New Extremely Low Carbon Bainitic High-Strength Steel Bar Having Excellent Machinability and Toughness Produced by TPCP Technology*



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Synopsis:

A non heat-treated high strength steel bar for machine structural use through a thermo-mechanical precipitation control process (hereafter, referred to as TPCP) has been developed. The newly developed TPCP is a technique for controlling the strength of the steel by precipitation hardening effected with the benefit of an extremely low carbon bainitic microstructure. The carbon content of the steel is decreased to below 0.02 mass% for realizing the proper microstructure, which improves both the notch toughness and machinability. In order to make the microstructure bainitic and to obtain effective precipitation hardening, some micro-alloying elements are added. The developed steel manufactured with these advanced techniques showed a higher impact value, higher yield strength and better machinability than those of the quenched and tempered AISI 4137 steel. The impact value of the steel is 250 J/cm^2 or more at room temperature. The problem of the reduction in yield ratio, inherent to non heat-treated steel, was overcome by strengthening the extremely low carbon single-phase bainitic microstructure with Cu precipitation which was minutely dispersed by nano order in the matrix structure, attaining the high levels of 85% or more in yield ratio of the steel. The considerable improvement of the durability of the tools, leading to the significant advantages of machinability through the suppression of the abrasion of tools, was also achieved.

1 Introdution

In the fields of automobiles and industrial machines where carbon steels and low alloy steels are used, the application of non heat-treated steels (non quench-tempered steels) has been carried out to reduce costs and lead time.[1)] As a result, machine components with a tensile strength in the 700 to 900 MPa class that were fabricated from quenched and tempered carbon steels for machine structural use have, for the most part, come to be fabricated from non heat-treated steels.

Although most of these non heat-treated steels are 0.2 to 0.5 mass%C ferrite-pearlite steels strengthened by V carbonitrides,[2–4)] these steels have low toughness and their applications are limited. Furthermore, although non heat-treated bainitic steels that can provide higher strength and toughness than ferrite-pearlite steels have been developed,[5–7)] because of their low yield ratio and great mass effect, the sizes of machine components to which they are applied are limited, thus posing a problem. Therefore, these non heat-treated bainitic steels has little practical use.

At Kawasaki Steel, non heat-treated steels which can overcome these disadvantages of conventional steels and which are stronger and tougher than conventional steels were examined[8)] on the bases of findings related to extremely low carbon bainitic steels, and a new structure control technique called the TPCP (thermo-mechanical precipitation control process) was developed.[9)] Moreover, a new extremely low carbon non heat-treated bainitic steel that can replace quench-tempered low-alloy steels for machine structural use and has better properties than these steels was developed by applying this TPCP.

The basic concept of the TPCP is to select a steel structure in which the cooling rate dependence of the microstructure is extremely low and to strengthen the steel by precipitation control, and not by cooling control

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as before. A non heat-treated steel obtained by this technique has excellent strength-toughness balance and machinability.

This article describes the metallurgical features of the TPCP technology and the properties of an 800 MPa class non heat-treated steel for machining developed by using this technology.

2 TPCP Technology

The basic concept of the TPCP technology is to select a steel structure in which the cooling rate dependence of the microstructure is extremely small and to control strength by controlling precipitation. In this chapter, the principal techniques of the TPCP, microstructure control and precipitation control, are described.

2.1 Microstructure Control

In the TPCP it is important to obtain a uniform microstructure that has small cooling rate dependence after hot deformation. By lowering the carbon content of steel to less than 0.02 mass% at which carbon partition does not occur during austenite to ferrite transformation and by optimizing other alloying elements, it is possible to obtain a uniform, extremely low carbon bainitic microstructure that has small cooling rate dependence.

Table 1 shows typical chemical compositions of AISI 4137—a general low alloy steel—and of an extremely low carbon bainitic steel. The continuous cooling transformation diagrams of these steels are shown in **Fig. 1**. In AISI 4137, the microstructure changes from martensite to ferrite-pearlite as the cooling rate decreases, and hardness also changes greatly from Hv567 to Hv219 as the microstructure changes.

