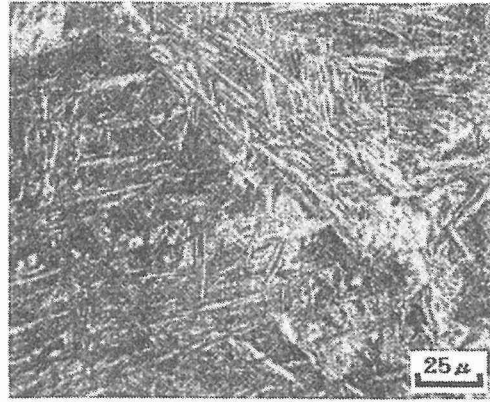


Time 50sec Hv 203

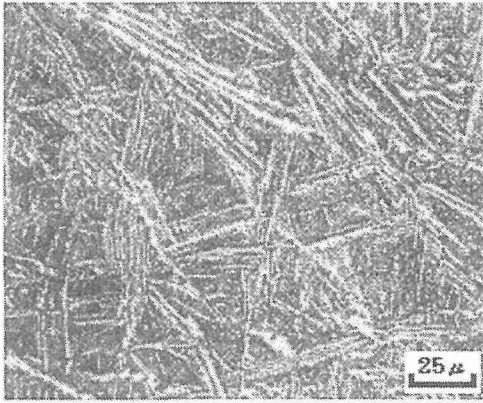




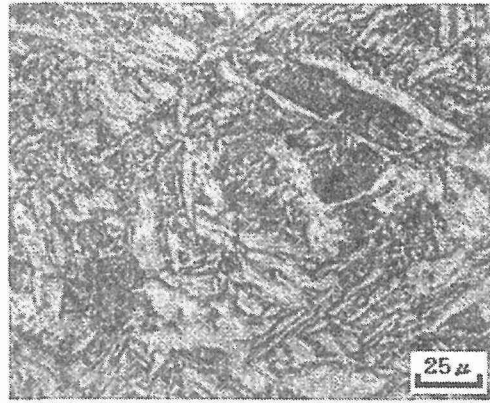
Time 3sec Hv 423



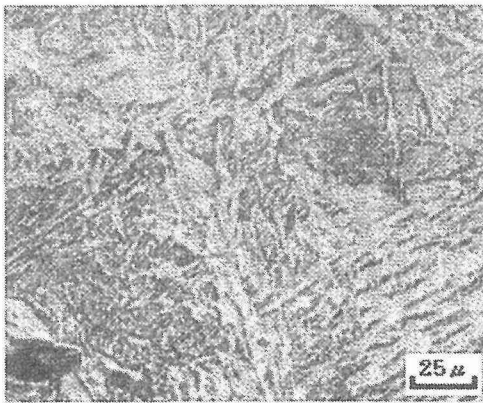
Time 6.5 Hv 361



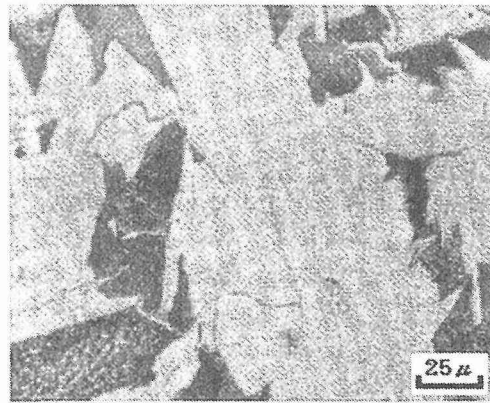
Time 9sec Hv 302



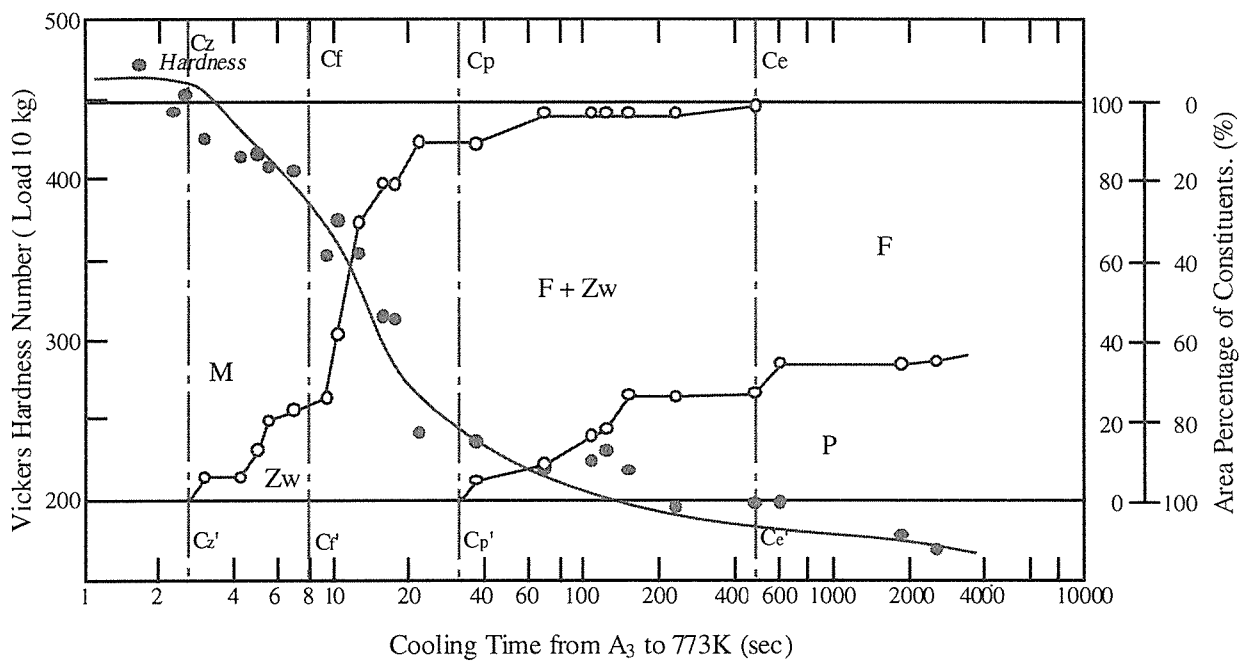
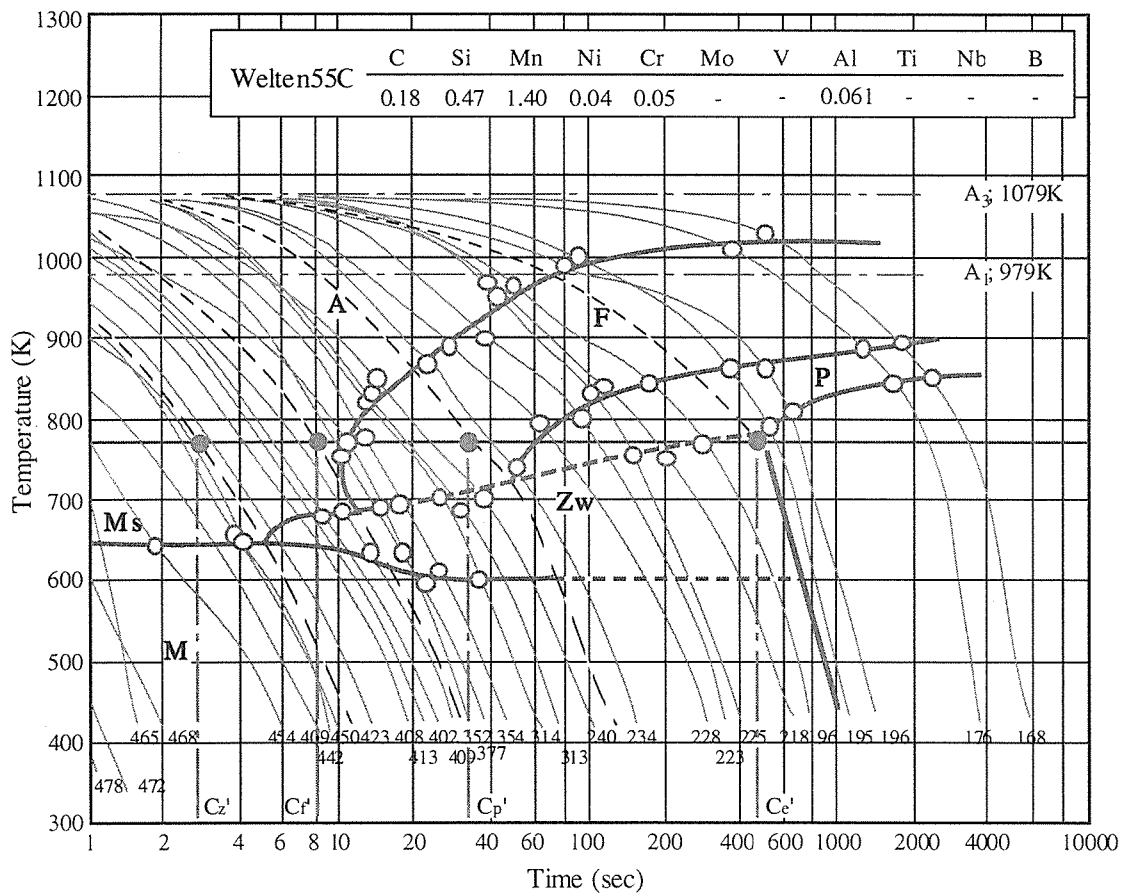
Time 35sec Hv 231

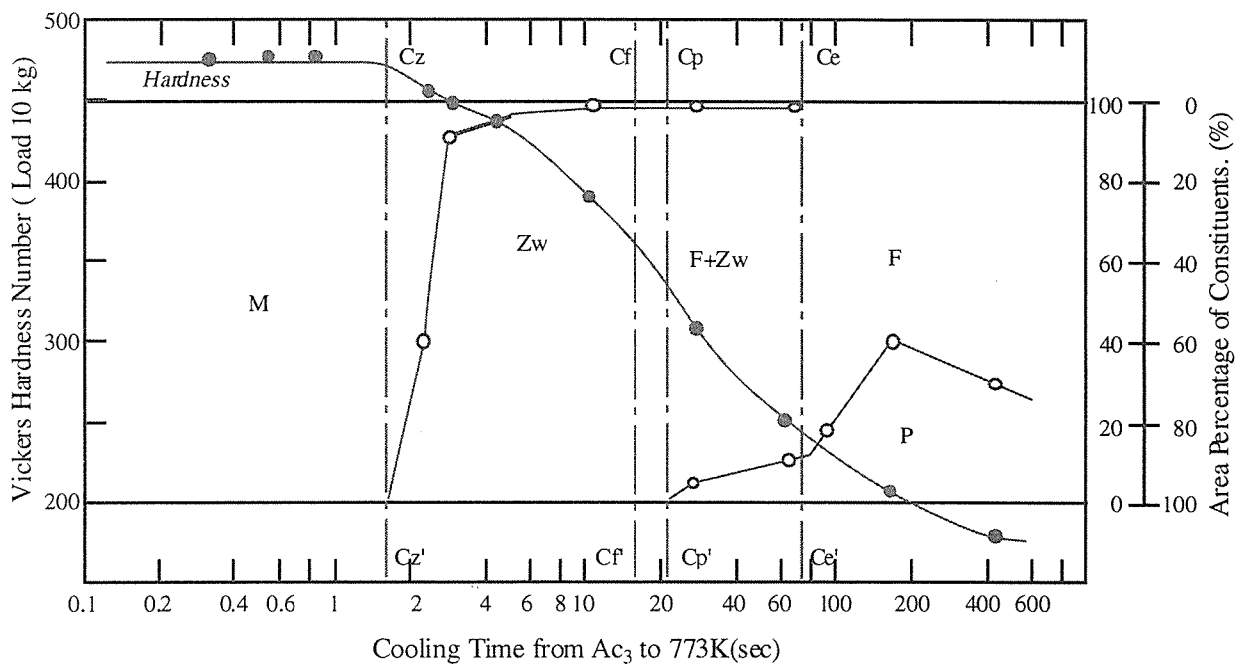
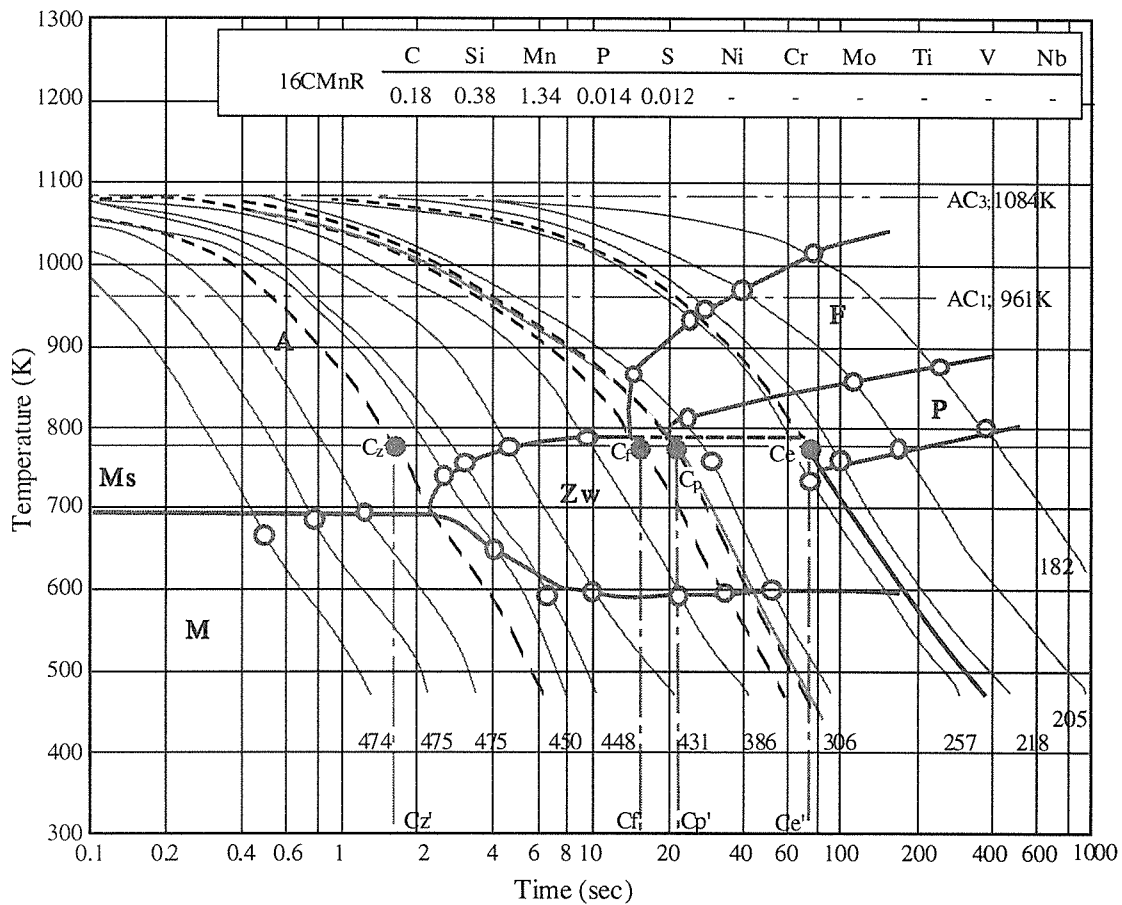


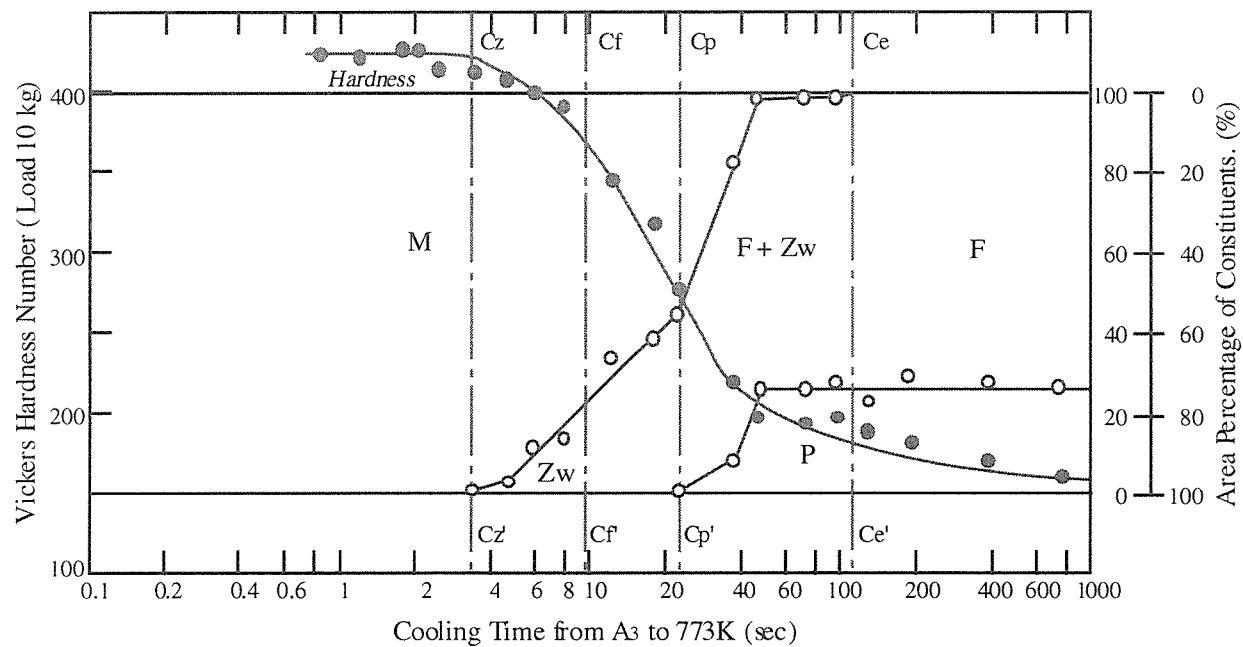
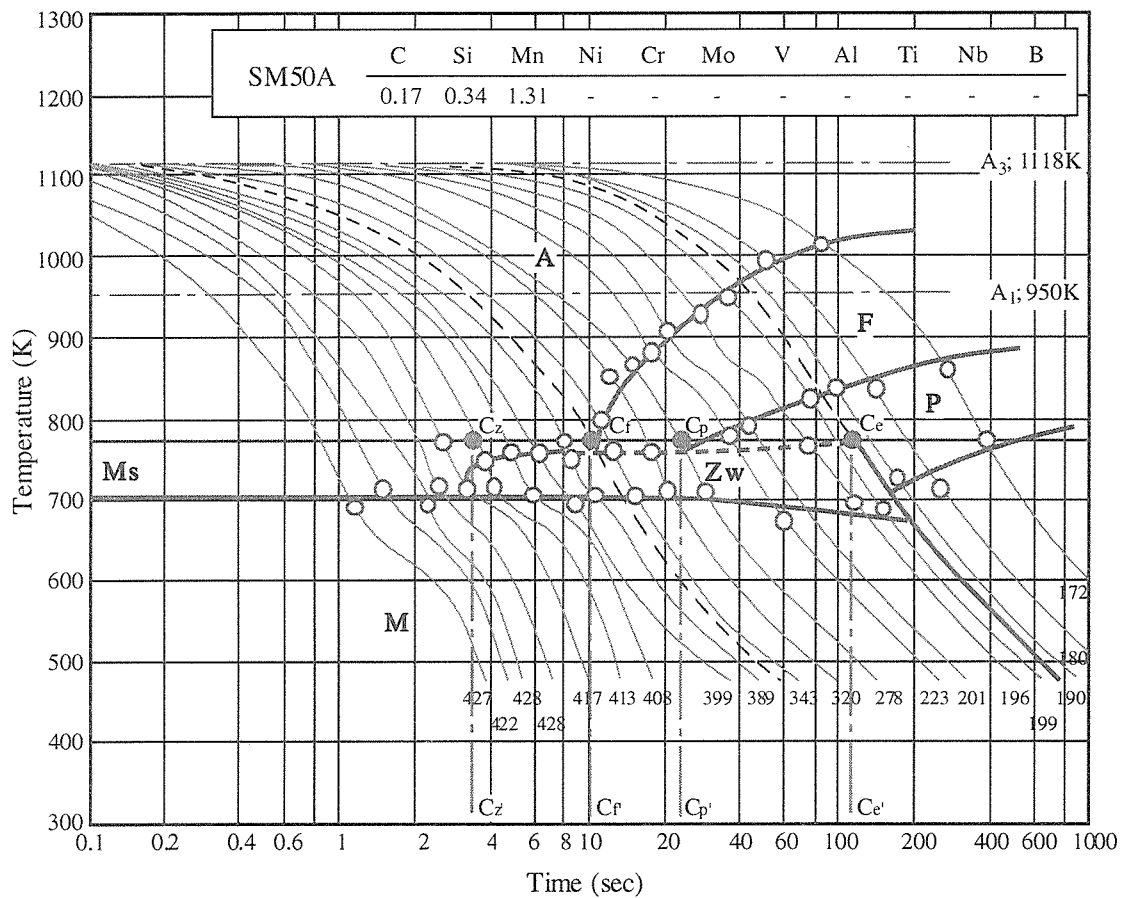
Time 150sec Hv 217