On the other hand, the extremely low carbon bainitic steel undergoes little change in its microstructure even when the cooling rate changes. That is, when the cooling rates is greatly high or low, bainitic ferrite ($\alpha_B°$)[10] or quasi-polygonal ferrite (α_q),[10] respectively, is formed. However, because the principal part of the microstructure is granular bainitic ferrite (α_B),[10] the change in hardness, from Hv225 to Hv174, is very small compared with AISI 4137 in wide range of cooling rates. Thus, by applying an extremely low carbon bainitic steel it is possible to ensure uniform strength within the section even in a heavy gauge steel products.

The relationship between the transformation starting temperature and hardness of the extremely low carbon bainitic steel is shown in **Fig. 2**. Because the hardness of the extremely low carbon bainitic steel is unequivocally determined by the transformation starting temperature,[11] hardness control, i.e., strength control is possible by controlling the transformation starting temperature by adjusting the amounts of alloying elements.

According to recent researches, extremely low carbon bainitic steels show excellent strength-toughness balance,[8] and, unlike conventional non heat-treated steels, it can achieve notch toughness that is equal to or better than that of quench-tempered low alloy steels.

2.2 Precipitation Control Technique

In the TPCP, a precipitation control technique is important for achieving target strength. Because carbides are not formed in the extremely low carbon bainitic steel, it is necessary to select precipitates other than carbides. Although Cu is known as an effective precipitation hardener of steel, it has a generally been used in a quenching process followed by aging treatment,

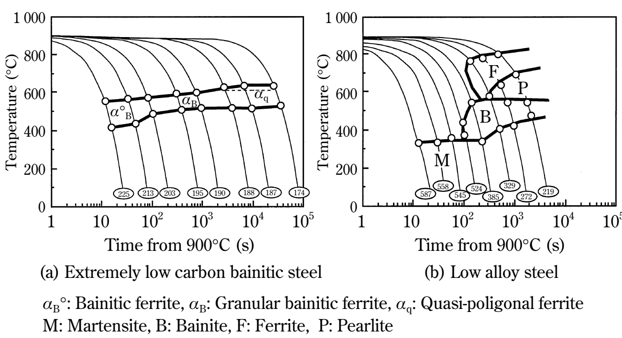


Fig. 1 CCT diagram of extremely low carbon bainitic steel and conventional low alloy steel

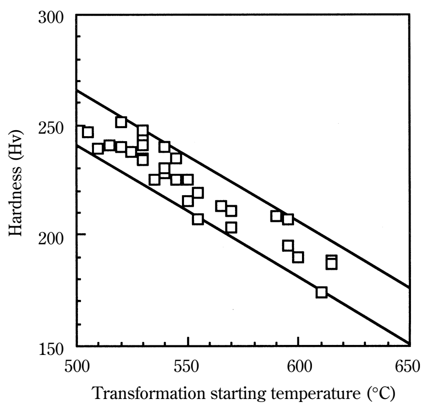


Fig. 2 Relationship between transformation starting temperature and hardness of the extremely low carbon bainitic steel

Table 1 Chemical compositions of steels examined

(mass%)

Steel	C	Si	Mn	P	S	Al	Cr	Mo	Others
Extremely low carbon bainitic steel	0.009	0.26	1.99	0.015	0.015	0.034	Tr.	Tr.	Nb, Ti, B
Conventional low alloy steel (AISI 4137)	0.34	0.22	0.80	0.016	0.014	0.026	1.08	0.21	—

such as with maraging steels.[12–14)] In order to apply the age hardening effect of Cu to non heat-treated steels, attention was paid to the precipitation hardening phenomenon of Cu in the cooling process after rolling.