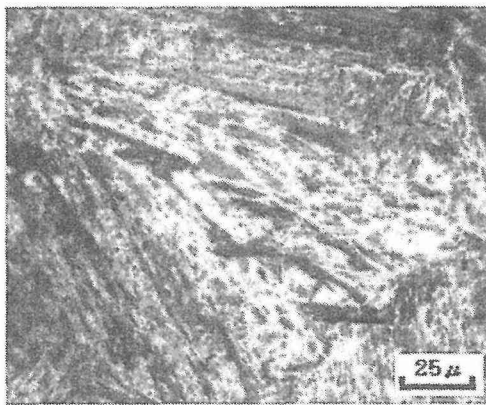


Time 800sec Hv 174

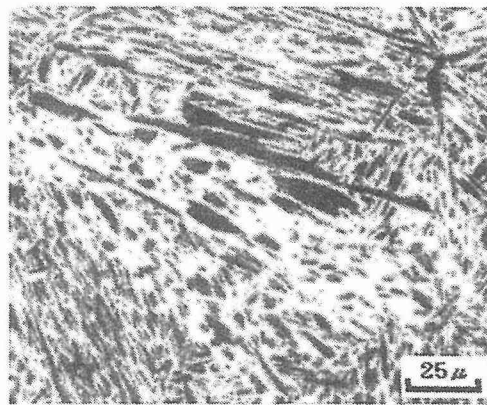








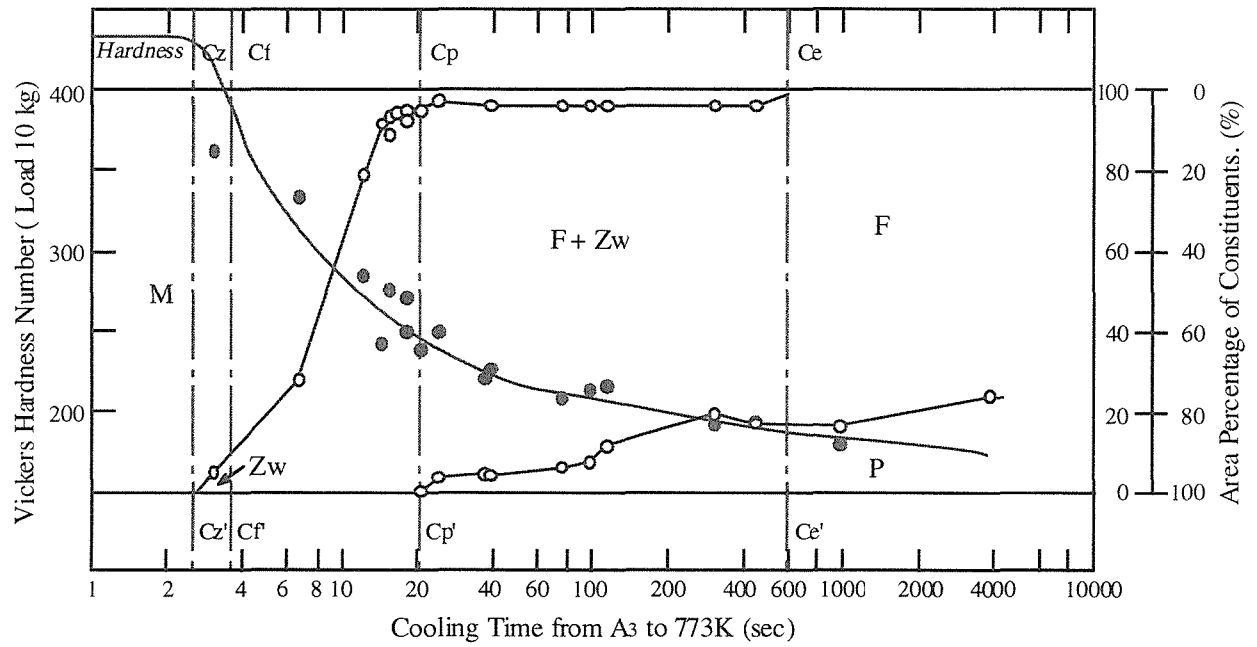
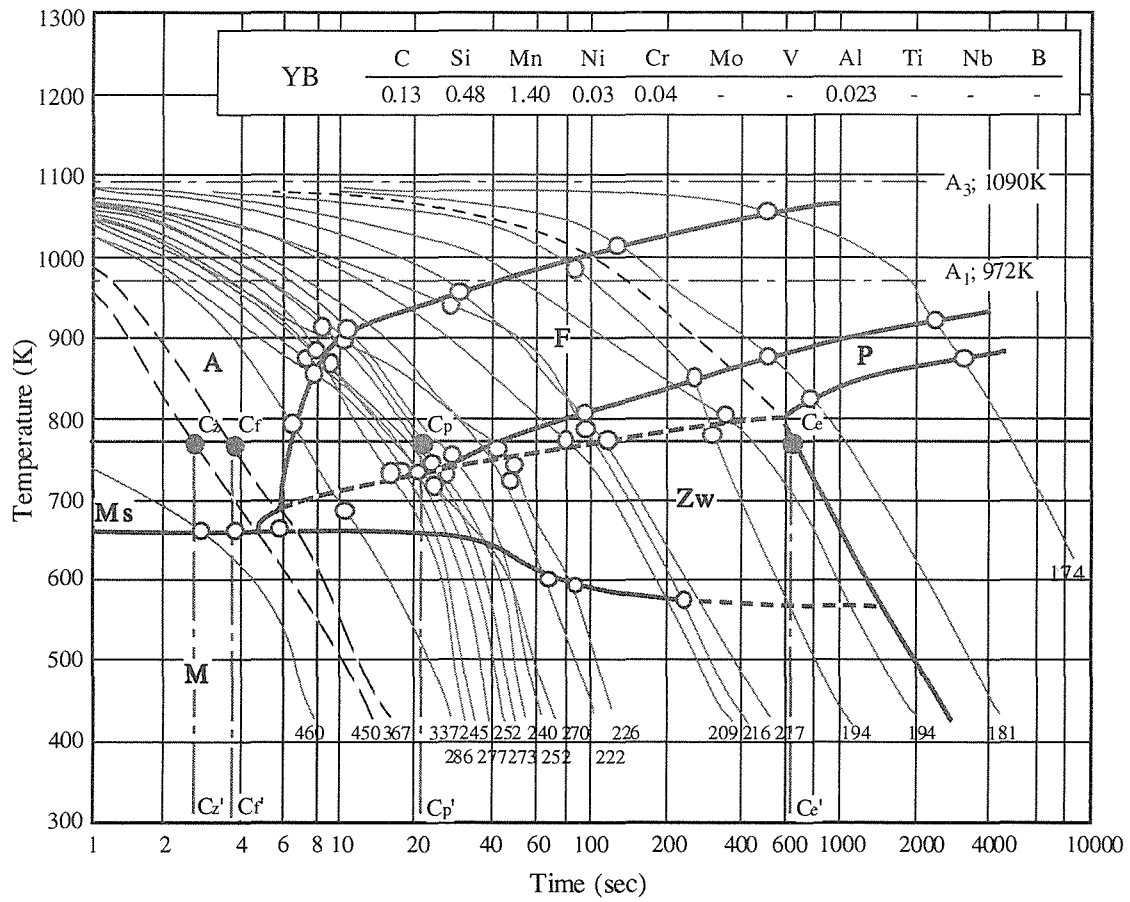
Time 15sec Hv 343

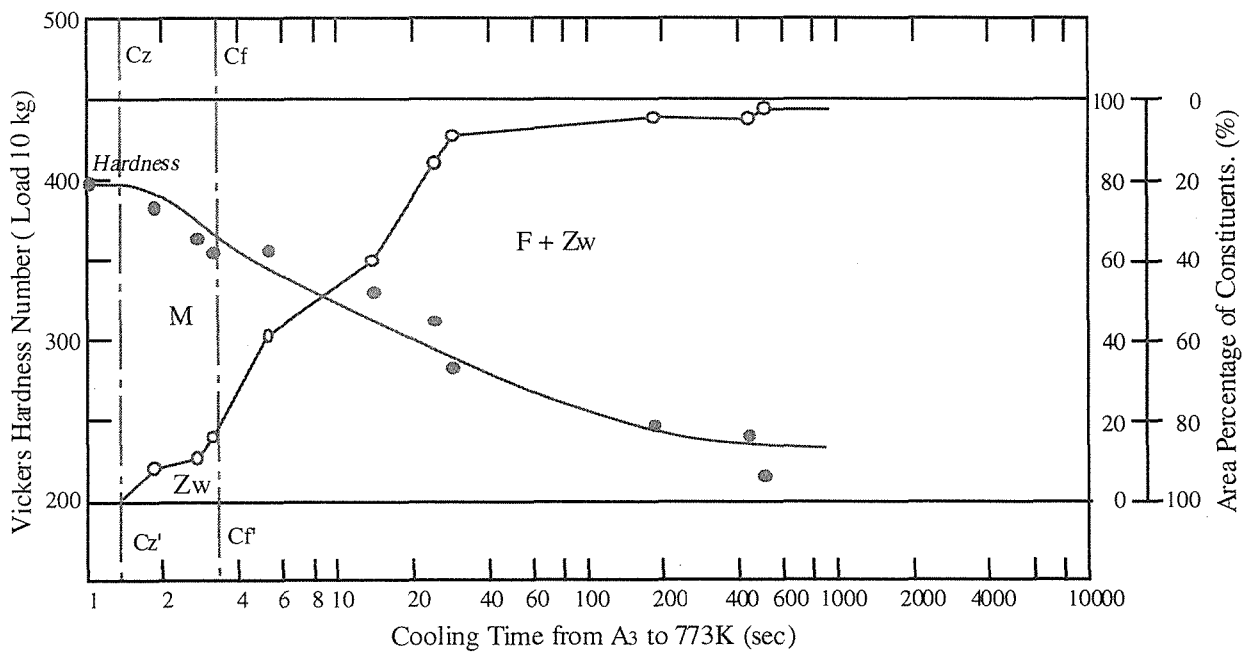
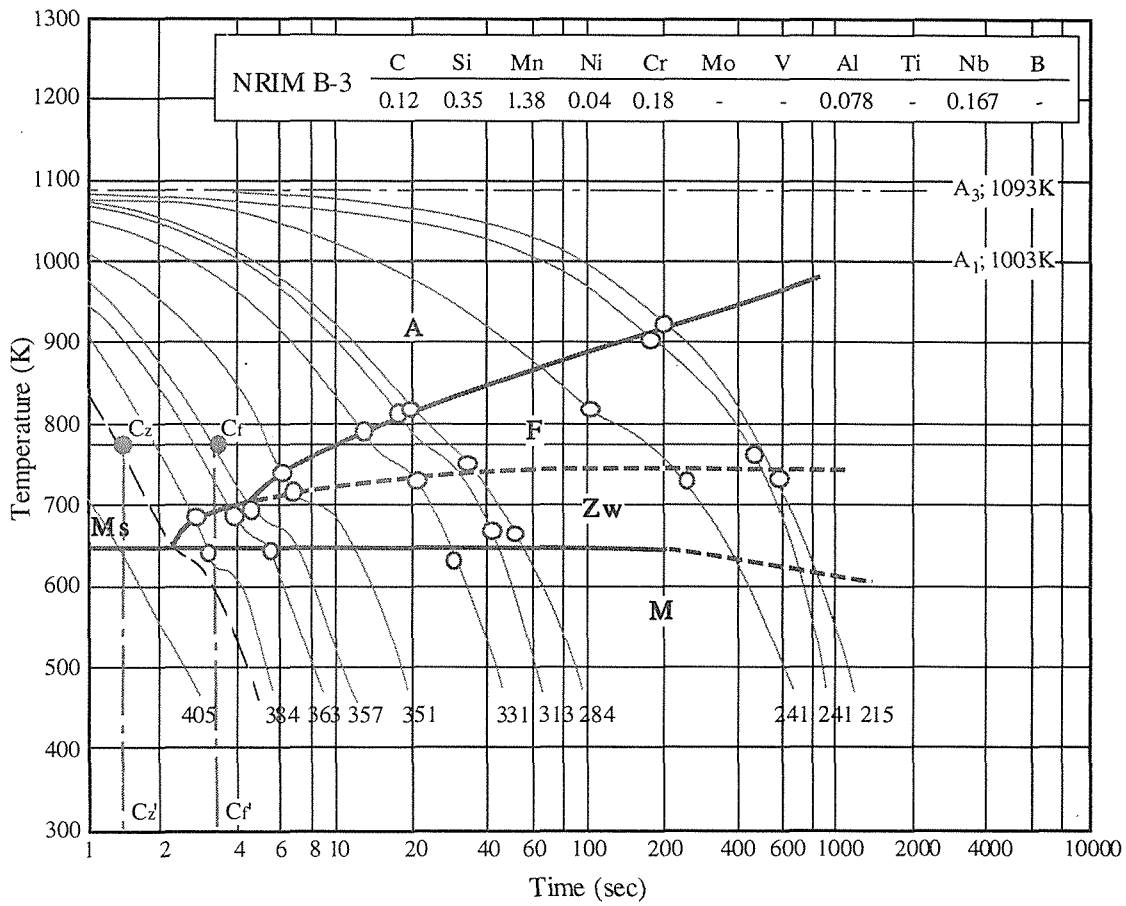


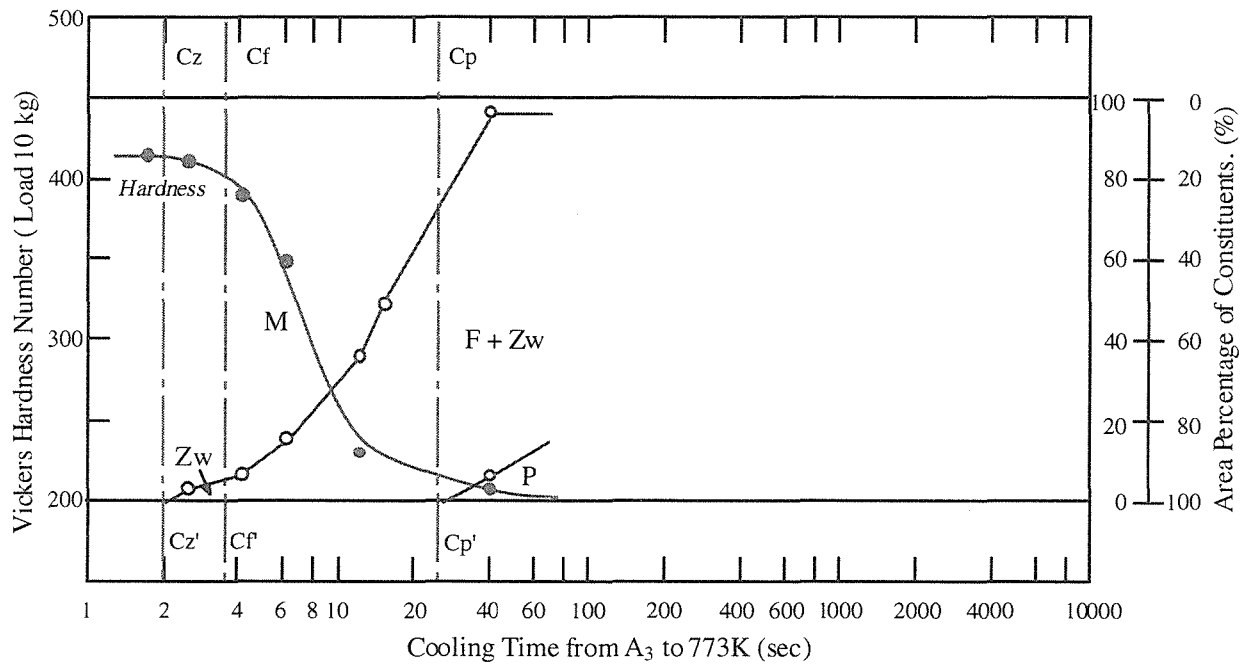
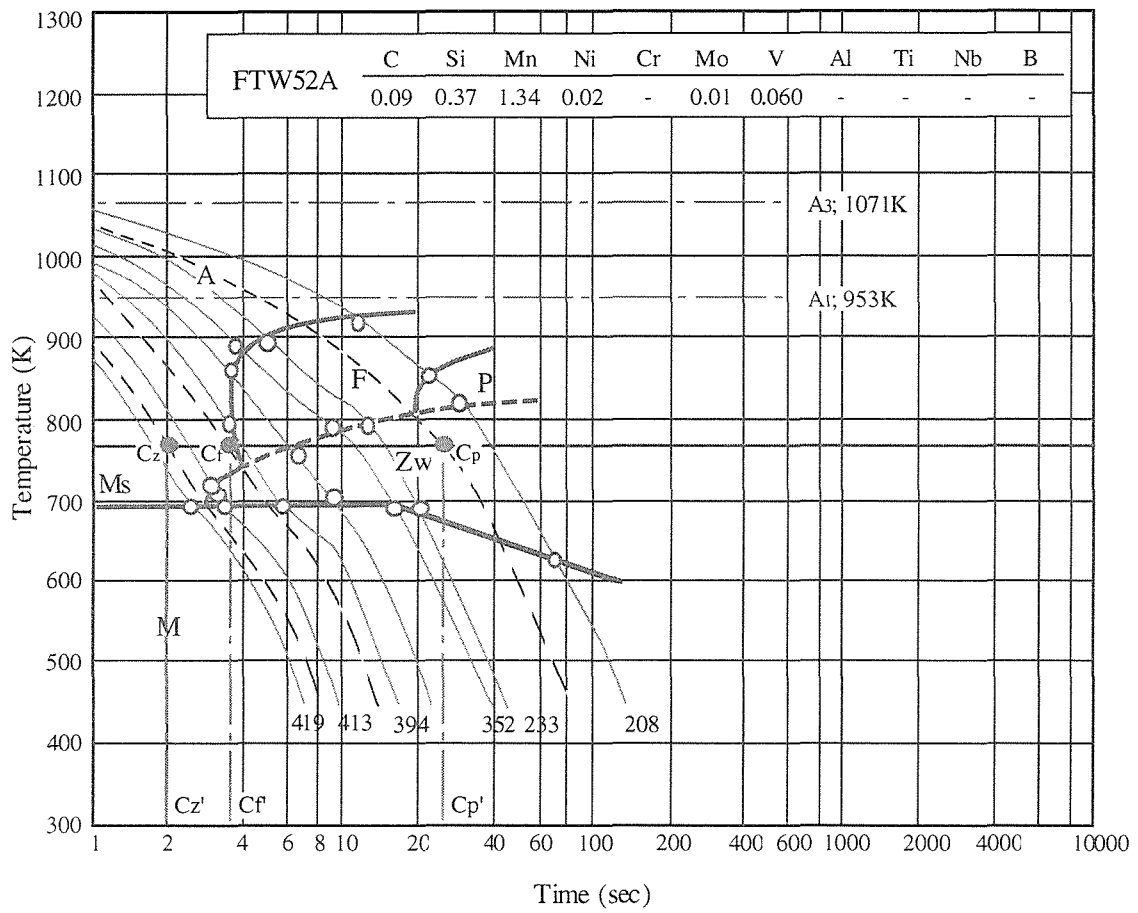
Time 25sec Hv 278

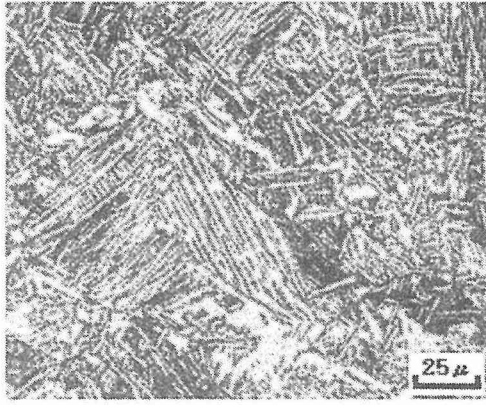
HT-60 kg/mm² Class

Steel	Chemical Composition (mass%)														Page	Ref.
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ti	Nb	Al	B		
YB	0.13	0.48	1.4	0.016	0.007	0.03	0.04	0.15	-	-	-	-	0.023	-	152	P
NRIM B-3	0.12	0.35	1.38	-	-	0.04	0.18		-	-	-	0.167	0.078	-	153	P
FTW52A	0.09	0.37	1.34	0.019	0.019	0.02	-	0.11	0.01	0.06	-	-	-	-	154	10
YA	0.17	0.24	1.34	0.024	0.019	0.04	0.02	0.21	-	-	-	-	0.027	-	156	P
YC	0.18	0.47	1.4	0.029	0.019	0.04	0.05	0.17	-	-	-	-	0.061	-	158	7
SM50BN1	0.19	0.04	1.00	-	-	0.02	0.62	-	-	-	-	-	-	-	160	P
NC	0.16	0.51	1.1	-	-	0.04	0.06	-	0.01	0.011	-	-	0.047	-	164	P
NA	0.16	0.45	1.12	-	-	0.04	0.06	-	0.02	0.011	-	-	0.017	-	165	P
YG	0.11	0.42	1.12	0.012	0.009	0.47	0.27	0.07	0.16	0.13	0.015	-	0.047	-	166	7
NB	0.16	0.43	1.31	-	-	0.04	0.06	-	0.02	0.017	-	-	0.05	-	168	P
S-5	0.16	0.46	1.35	0.018	0.027	-	-	0.15	-	-	-	-	0.02	-	169	P
ASTMA302B	0.19	0.23	1.25	-	-	0.66	0.07	-	0.54	-	-	-	-	-	170	P
S-1	0.13	0.48	1.37	0.014	0.007	-	0.22	-	-	0.13	-	-	0.022	-	171	P
2HA	0.15	0.53	1.2	-	-	0.09	0.03	-	-	-	-	-	0.08	-	172	P
NF	0.21	0.48	1.19	-	-	0.06	0.05	-	0.01	0.009	-	-	0.1	-	173	P
2H-Te	0.11	0.17	1.24	-	-	0.21	0.18	-	0.15	-	-	-	0.029	-	174	P
6NA	0.12	0.45	1.17	-	-	-	0.32	-	0.25	0.14	-	-	-	-	175	P
S-6	0.07	0.2	0.75	0.01	0.01	0.43	0.51	0.21	0.11	0.08	-	-	0.01	-	176	P
6NC	0.15	0.35	1.28	-	-	0.47	0.08	-	0.21	0.1	-	-	-	-	177	P
NE	0.2	0.4	1.12	-	-	0.05	0.09	-	0.01	0.009	-	-	0.048	-	178	P
6NF	0.15	0.26	1.02	-	-	0.6	0.1	-	0.37	0.08	-	-	-	-	179	P
S-3	0.11	0.37	1.34	0.015	0.01	0.47	0.27	-	-	0.1	-	-	0.017	-	180	P
2HB	0.11	0.48	1.2	-	-	0.08	0.05	-	-	-	-	-	0.001	-	181	P
FTW58	0.17	0.38	1.31	0.026	0.017	0.04	-	0.11	0.01	0.04	-	-	-	-	182	10
6ND	0.14	0.26	1.28	-	-	0.86	0.5	-	0.46	-	-	-	-	-	184	P
E595	0.18	0.4	1.16	-	-	-	0.08	-	-	0.12	-	-	-	-	185	P
NRIM 37	0.07	0.5	1.49	-	-	0.5	0.12	-	0.3	-	-	-	-	-	186	P
NRIM 431L	0.08	0.41	1.45	-	-	0.49	0.29	-	0.39	-	-	0.15	-	-	187	P
NRIM 432M	0.13	0.47	1.44	-	-	0.1	0.19	-	-	-	-	0.15	-	-	188	P
NRIM 55	0.07	0.49	1.49	-	-	0.57	0.12	-	0.28	-	-	-	-	-	189	P
KQ (Hi-Z)	0.15	0.28	0.92	-	-	0.08	0.04	-	0.46	0.04	-	-	-	0.006	190	P
2HB1	0.13	0.45	1.08	-	-	0.05	0.32	-	-	0.15	-	-	0.019	-	191	P
WT-60	0.13	0.46	1.22	-	-	0.08	-	-	-	0.1	-	-	-	-	192	P