Figure 3 shows changes in hardness that occur when the extremely low carbon bainitic steel is cooled at various rates after heating to 1 100°C. In a steel not containing Cu, hardness tends to decrease with decreasing cooling rate. The behavior of Cu-bearing steels is such that at cooling rates of less than 1°C/s, hardness increases with decreasing cooling rate. **Photo 1** shows TEM micrographs of Cu precipitates in 2 mass% Cu steel for cooling rates of 0.4°C/s, 0.04°C/s and 0.01°C/s. The results of TEM observation of the specimens are shown in Photo 1. According to the micrographs, at 0.4°C/s no contrast of Cu precipitates was obtained at all, a weak strain contrast was observed at 0.04°C/s at which maximum hardness was shown, and at 0.01°C/s heterogeneous nucleation of coarse ε-Cu occurred along dislocations.

Furthermore, fine structure analysis of these specimens was carried out by three-dimensional atom probe (3DAP). According to the results of this analysis, which are shown in **Fig. 4**,[15)] clusters of Cu atoms (GP zones) were already present in the specimen cooled at 0.4°C/s and a considerable number of Cu atoms existed in the matrix in a solid solution state. And in the specimen of the maximum hardness cooled at 0.04°C/s, clusters (GP

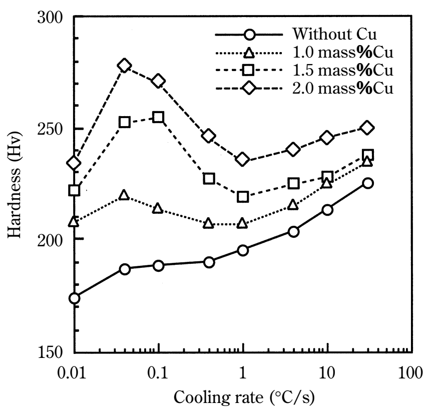


Fig. 3 Effect of cooling rate and Cu content on hardness of extremely low carbon bainitic steels

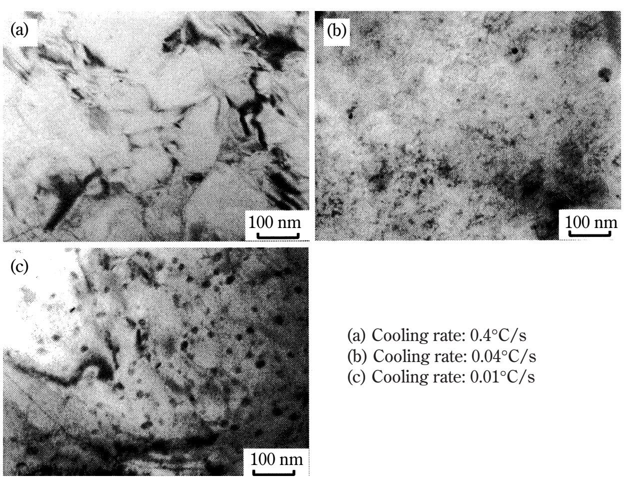


Photo 1 TEM micrographs of Cu precipitates in Cu-bearing extremely low carbon bainitic steel

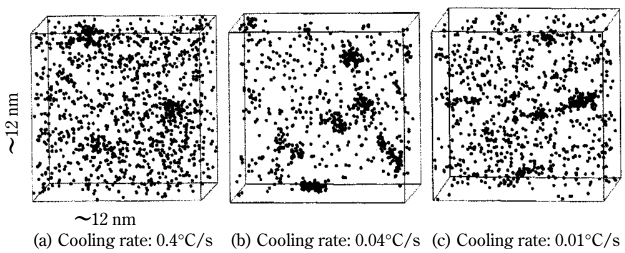


Fig. 4 3DAP Cu maps of Cu-bearing extremely low carbon bainitic steels with different cooling rates