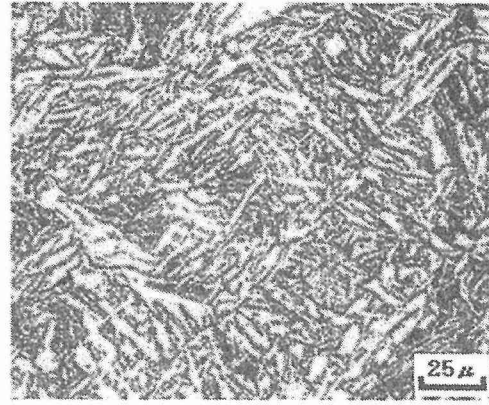




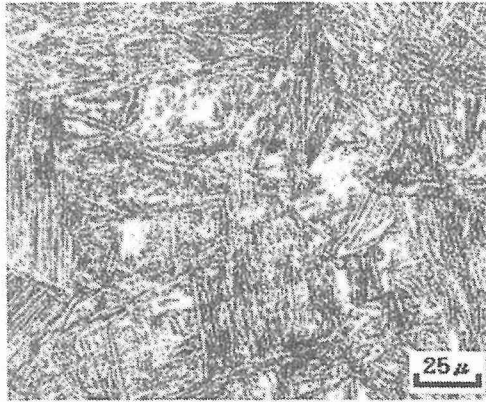




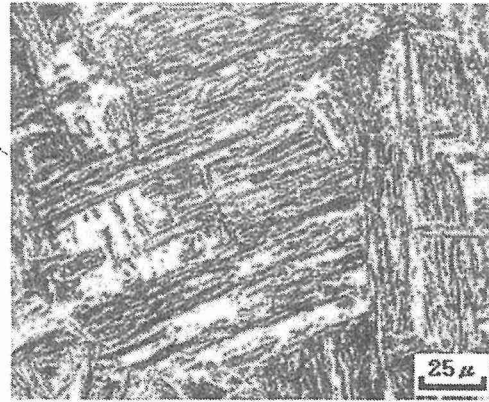
Time 1.8sec Hv 419



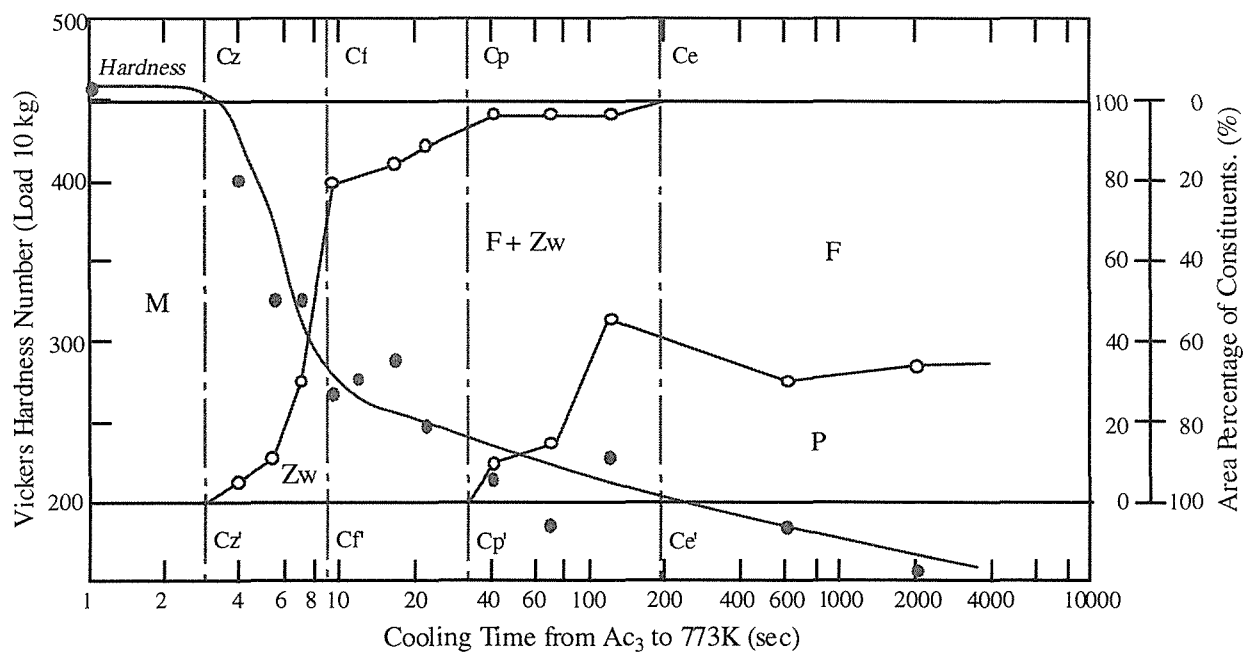
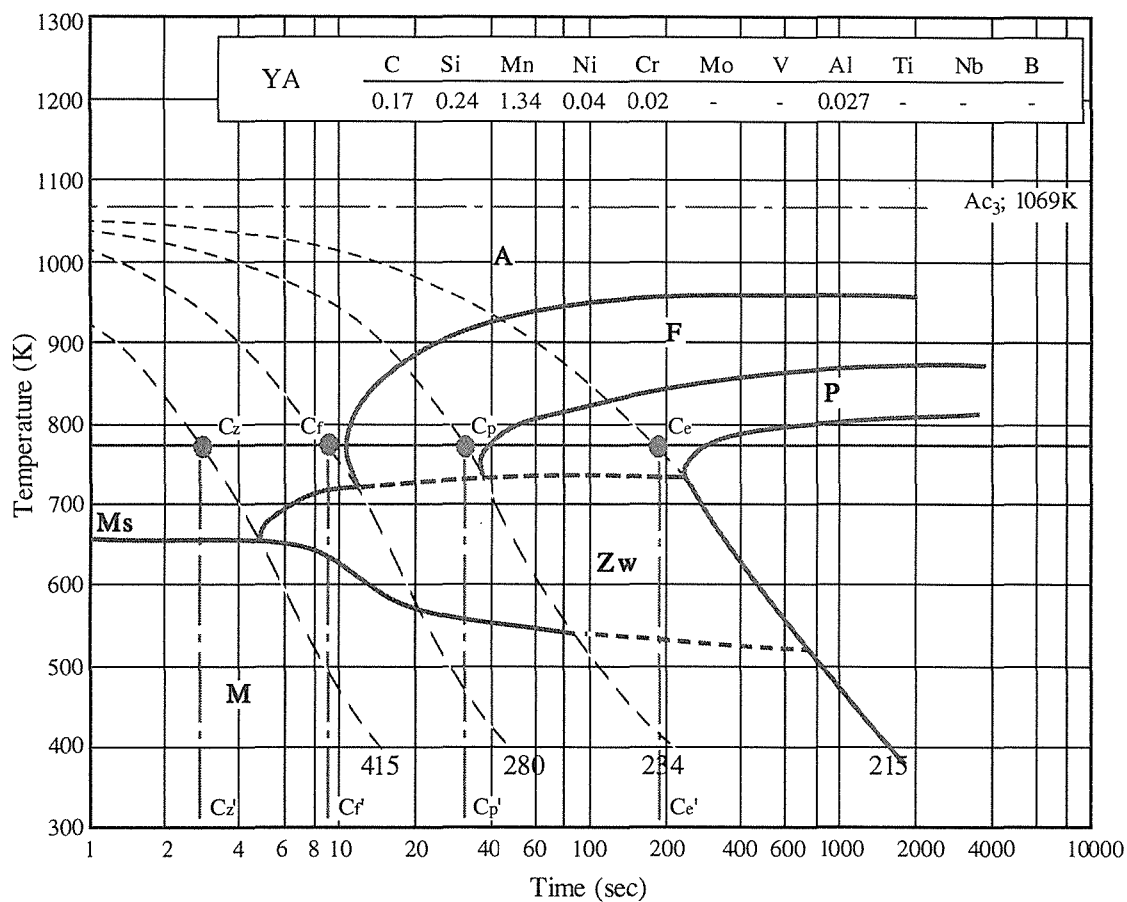
Time 4.1sec Hv 394

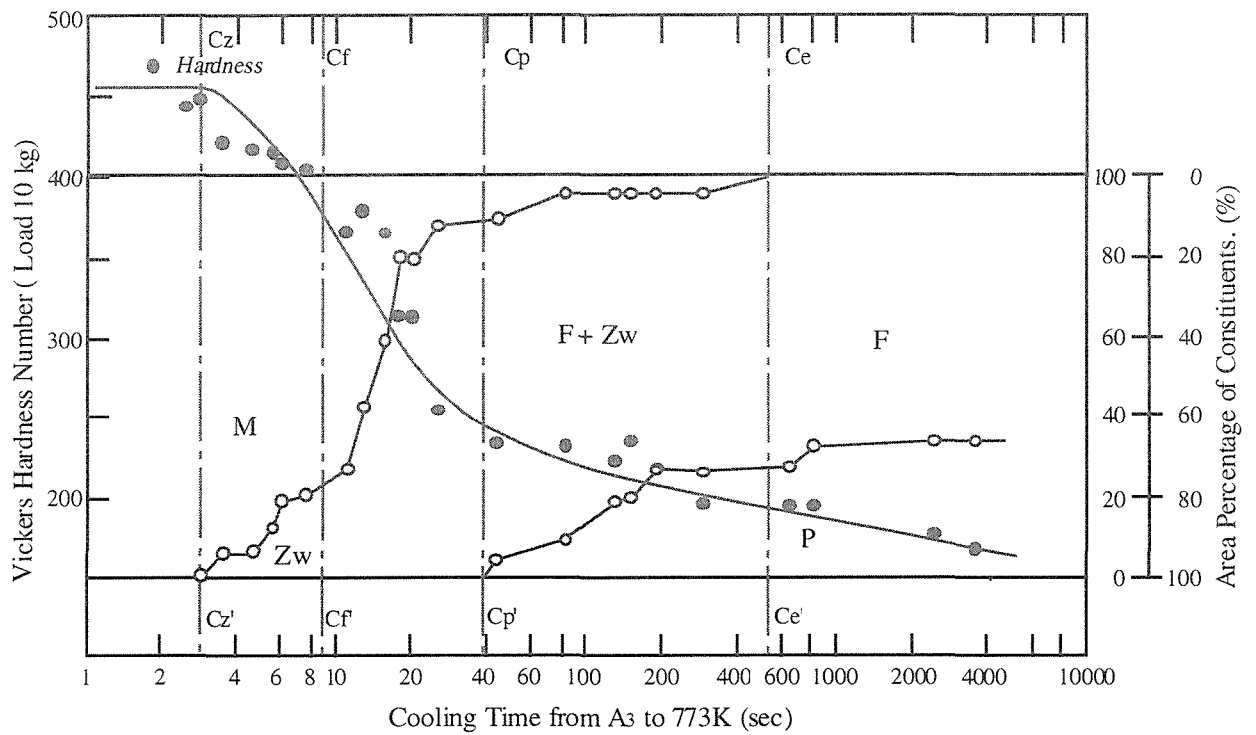
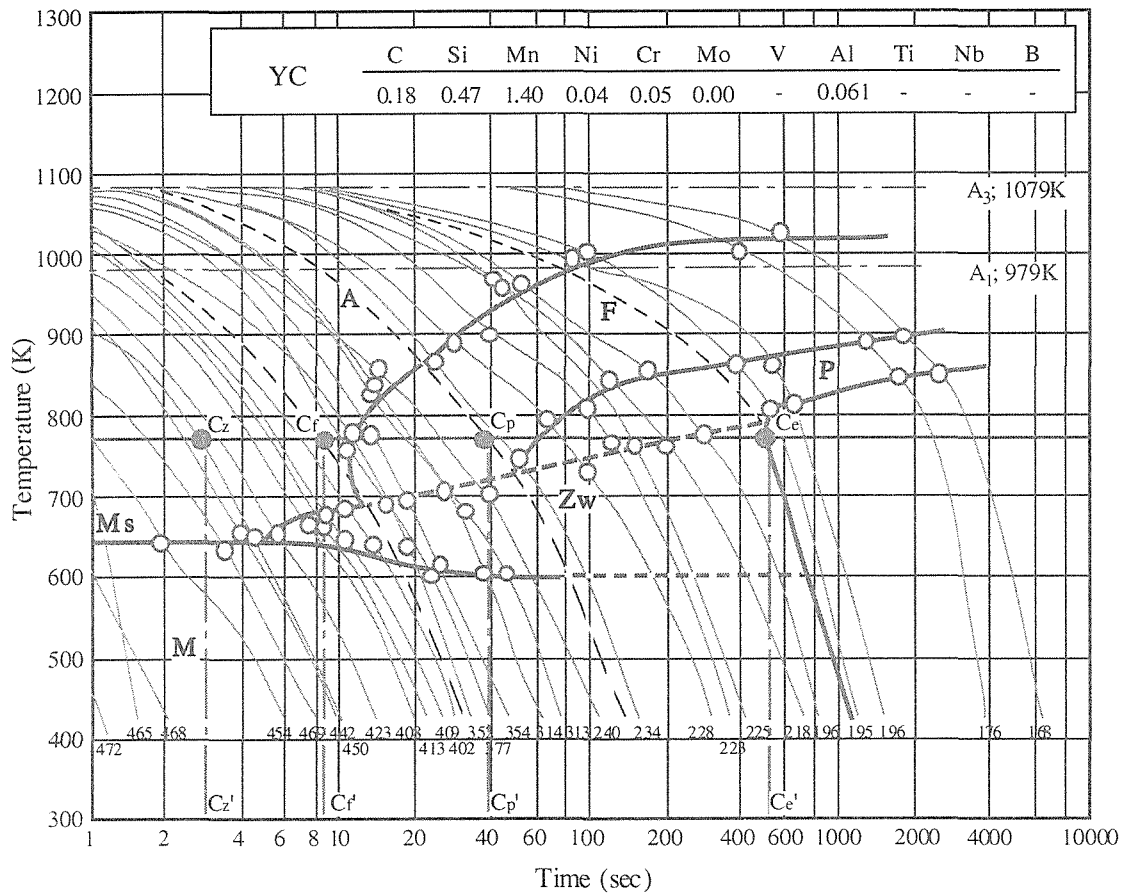


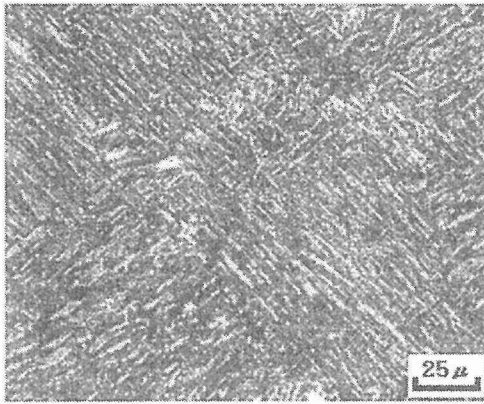
Time 12sec Hv 233



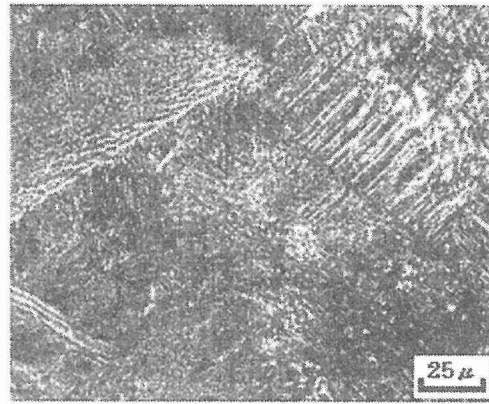
Time 40sec Hv 208



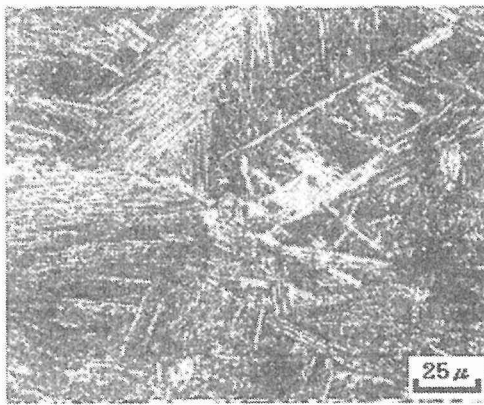




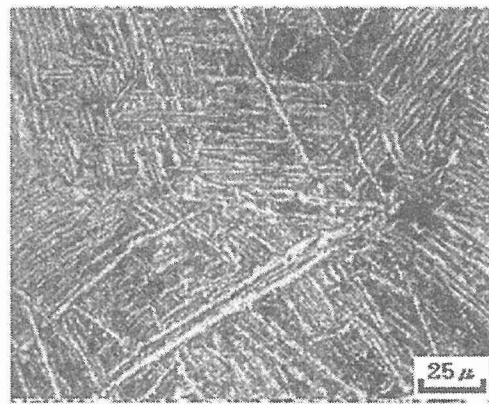
Time 2.5sec Hv 442



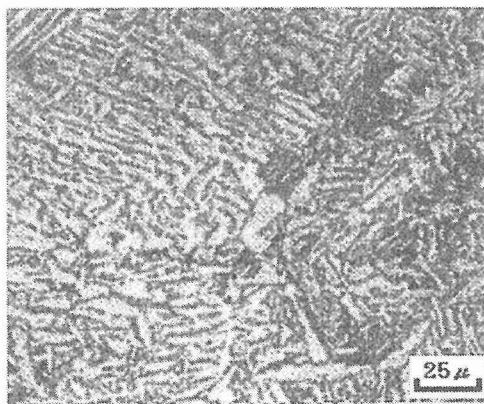
Time 5.8sec Hv 409



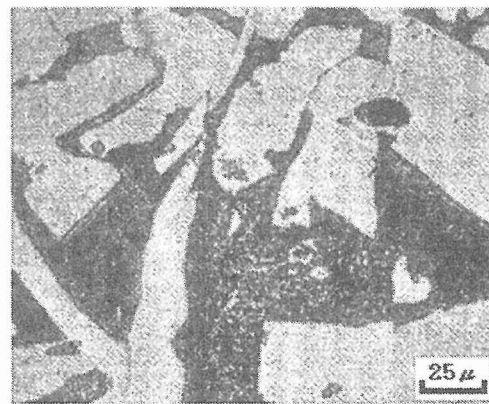
Time 12sec Hv 377



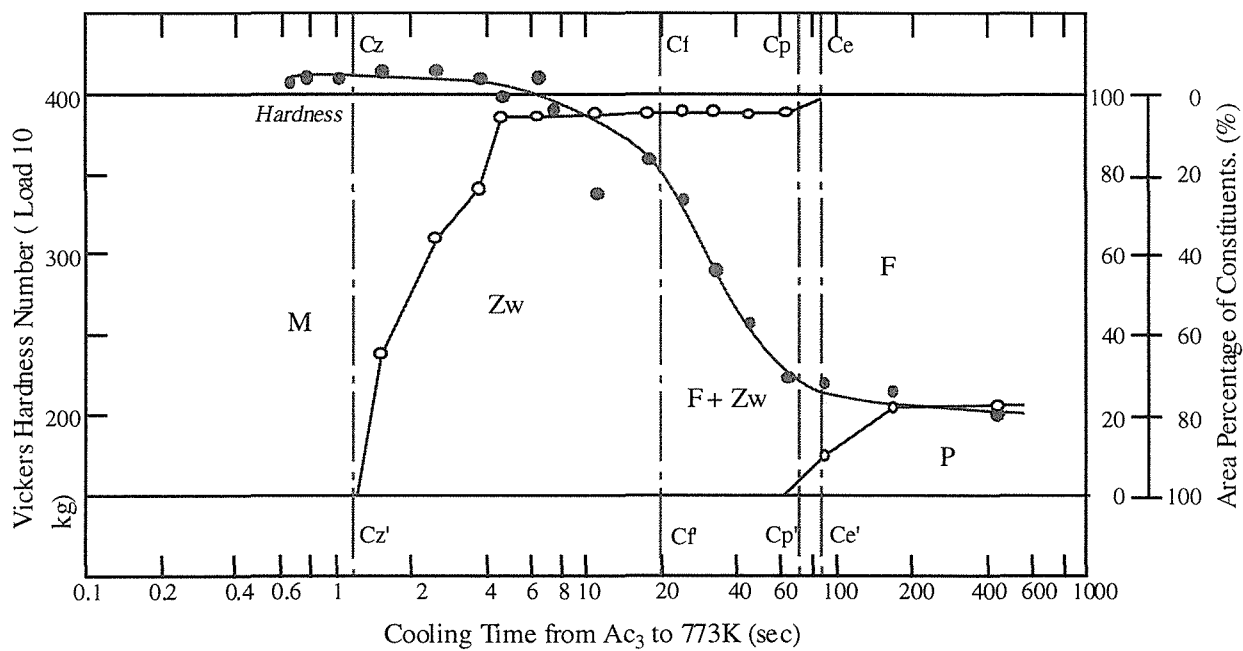
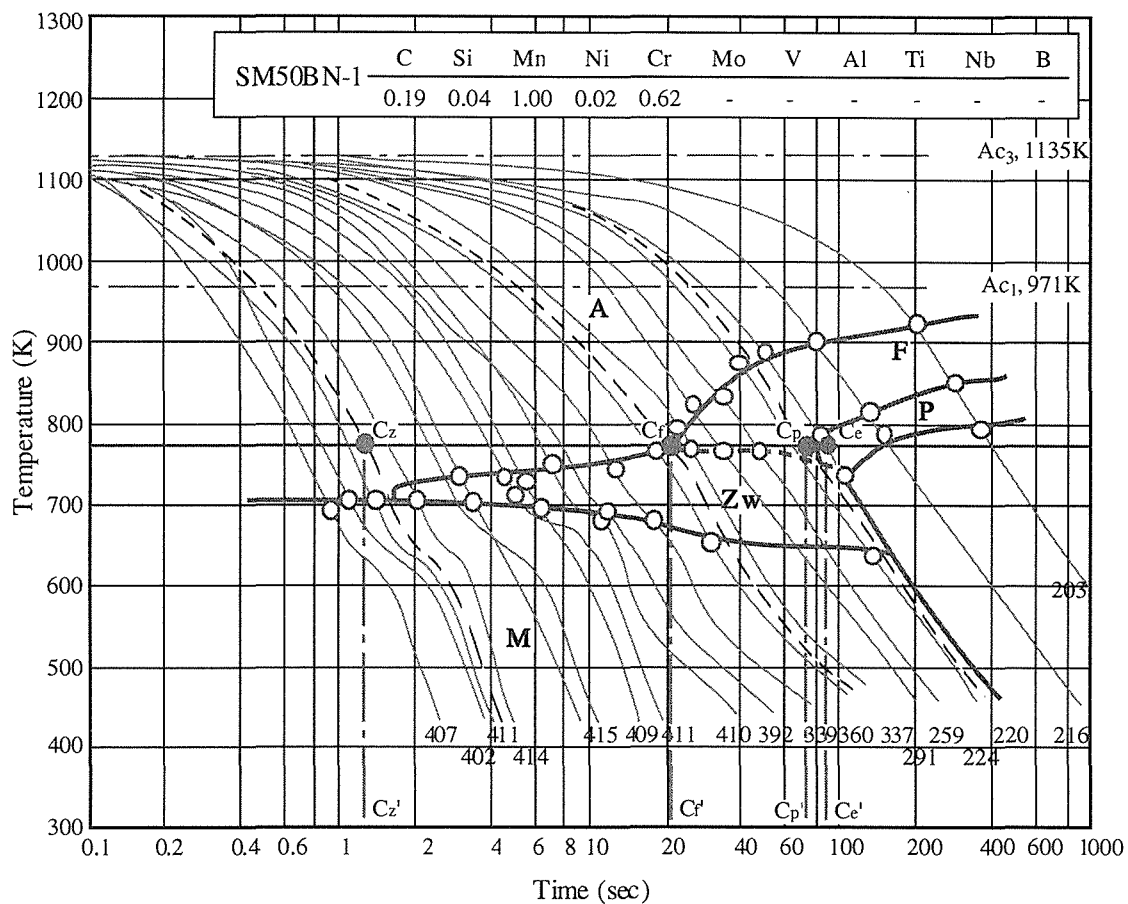
Time 17sec Hv 314

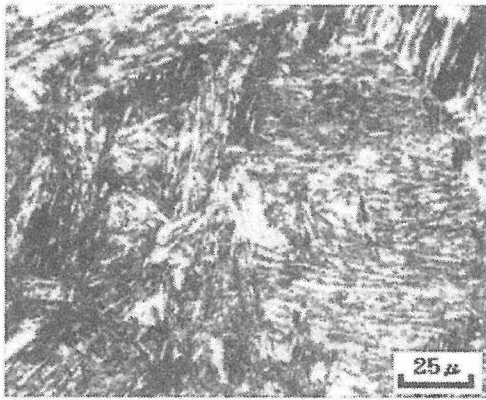


Time 42sec Hv 234

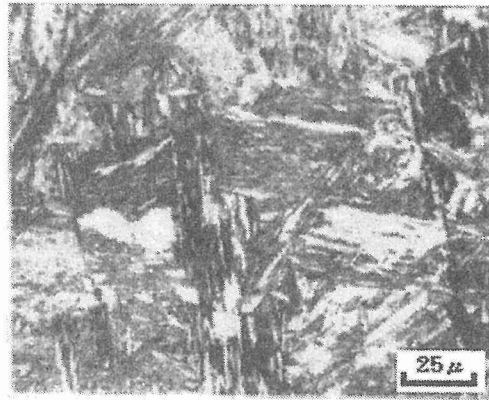


Time 3200sec Hv 168

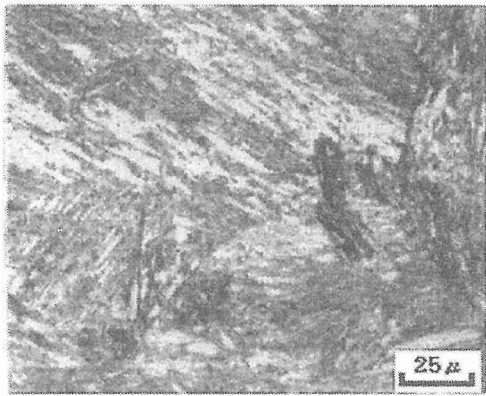




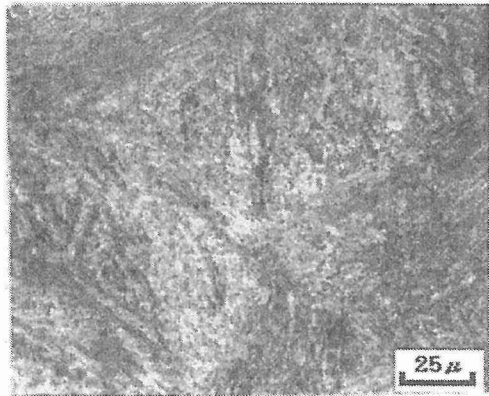
Time 0.7sec Hv 407



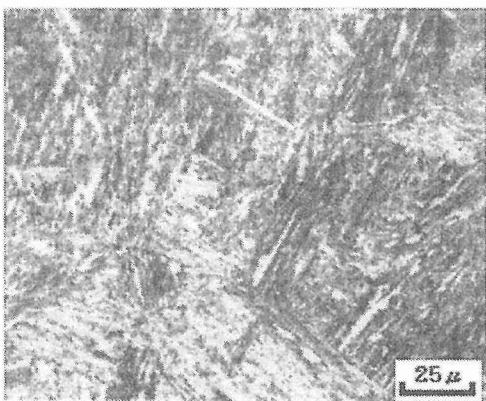
Time 0.82sec Hv 402



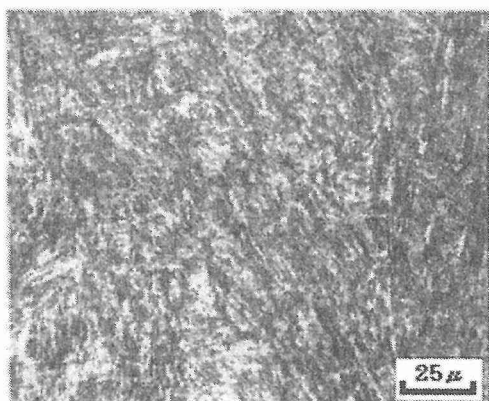
Time 1.1sec Hv 411



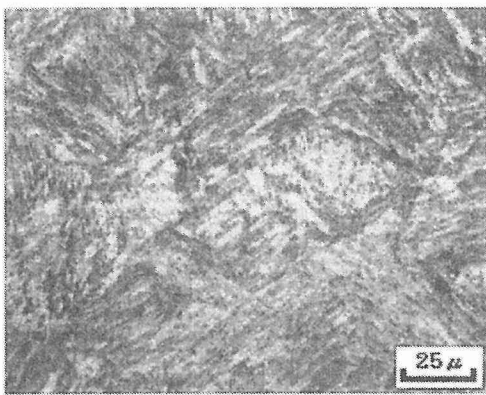
Time 1.7sec Hv 414



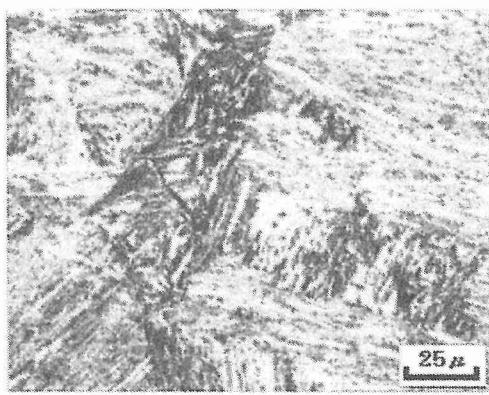
Time 2.4sec Hv 415



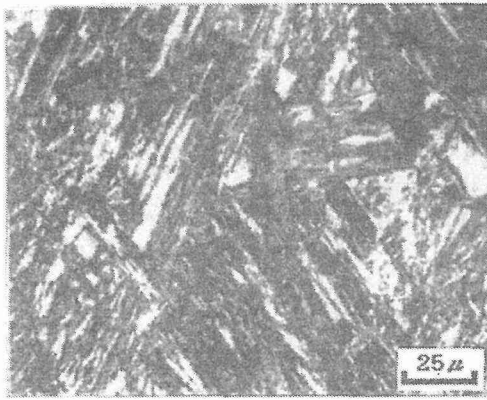
Time 4sec Hv 411



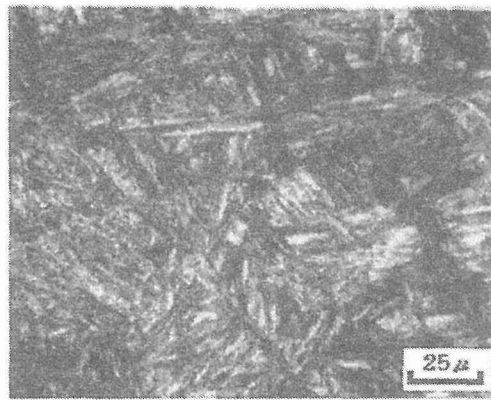
Time 4.5sec Hv 409



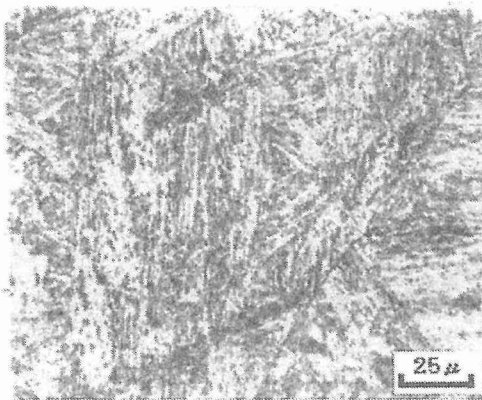
Time 6.5sec Hv 410



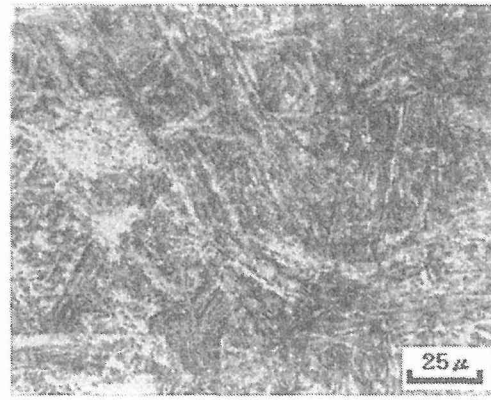
Time 8sec Hv 392



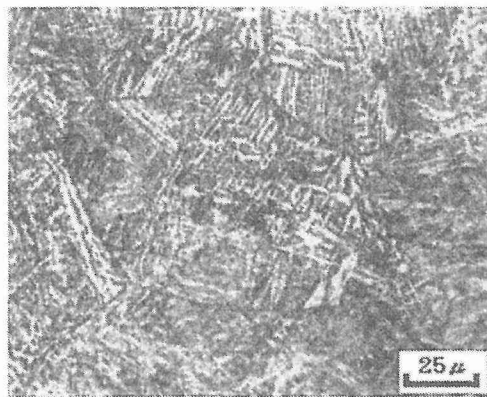
Time 12sec Hv 339



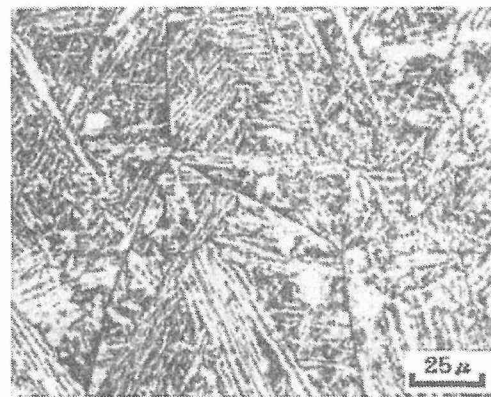
Time 18sec Hv 360



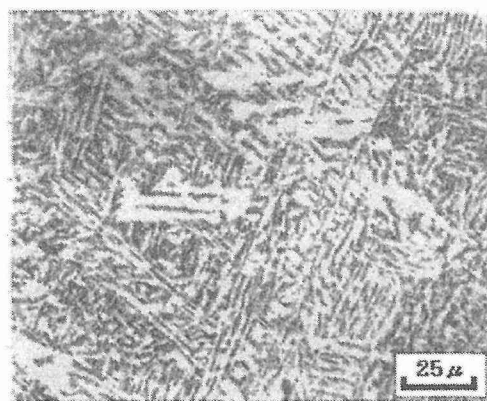
Time 25sec Hv 337



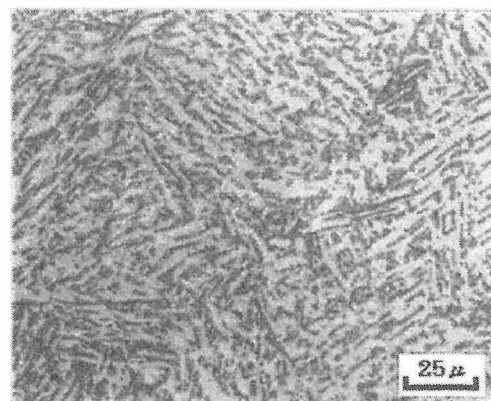
Time 32sec Hv 291



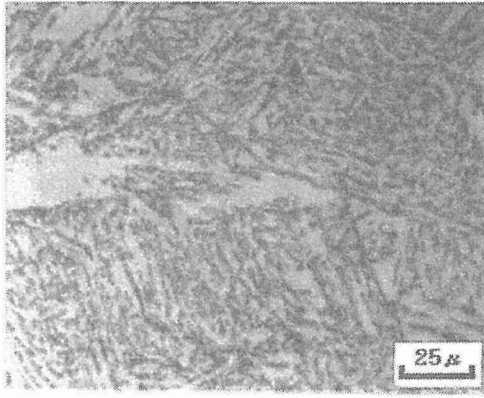
Time 48sec Hv 259



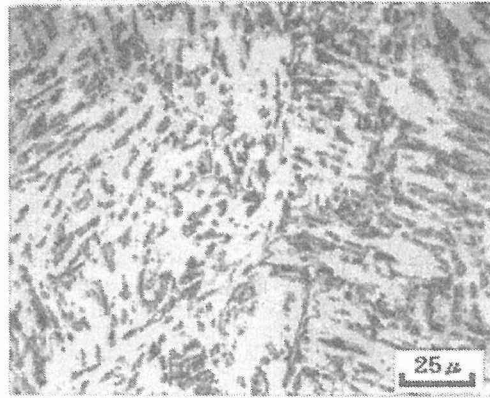
Time 68sec Hv 224



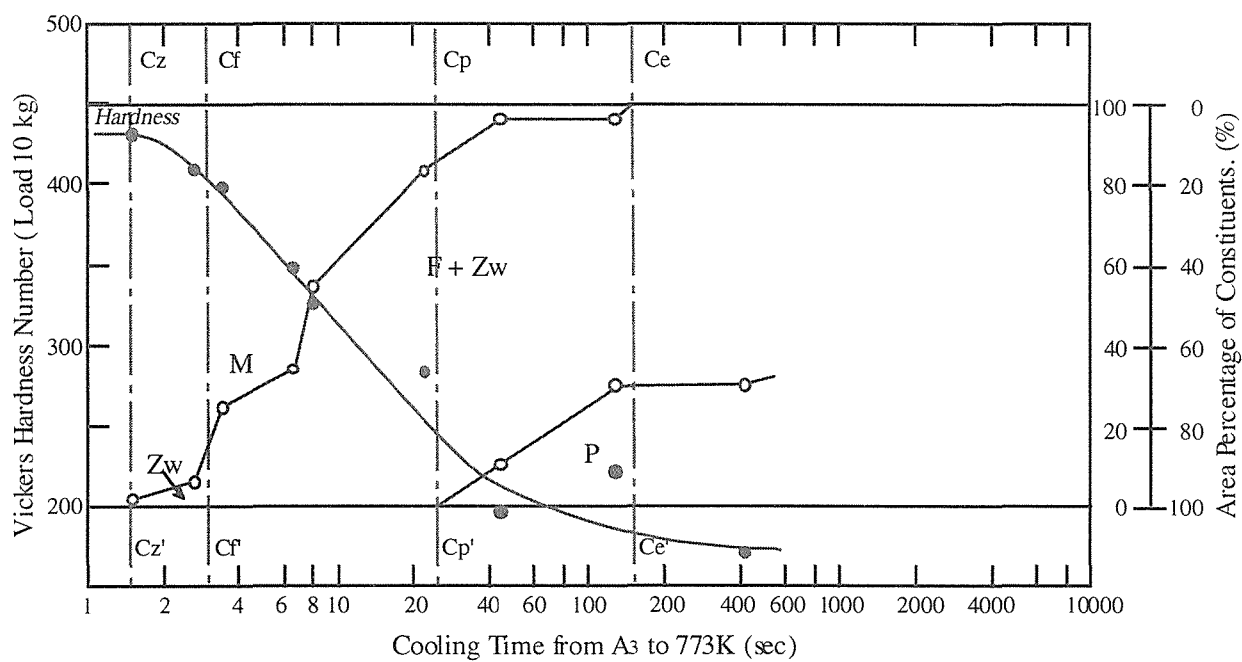
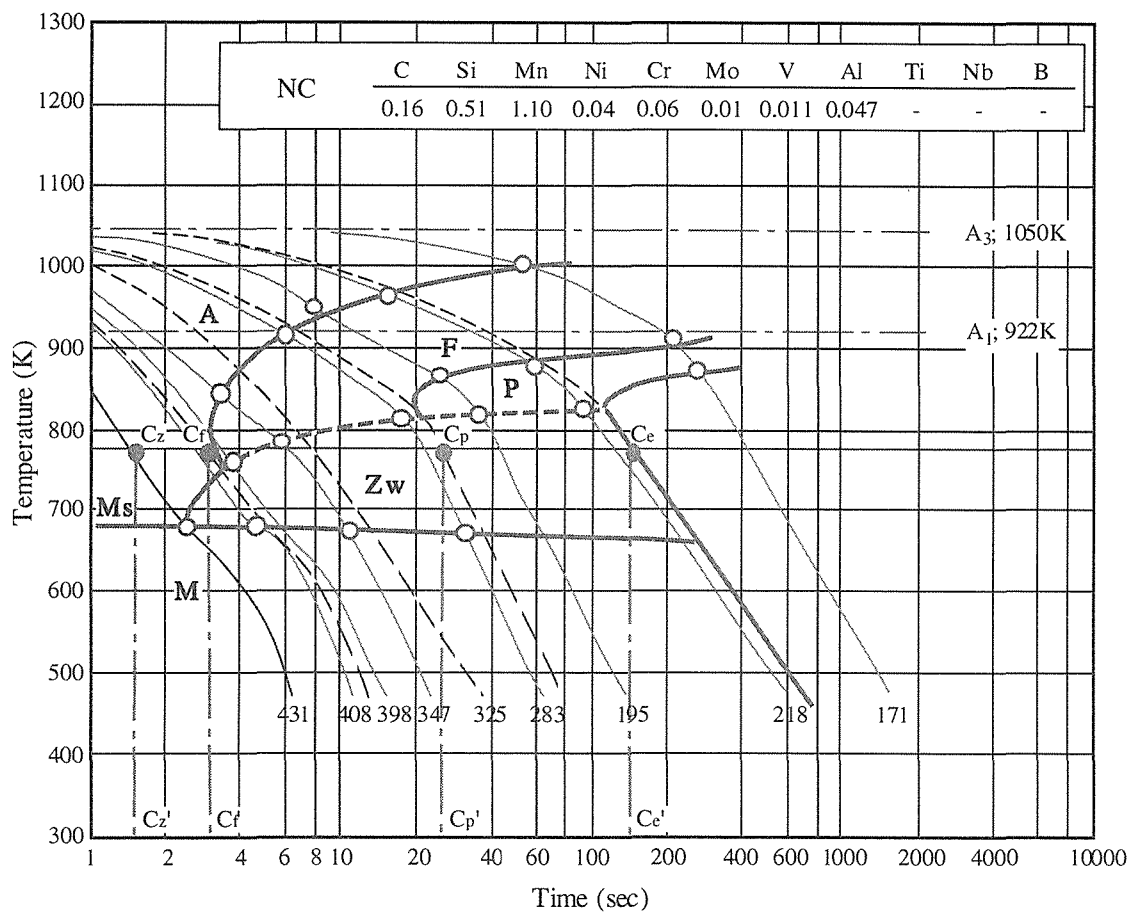
Time 88sec Hv 220

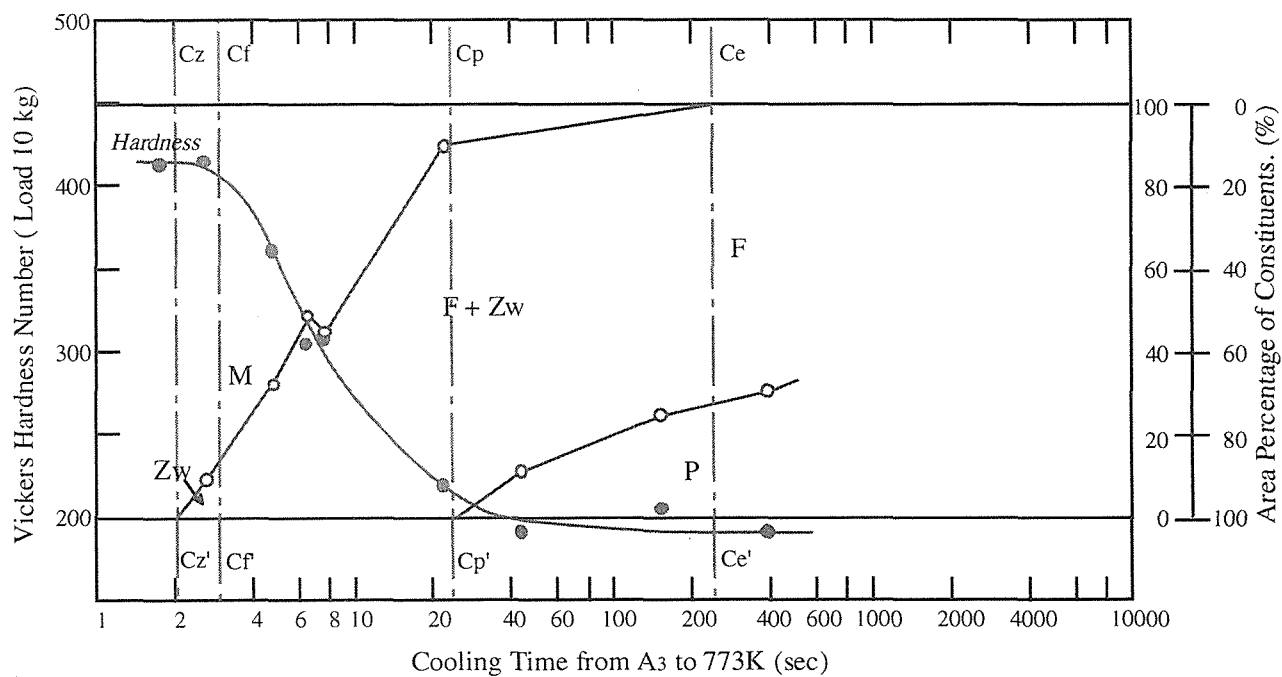
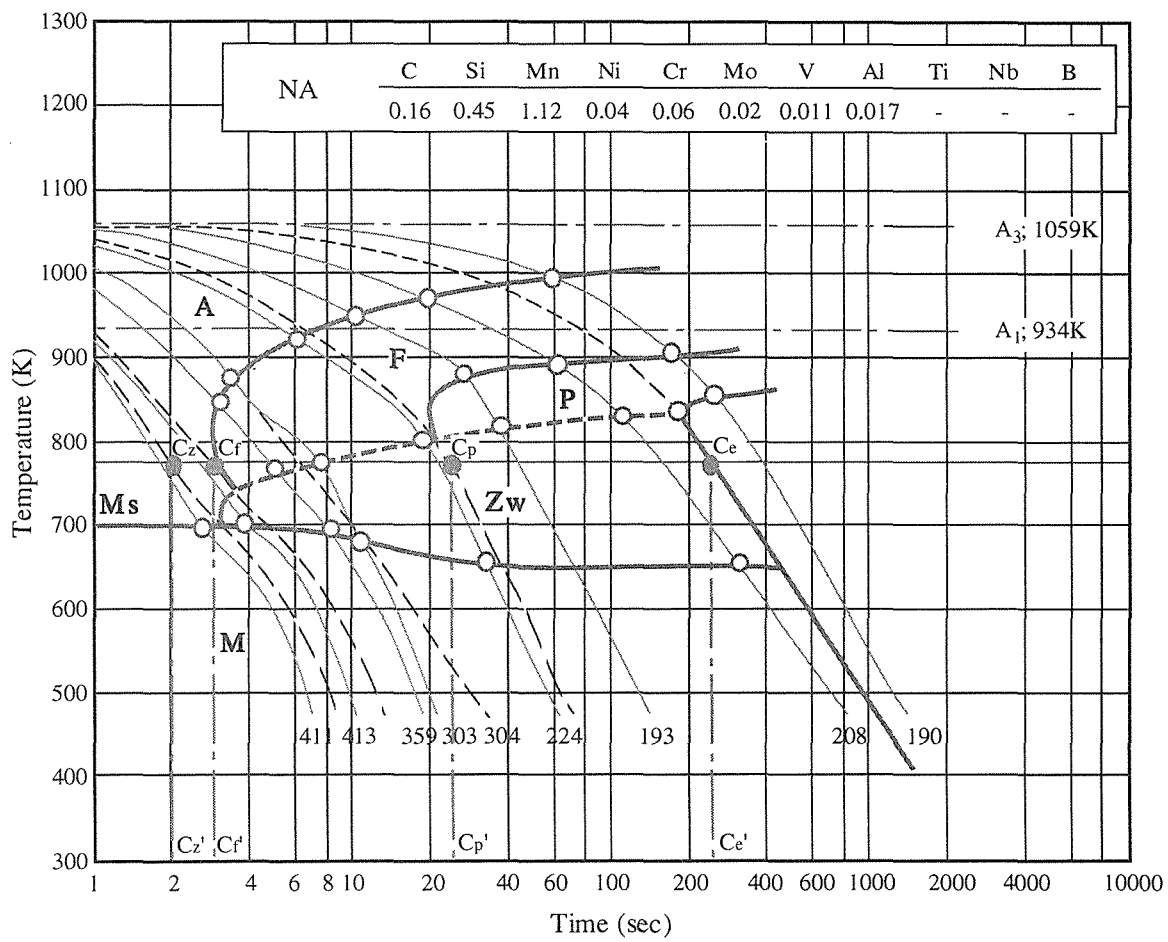


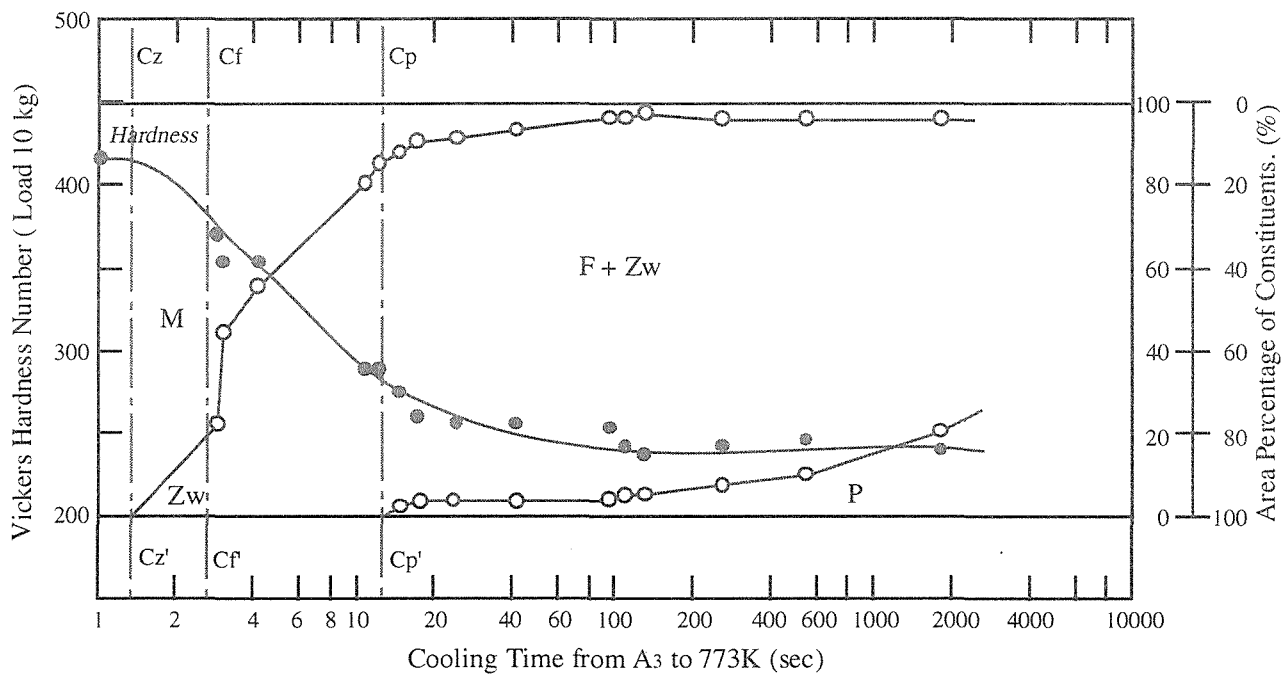
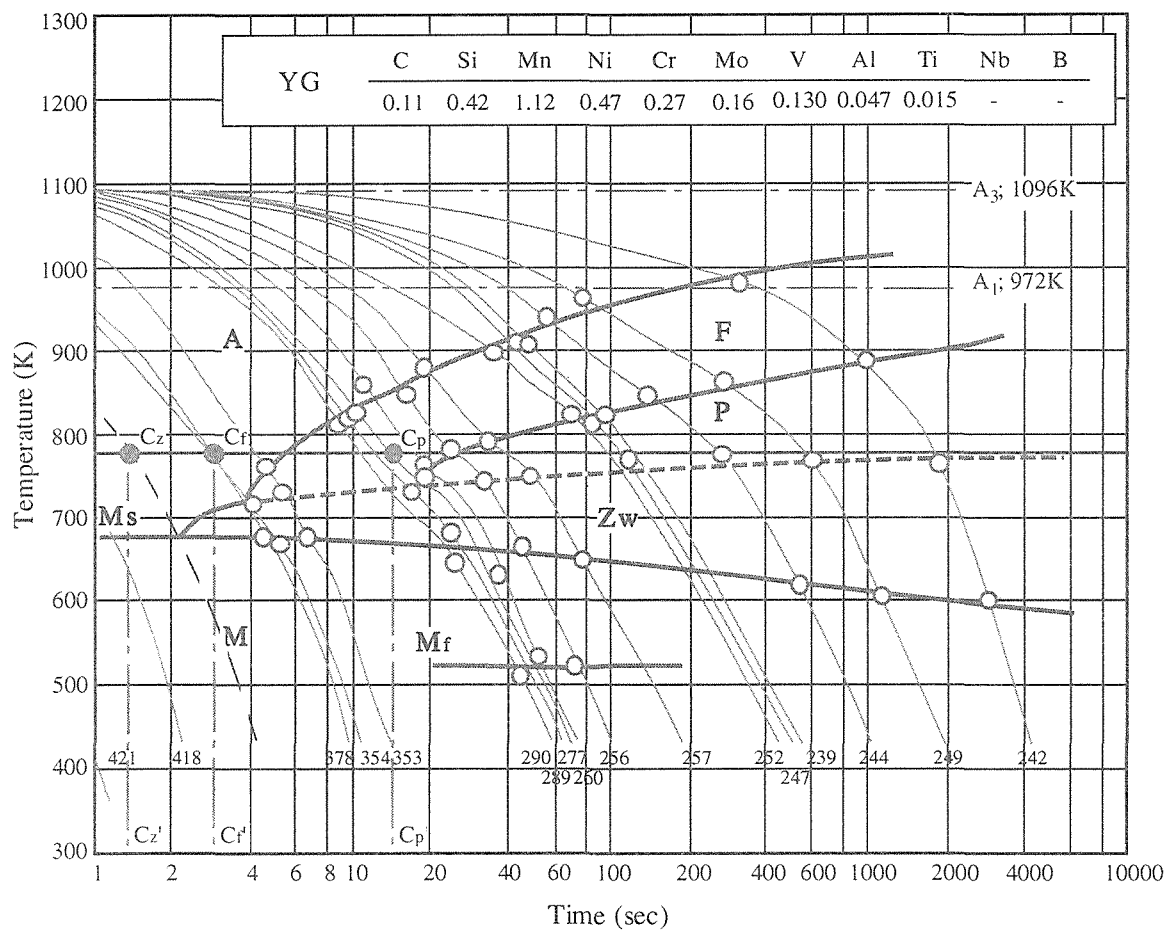
Time 160sec Hv 216

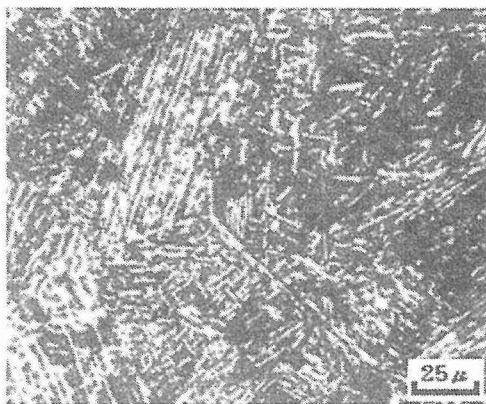


Time 400sec Hv 203

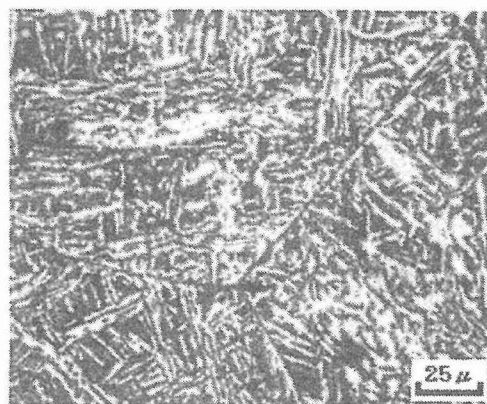




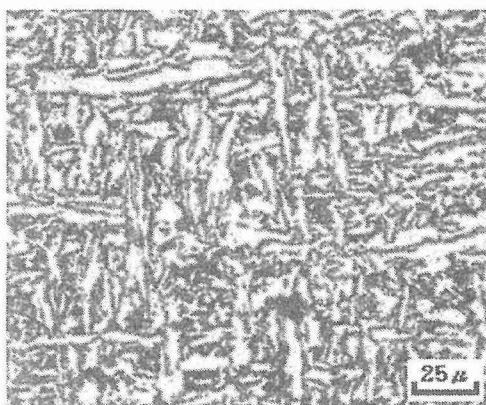




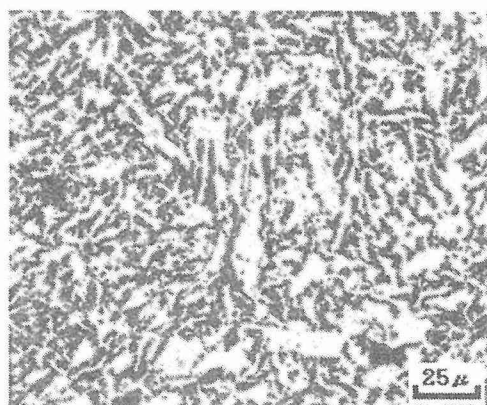
Time 3sec Hv 354



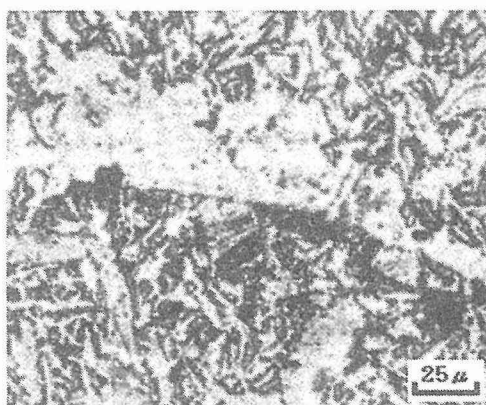
Time 15sec Hv 290



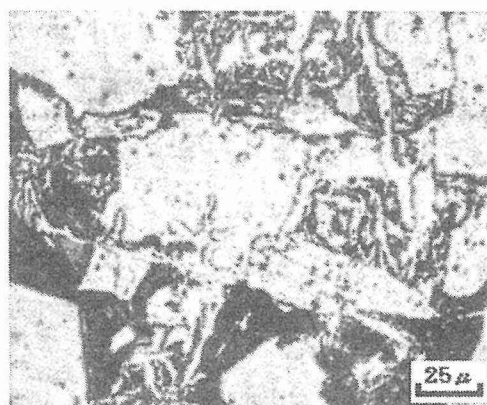
Time 25sec Hv 256



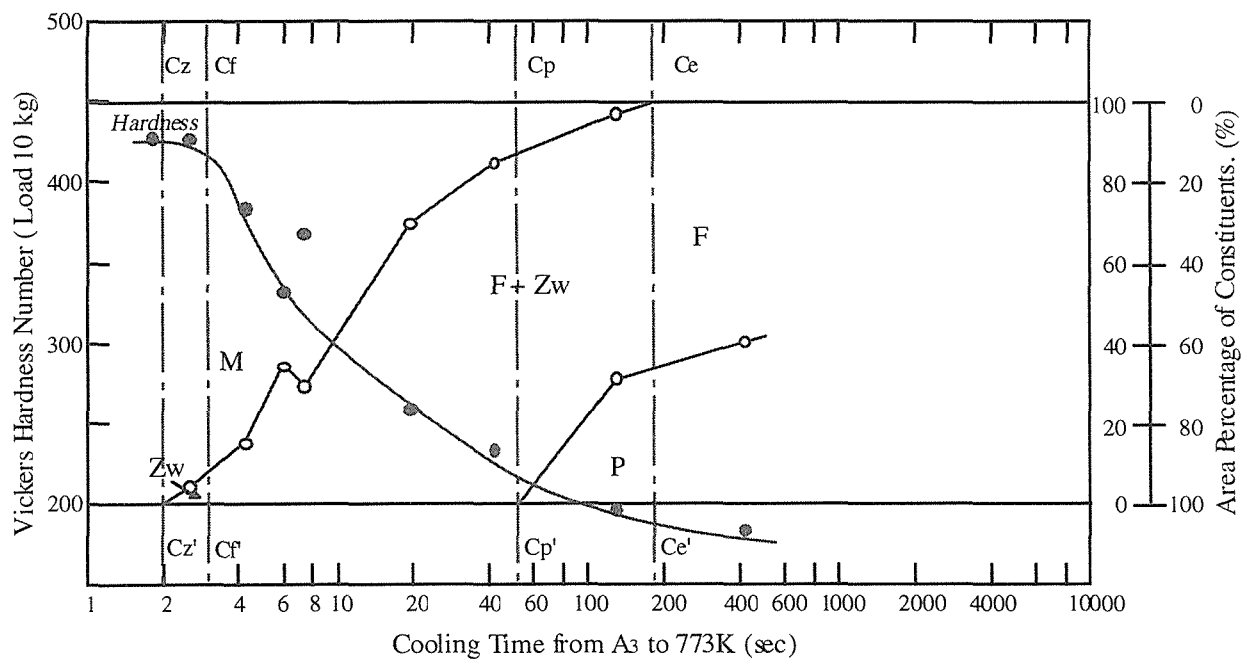
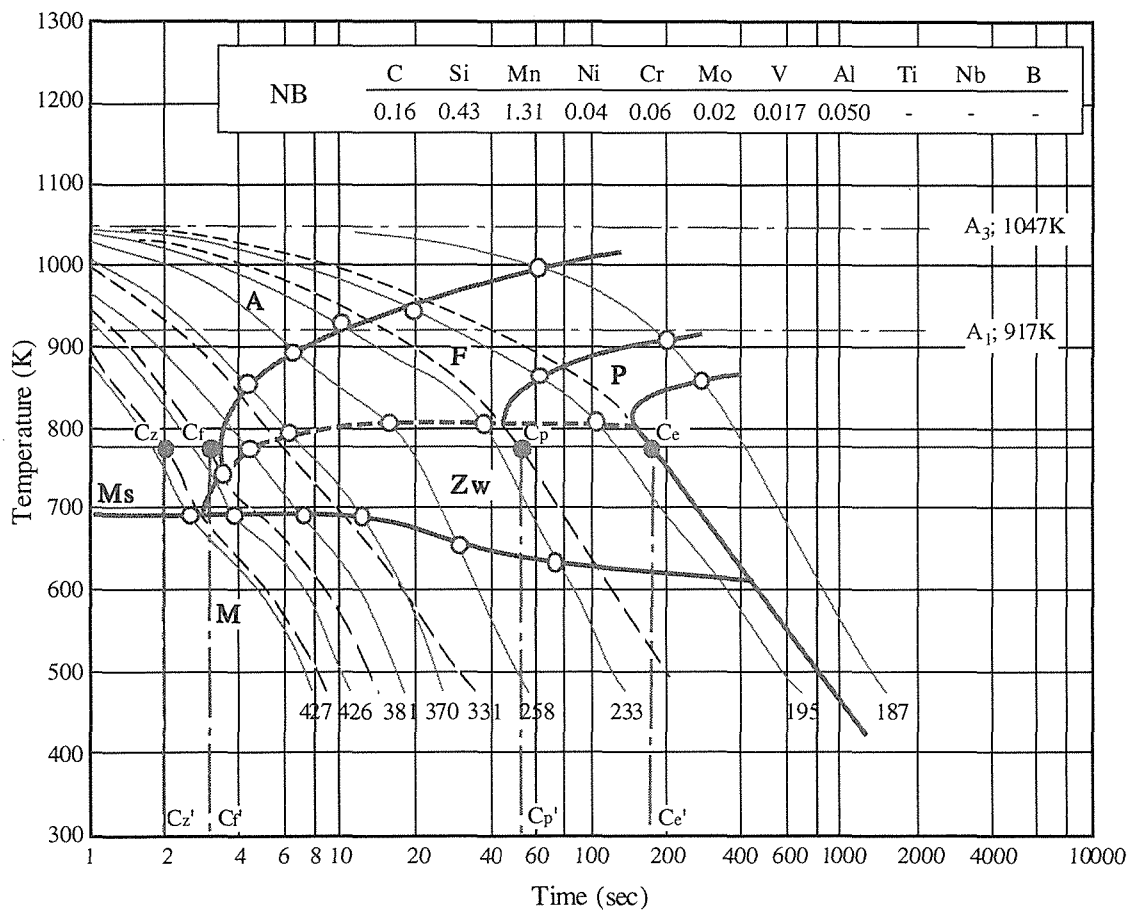
Time 140sec Hv 239

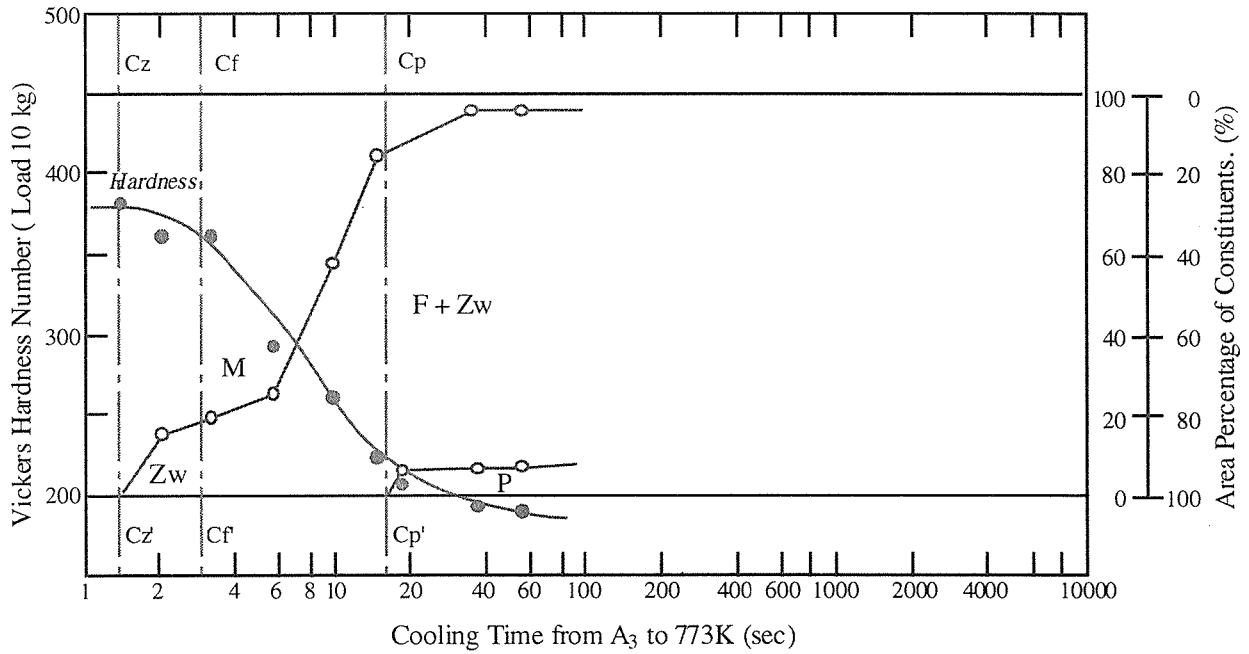
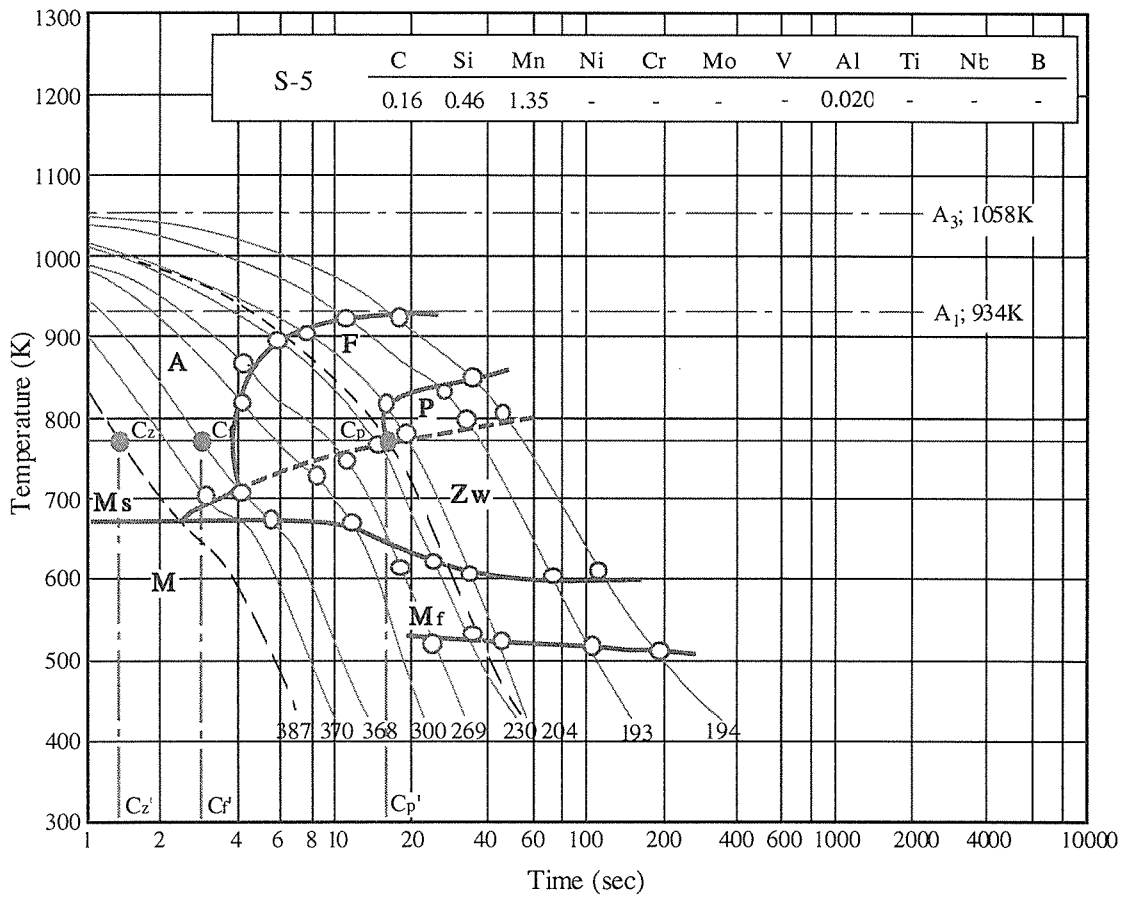


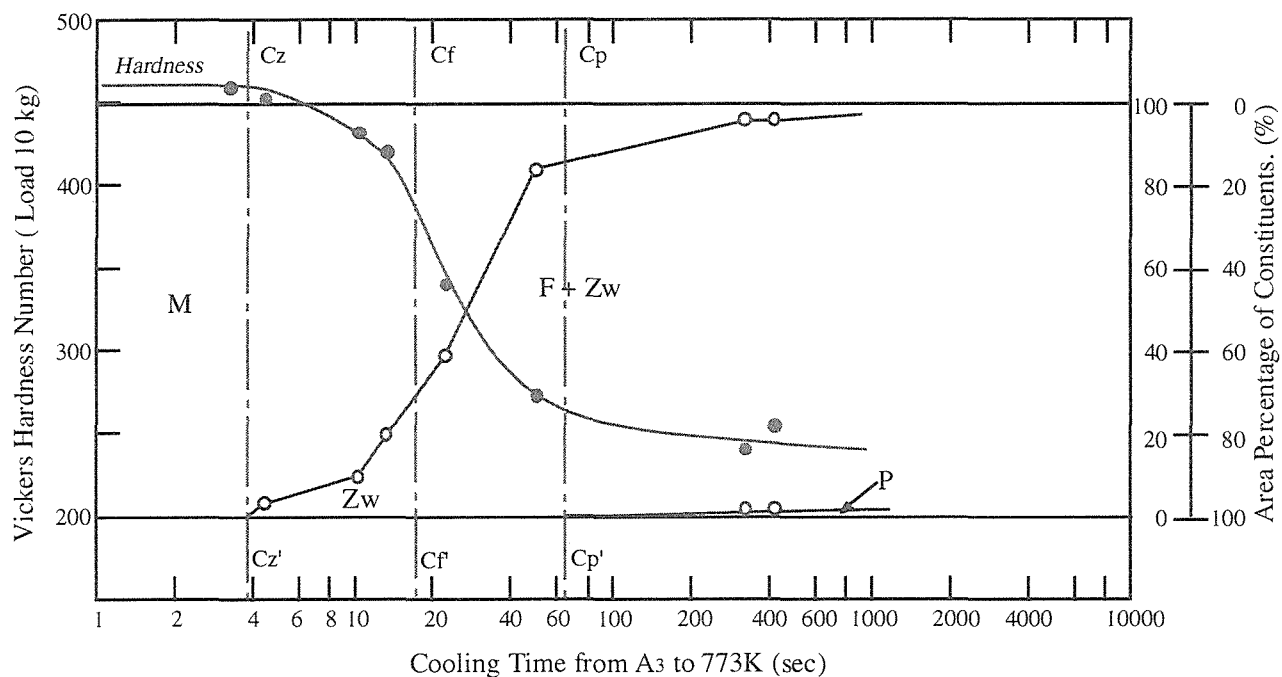
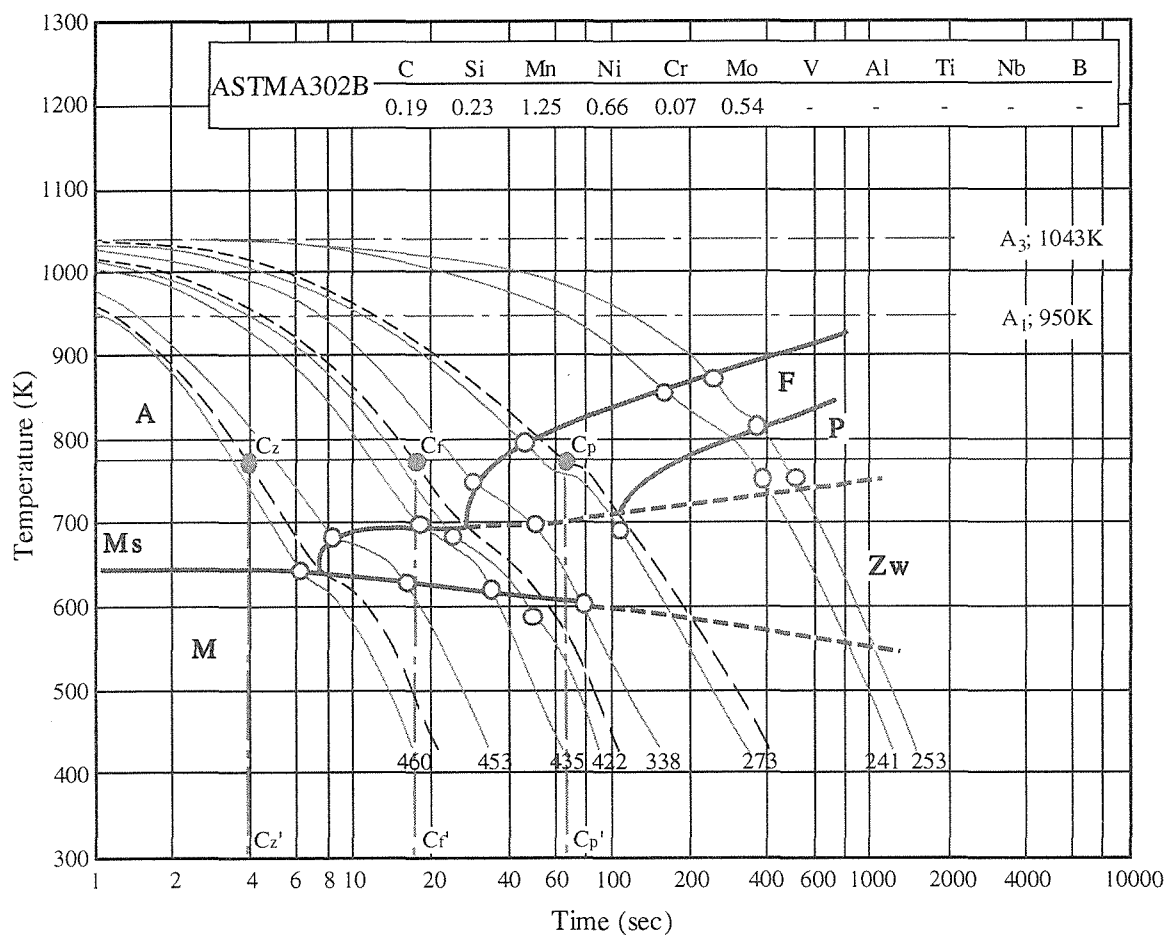
Time 590sec Hv 249

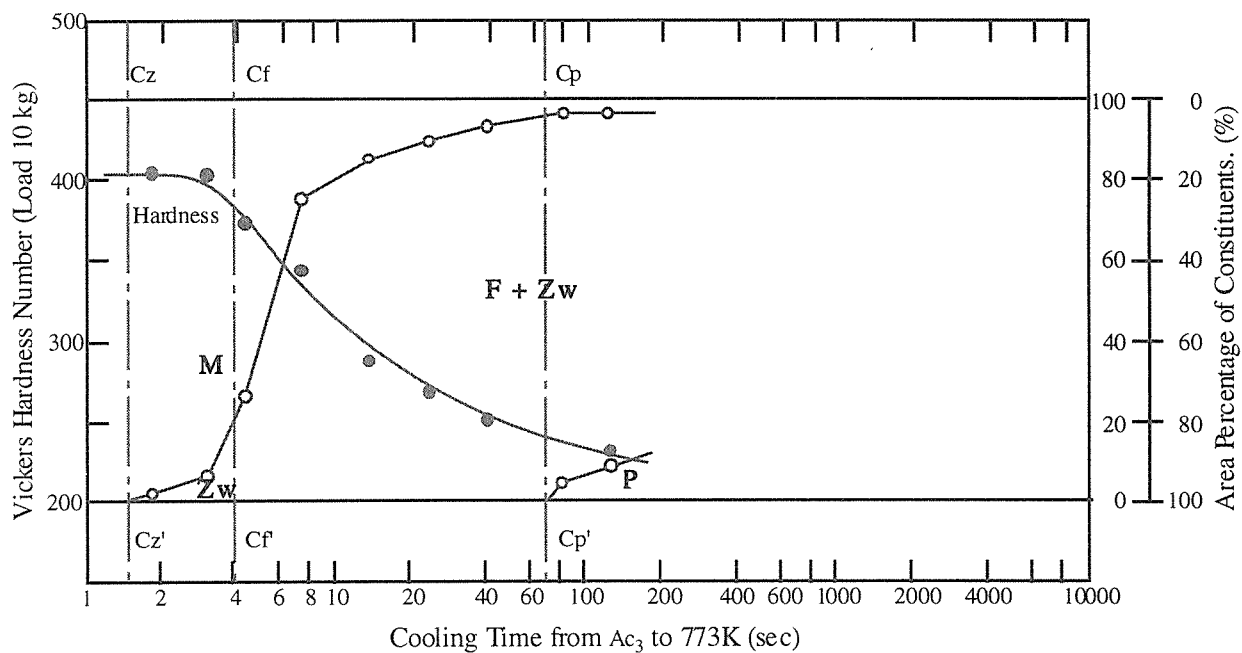
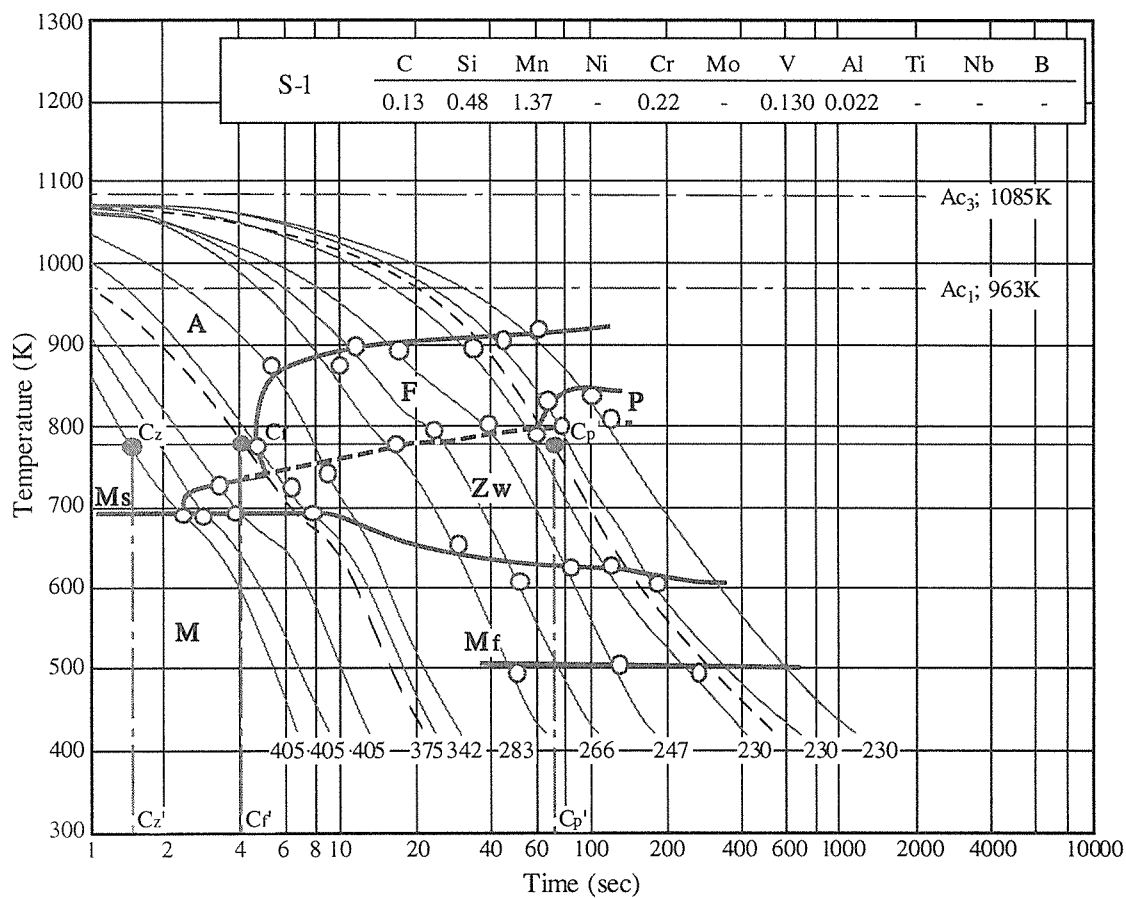


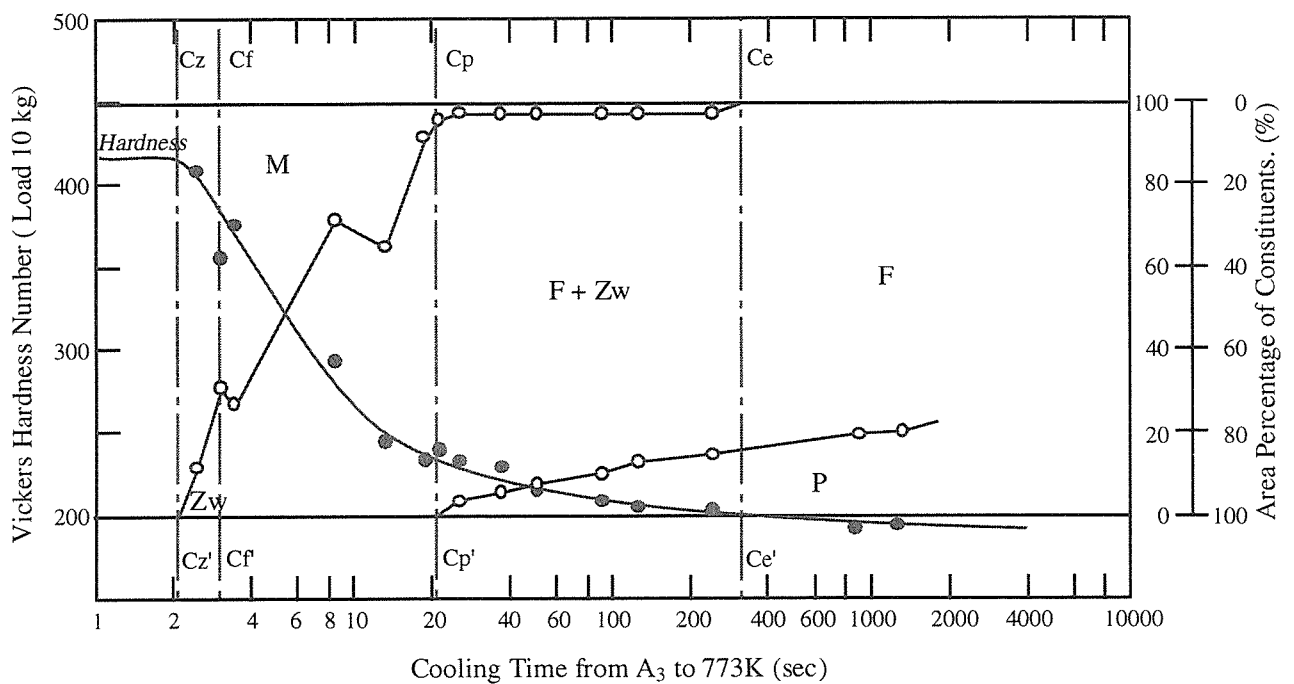
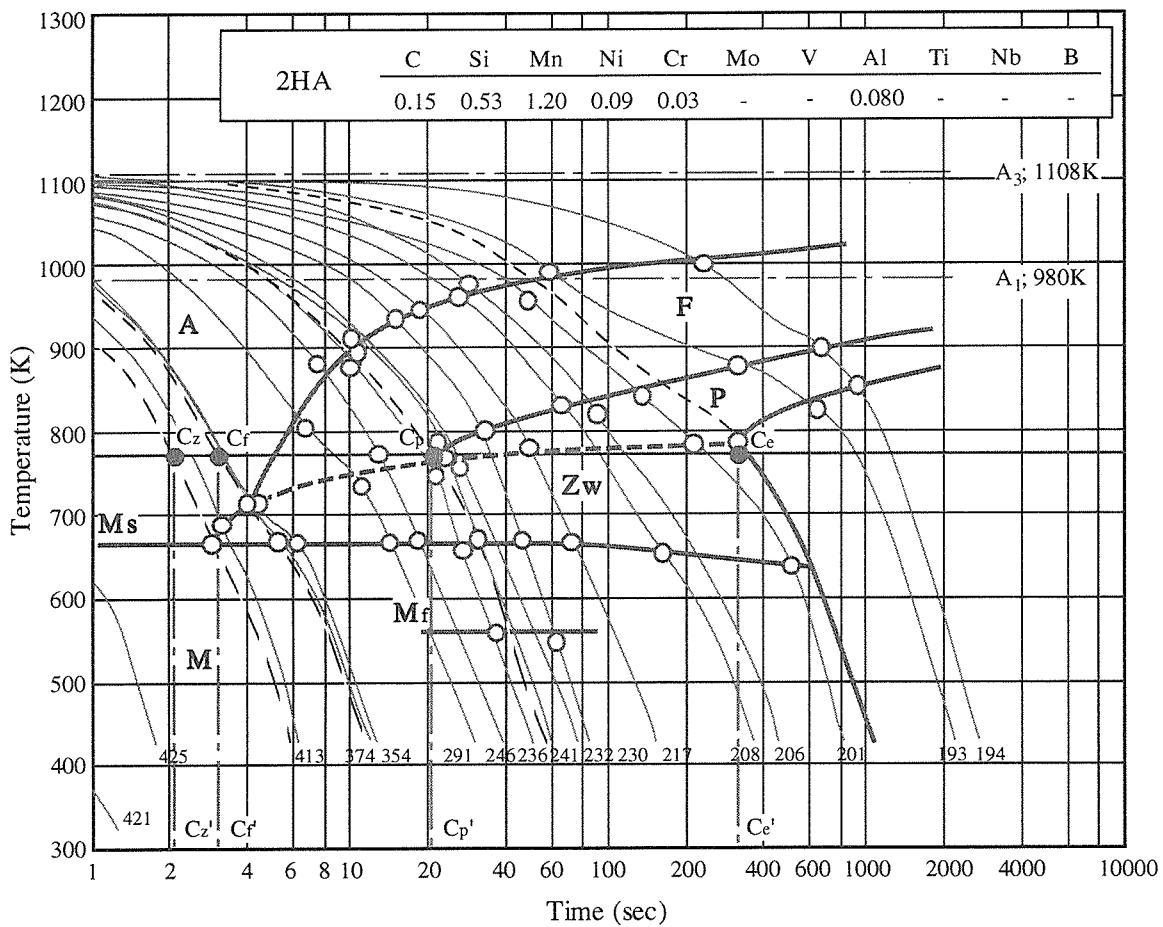
Time 1800sec Hv 242

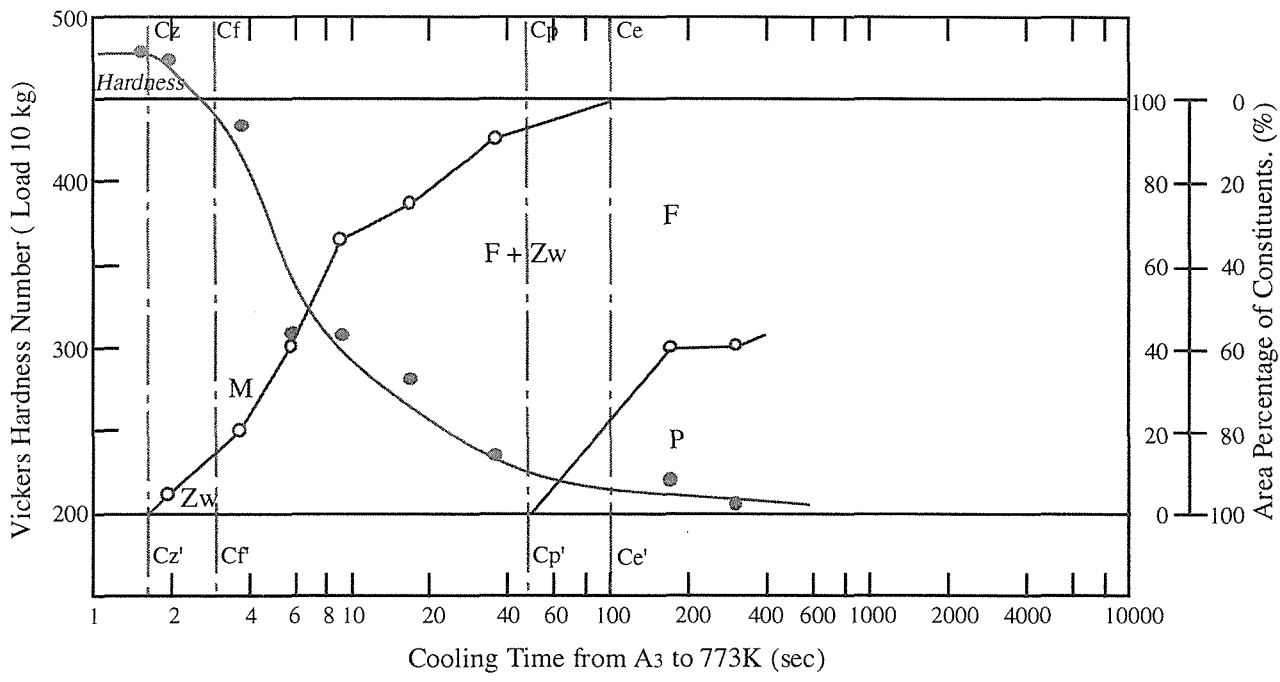
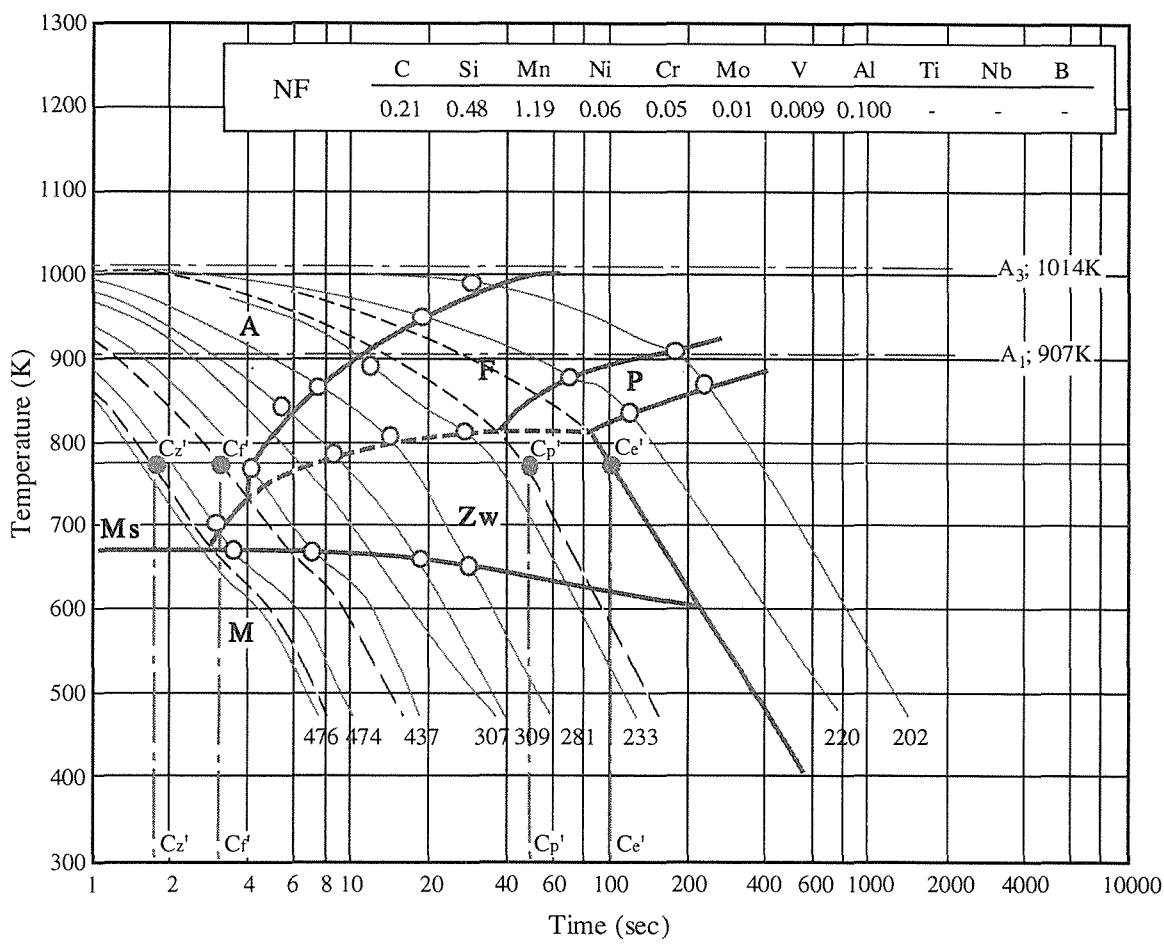


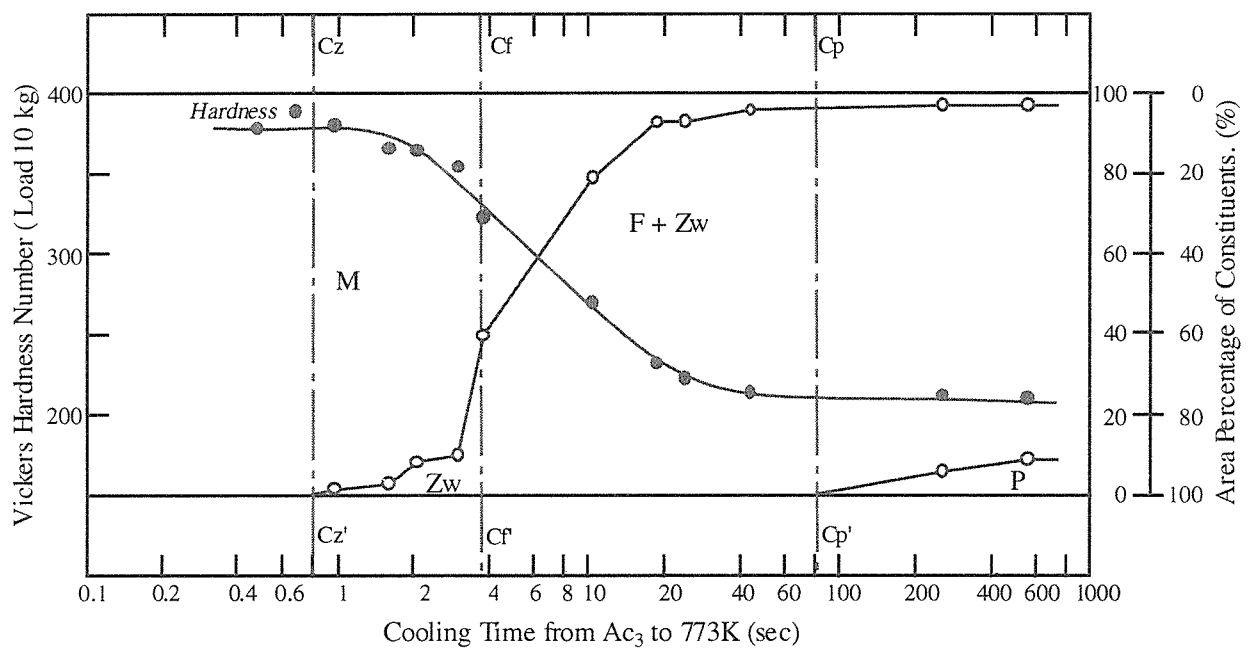
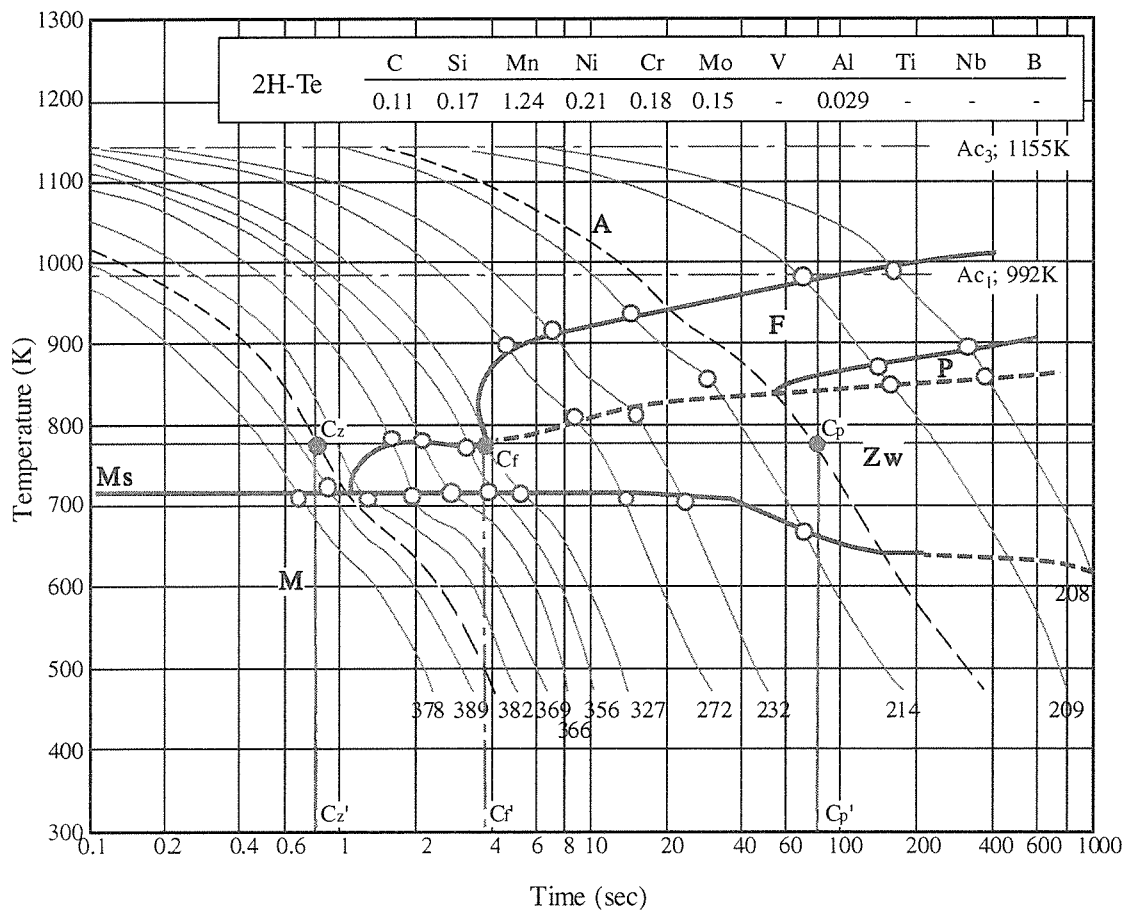


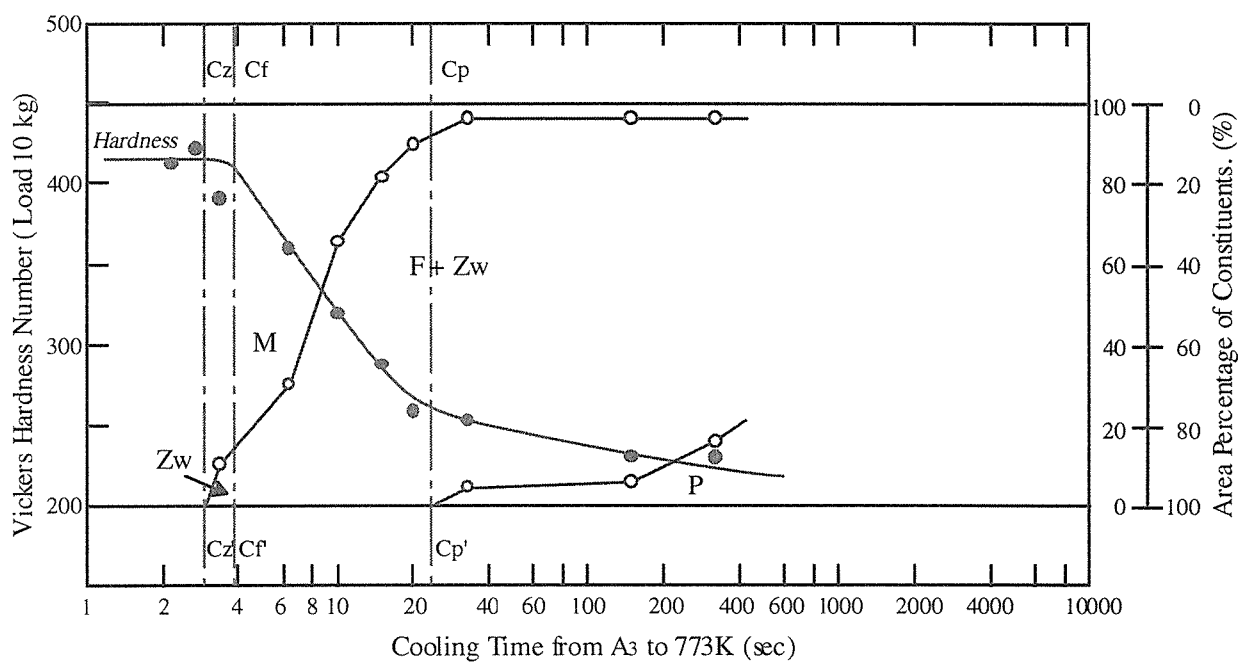
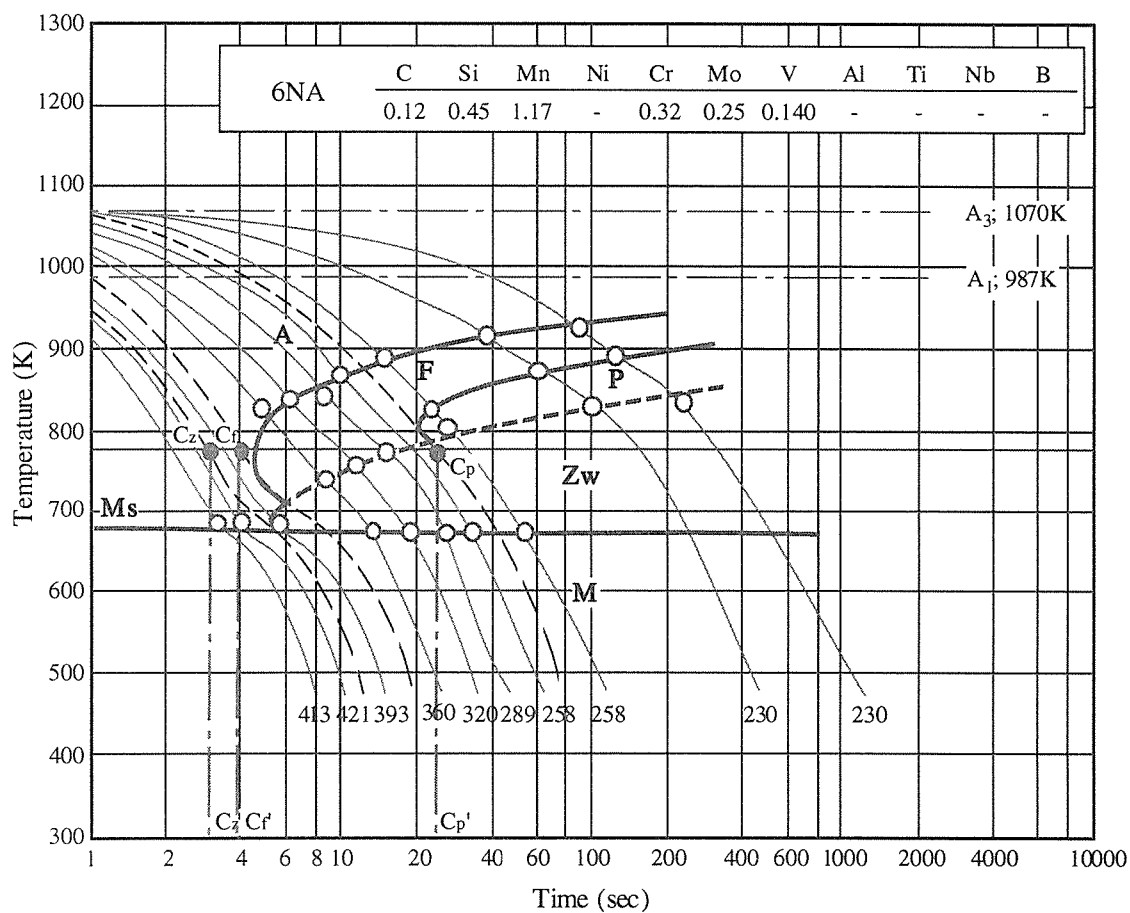


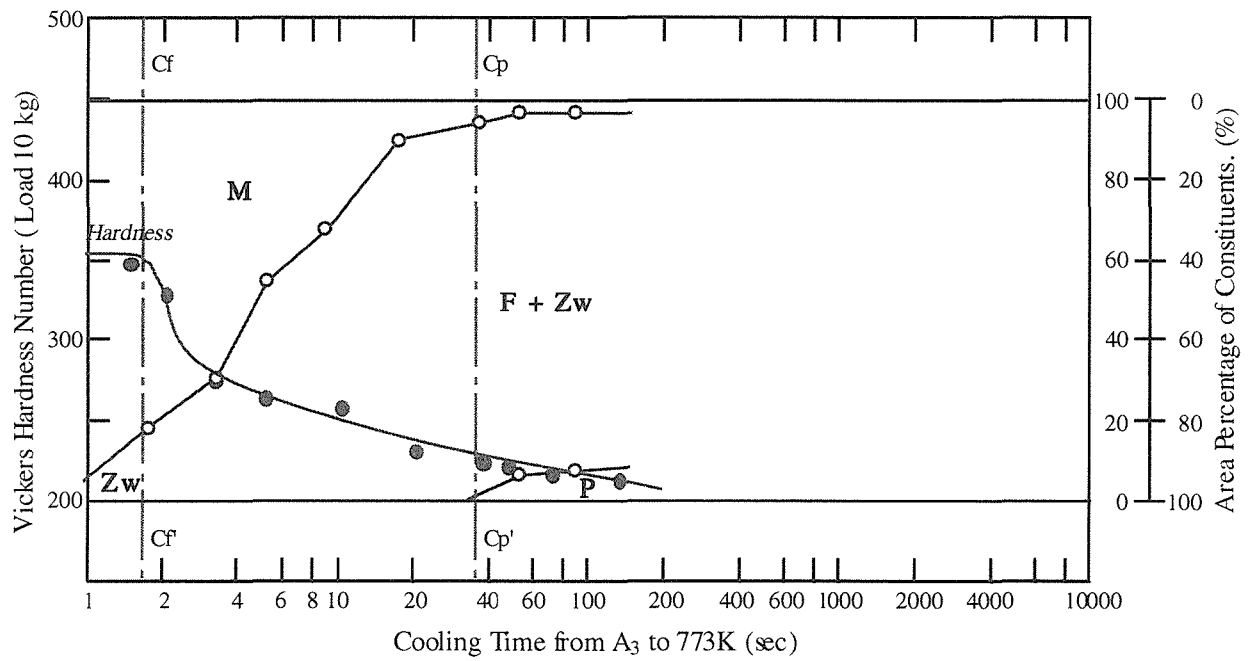
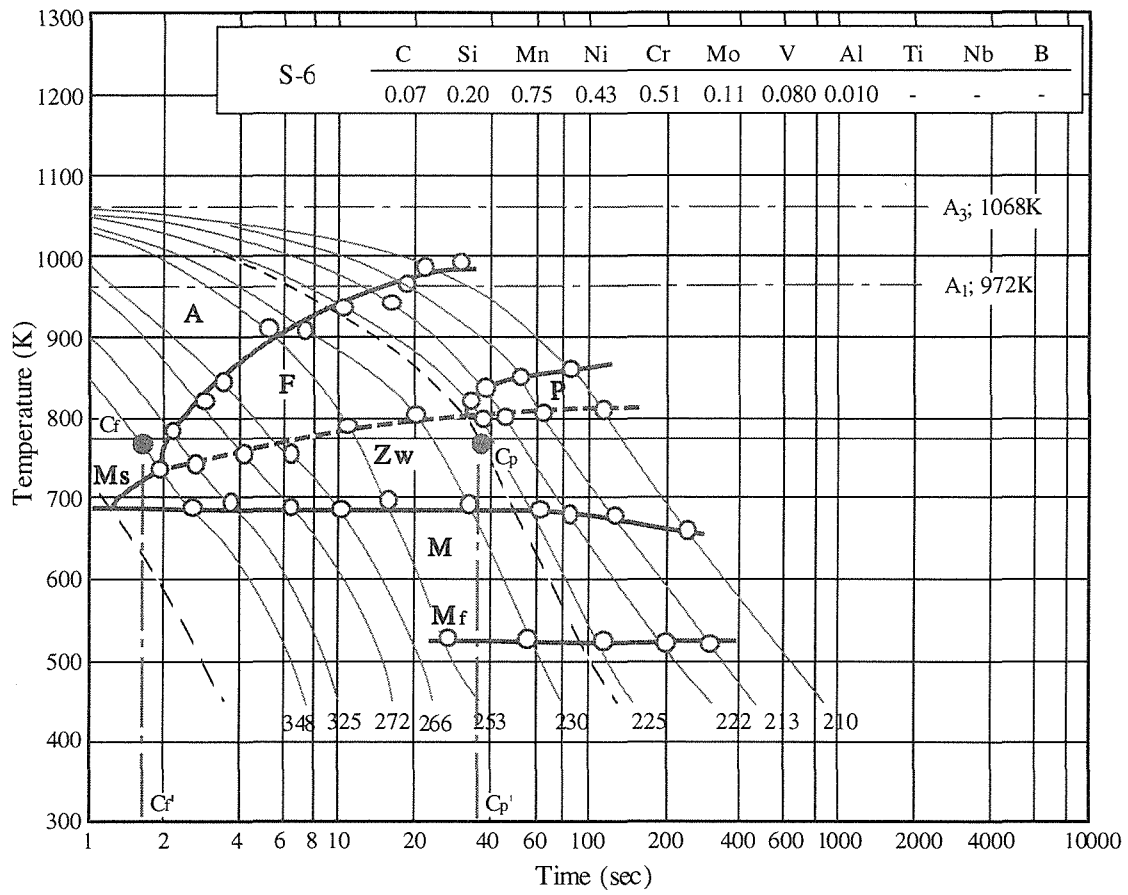


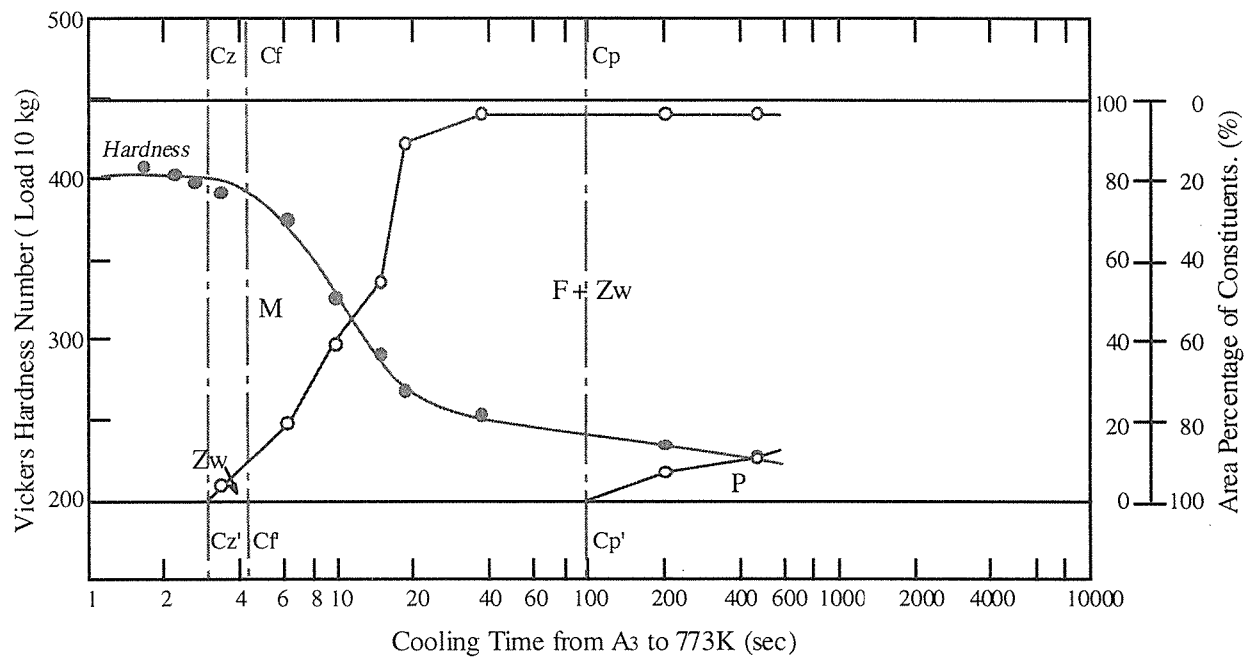
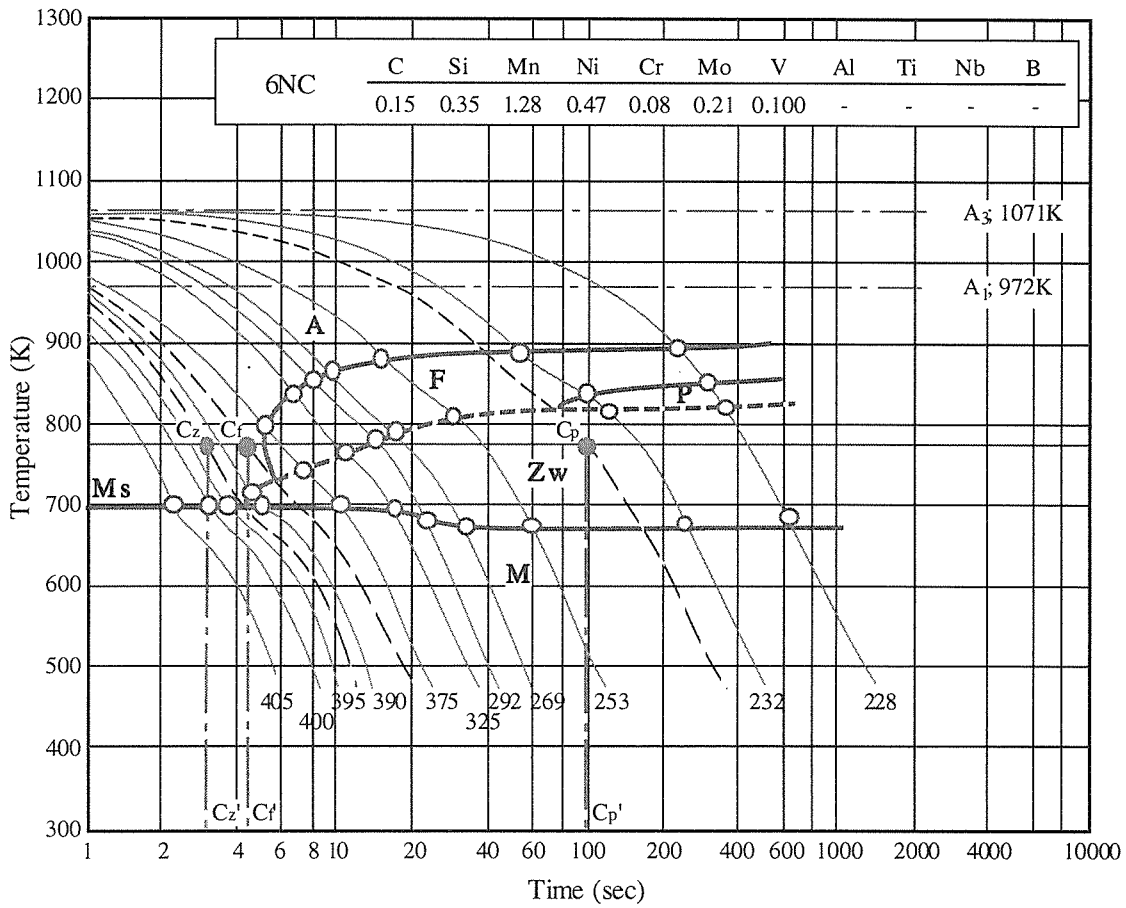


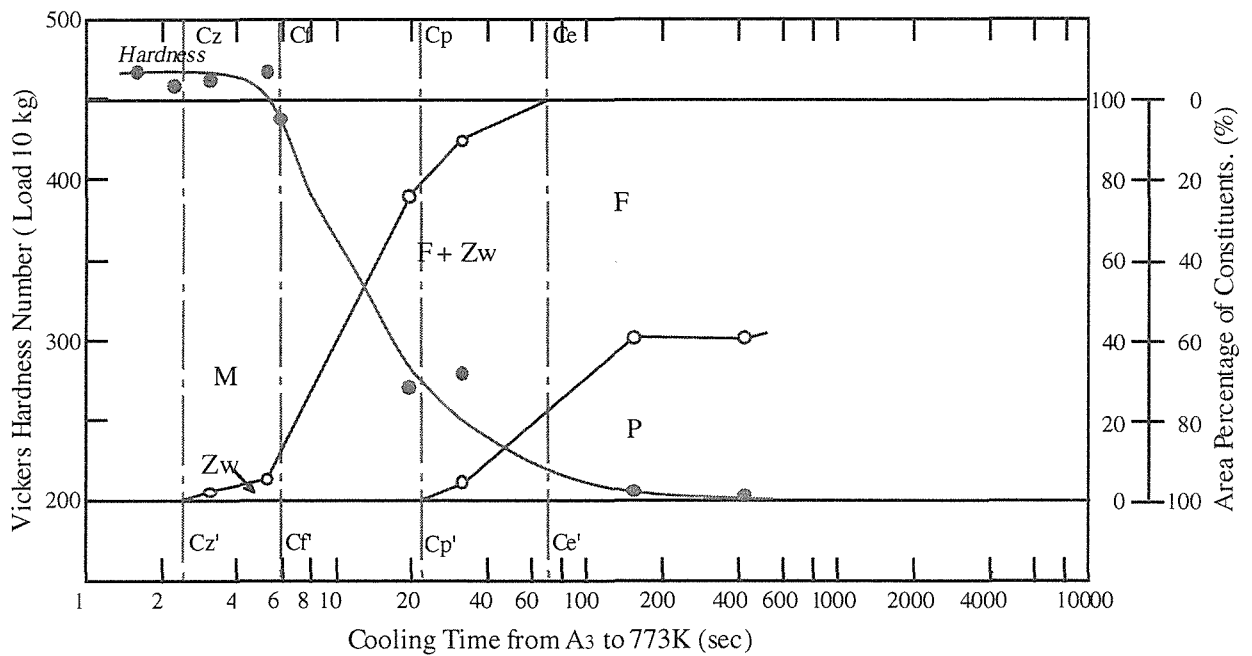
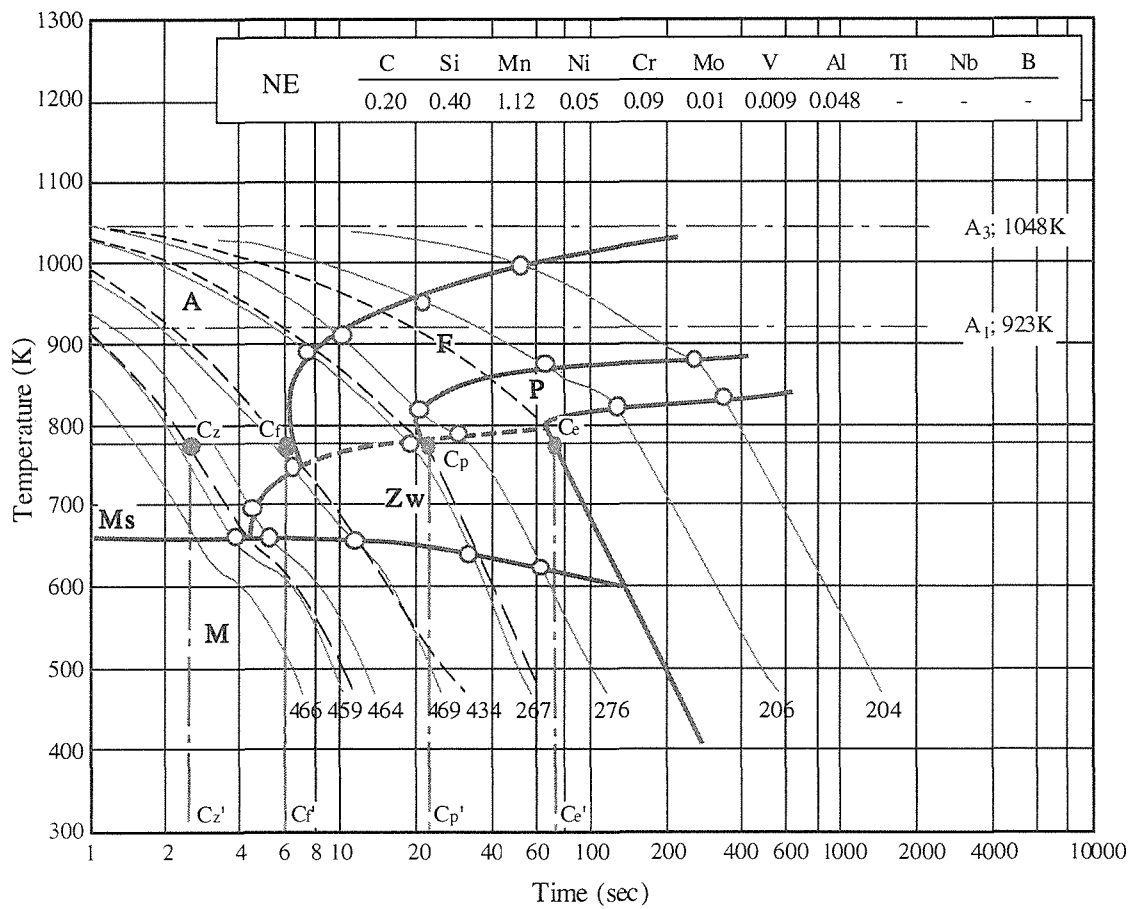


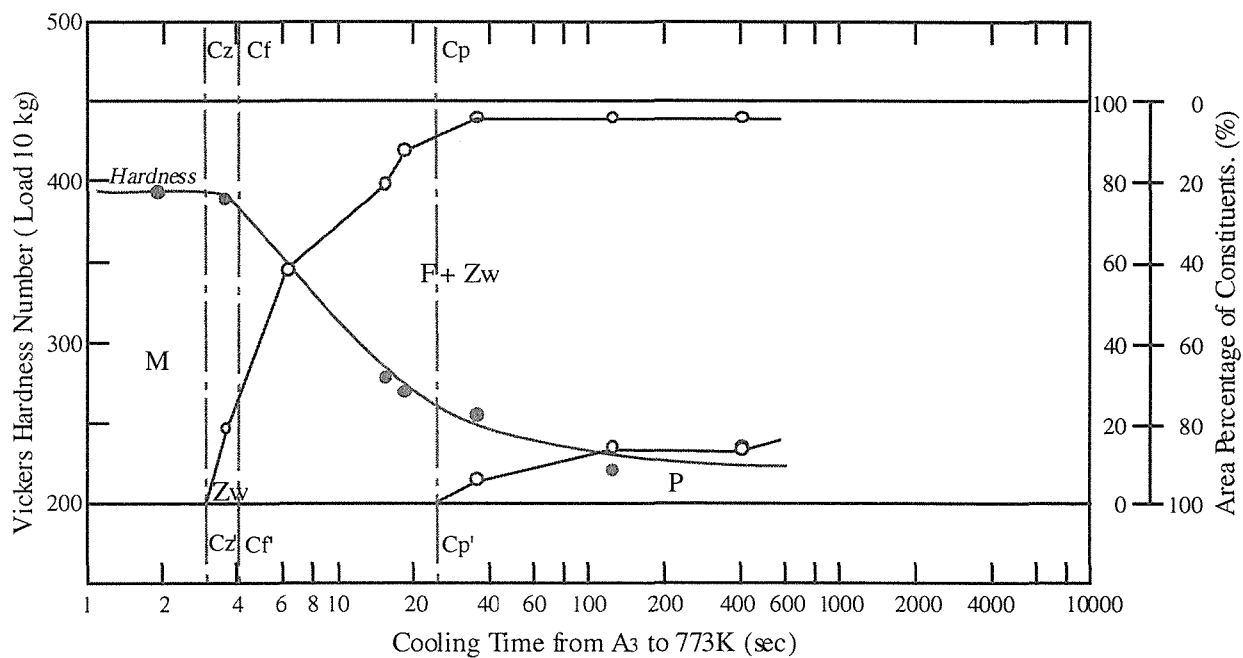
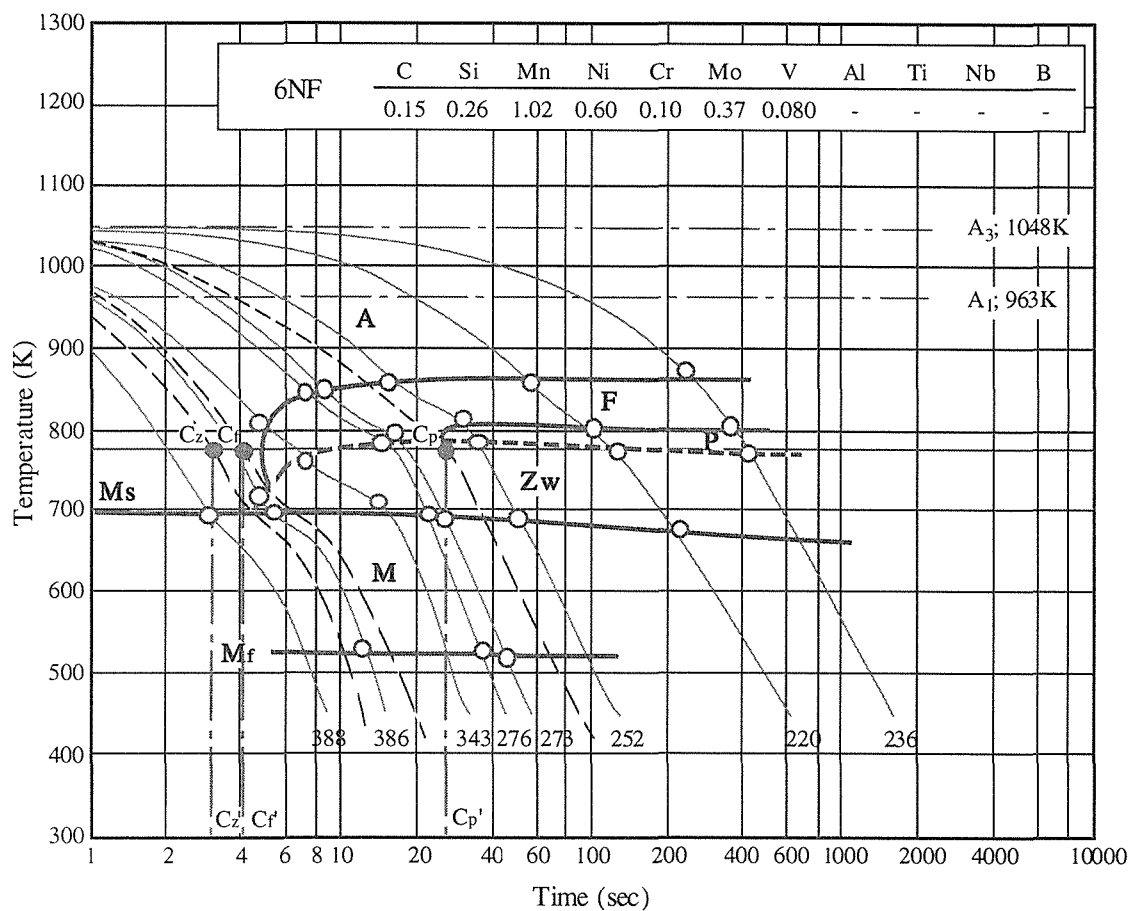


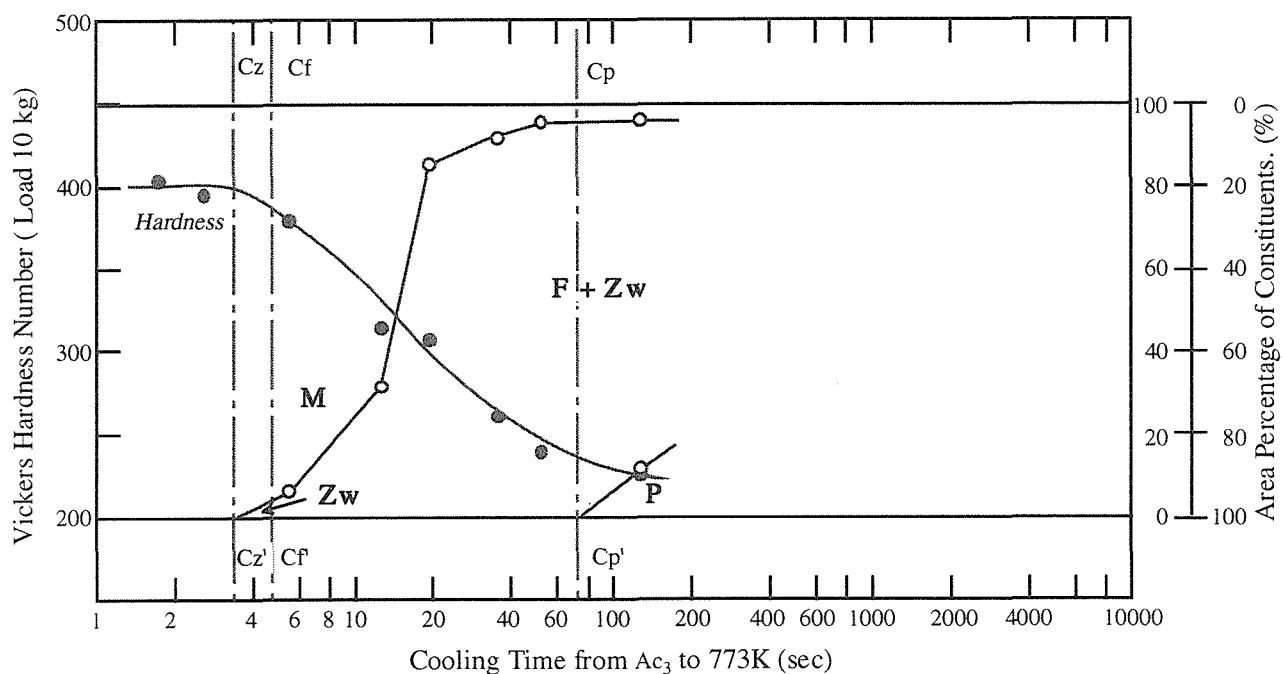
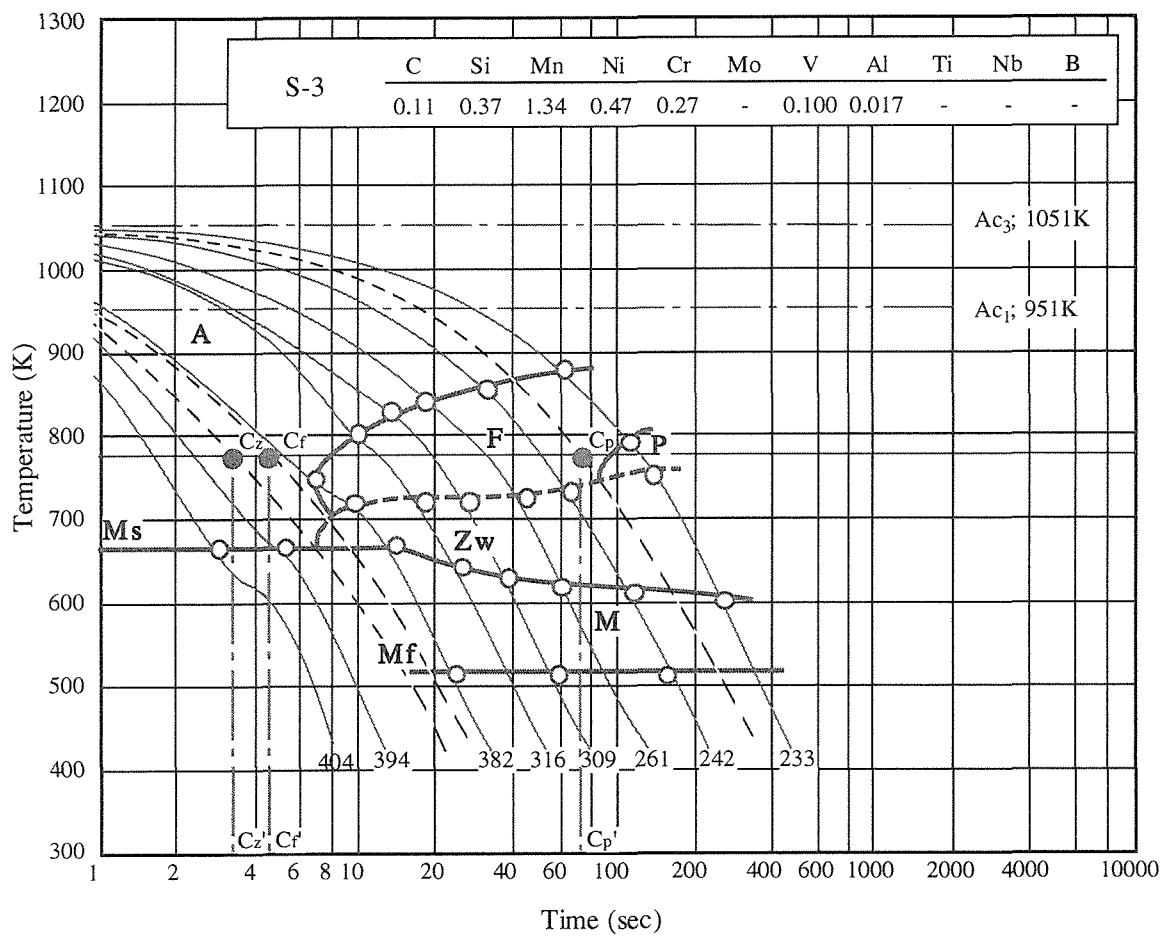


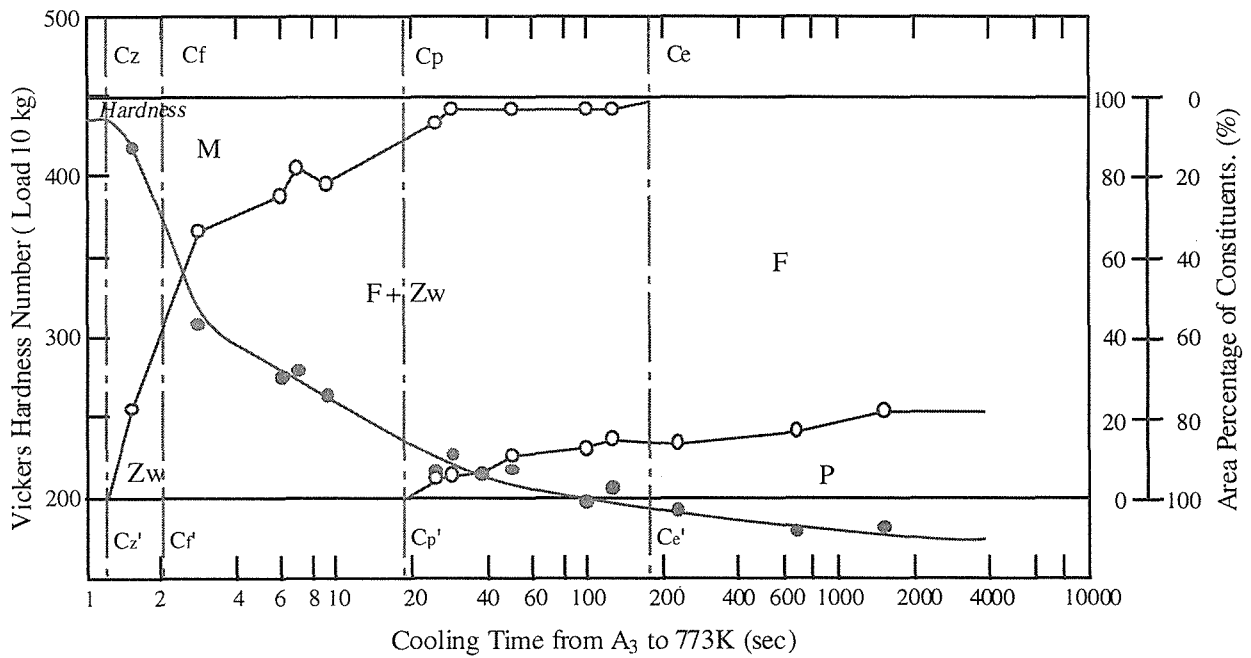
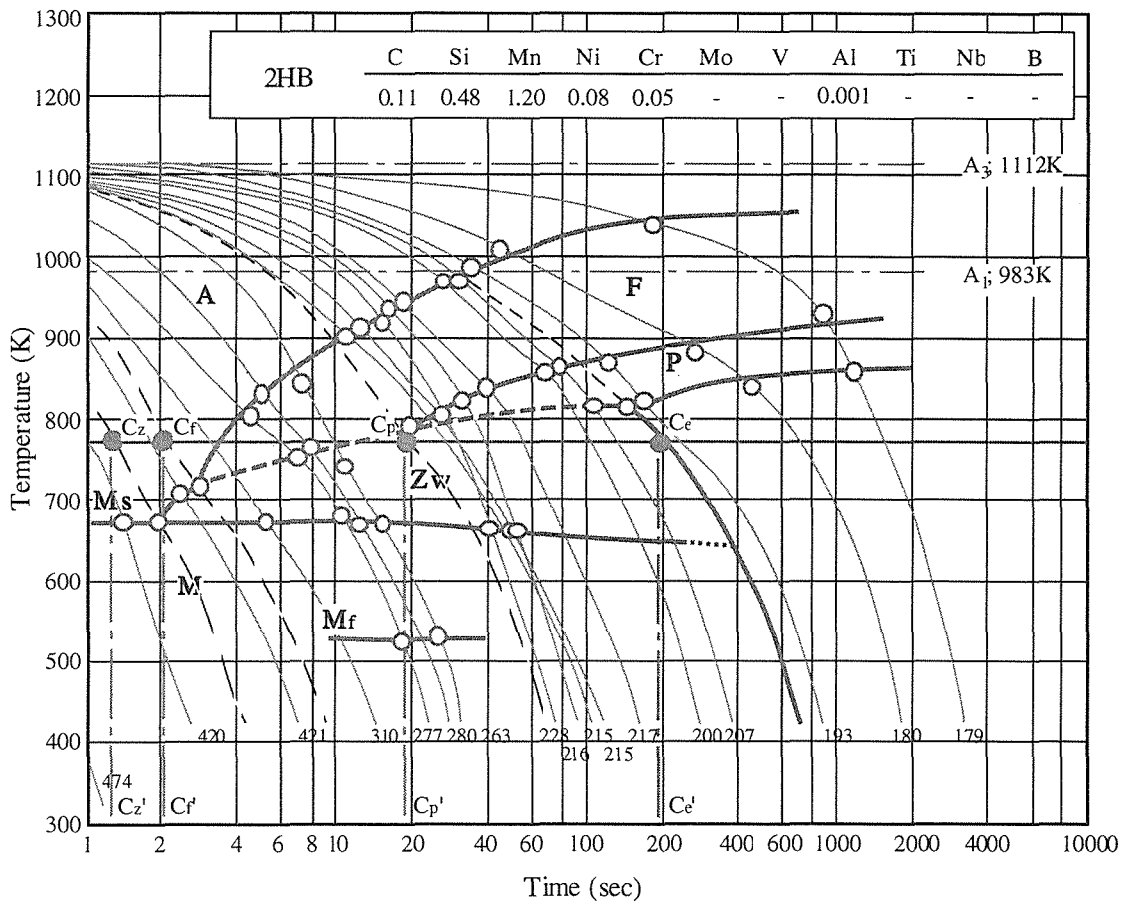


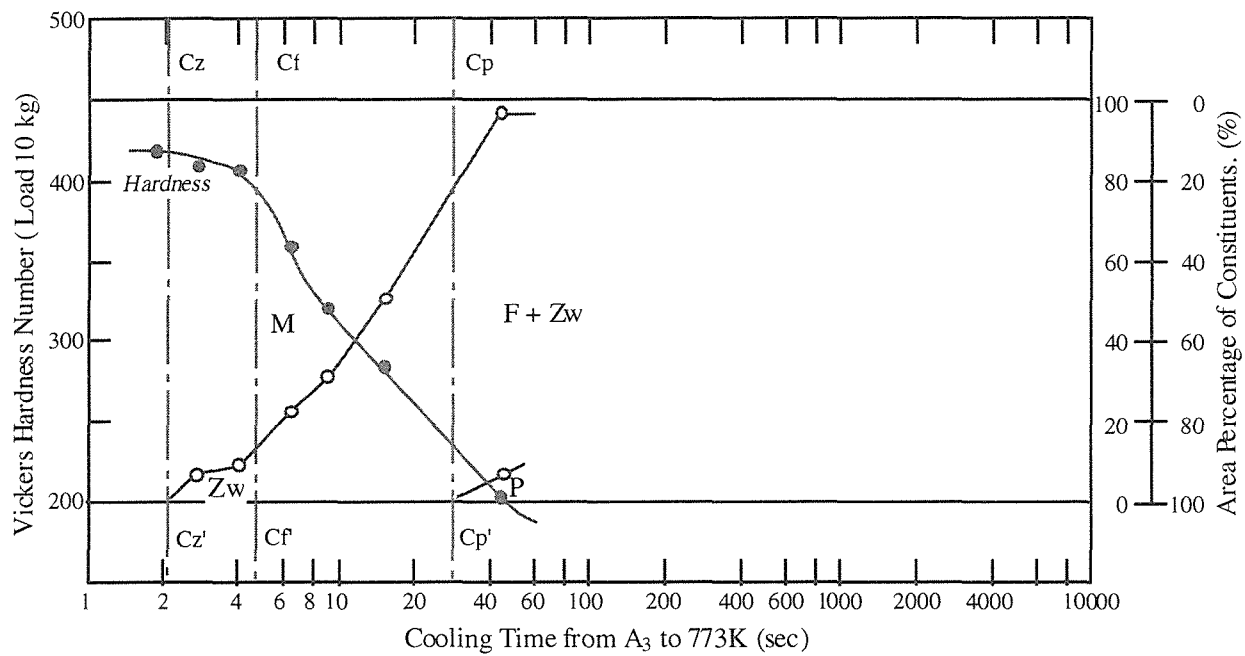
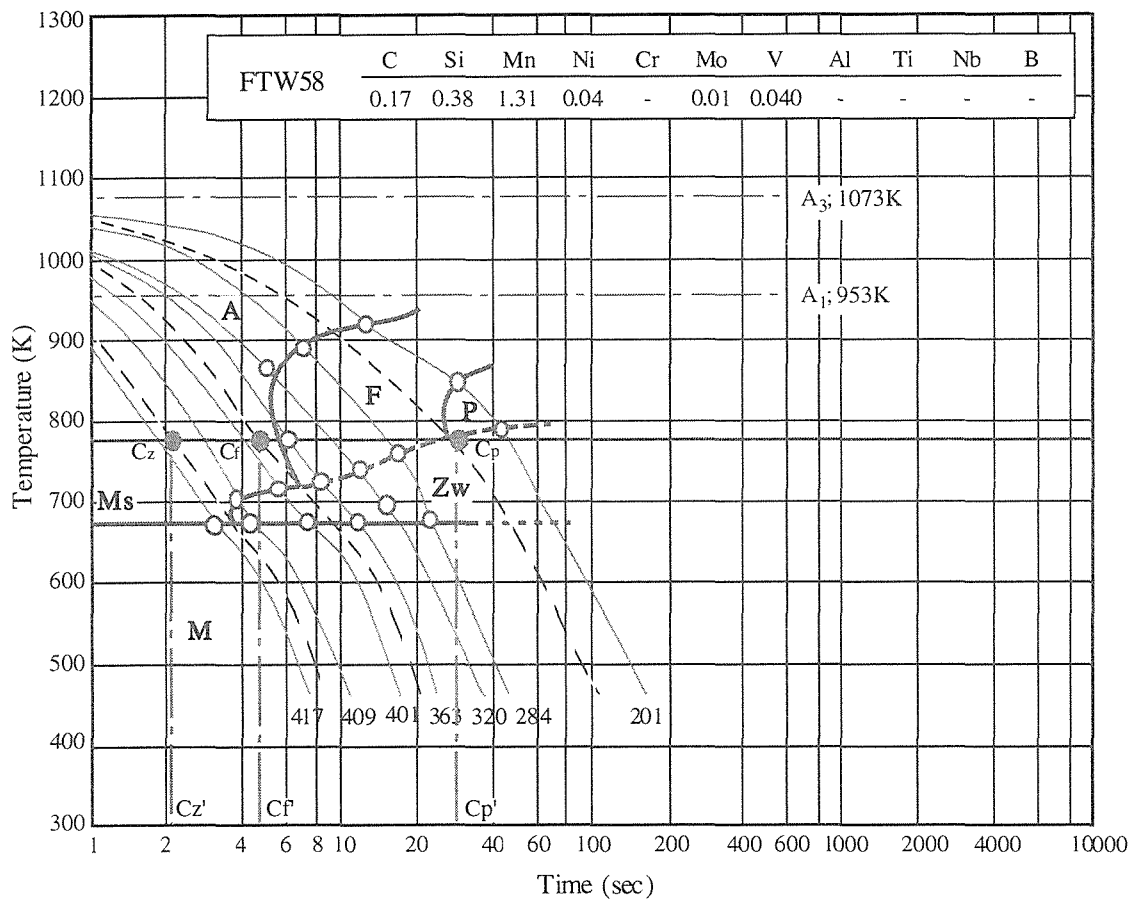


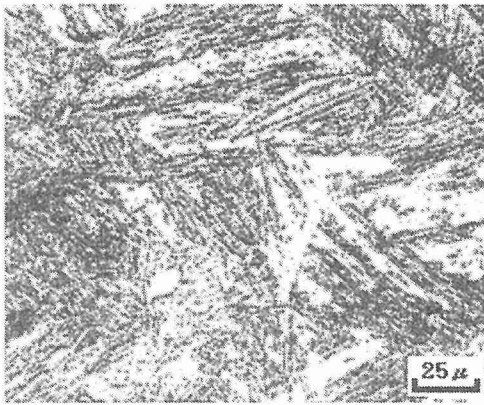




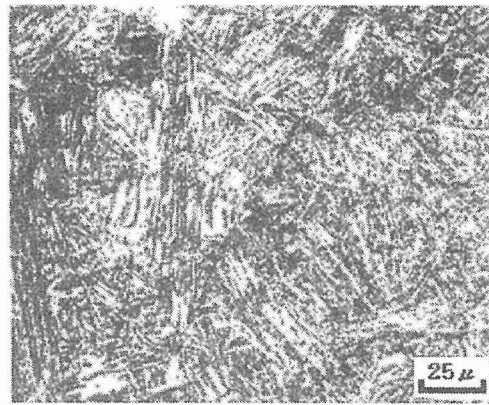








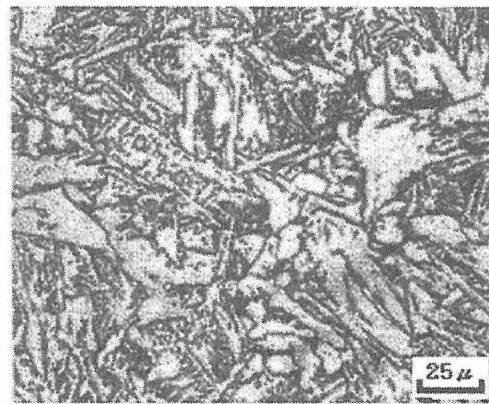
Time 1.8sec Hv 417



Time 6sec Hv 363



Time 16sec Hv 284



Time 43sec Hv 201