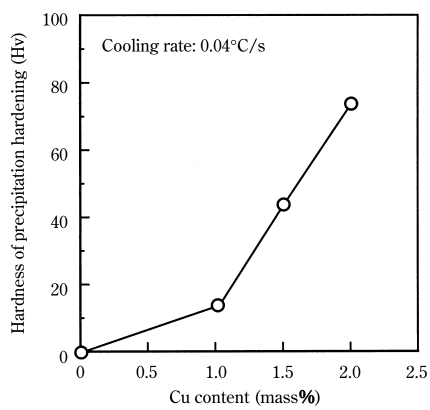


Fig. 5 Effect of Cu content on precipitation hardening on self-aging process

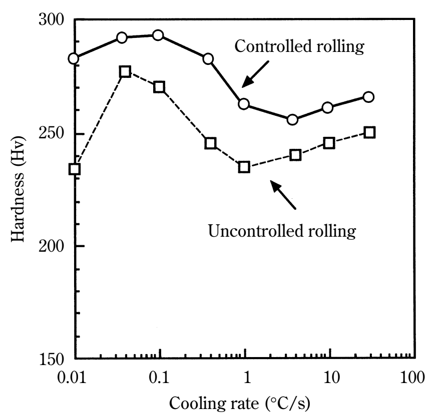
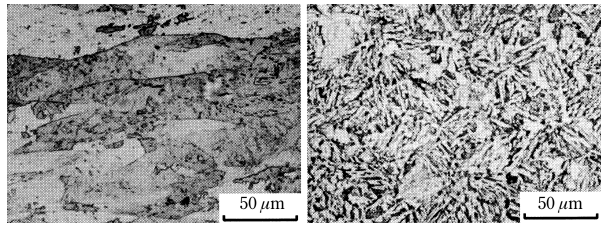


Fig. 6 Relationship between cooling rate and hardness of Cu-bearing extremely low carbon bainitic steels

zones) of higher density than those of the specimen cooled at 0.4°C/s were observed.

The effect of the Cu content on the hardness of precipitation hardening is shown in **Fig. 5**. The hardness of precipitation hardening is unequivocally determined by the Cu content. The cooling rate dependence of hardness in the case of controlled rolling is shown in **Fig. 6**.[16] By performing precipitation control by optimizing hot working conditions it is possible to ensure almost constant strength in a wide cooling rate range.

Thus, if precipitation is controlled in TPCP by both simultaneously selecting the amount of added precipitation hardener according to the strength level and selecting hot working conditions, almost constant strength can be ensured in a wide cooling rate range.



(a) TPCP steel (b) Quench-tempered AISI 4137

Photo 2 Optical microstructures of the TPCP steel bar and the quench-tempered AISI 4137 at the distance of 1/4 diameter from the surface rolling direction

3 Properties of Developed Steel

An 800 MPa class high-toughness non heat-treated steel that can replace the quench-tempered steel AISI 4137 for large bars was thus developed by applying the TPCP technology. The properties of developed steel are described below.

3.1 Chemical Composition and Microstructure

Table 2 shows the chemical compositions determined from ladle analysis for the developed steel and AISI 4137. In the developed steel, the C content was lowered to less than 0.02 mass% and other alloying elements were optimized in order to produce a uniform, extremely low carbon bainitic microstructure that has small cooling rate dependence. Furthermore, Cu was added as a precipitation hardener in order to obtain the same strength as the quench-tempered steel for large bars AISI 4137.

The developed steel was produced in the basic oxygen furnace-continuous casting process and control-rolled into steel bars with a diameter of 190 mm. The steel AISI 4137 was produced by the same process and rolled into bars with a diameter of 190 mm. After that, the bars were subjected to quenching and tempering treatment.

Photo 2 shows the microstructures of the steel bars at the distance of 1/4 diameter from the surface in the rolling direction. The developed steel had an α_B microstructure, which is classified as an extremely low carbon bainitic microstructure, and the microstructure of AISI 4137 was classic tempered upper bainite.

3.2 Mechanical Properties

The results of tensile tests for the developed steel and quench-tempered AISI 4137 are shown in **Table 3**. The developed steel showed a 0.2% proof stress of 680 MPa or more and a tensile strength of 810 MPa or more and better properties than the quench-tempered AISI 4137 in both elongation and reduction of area. Especially noteworthy is the fact that the developed steel has a yield ratio of 85% or more although it is a non heat-treated steel.

The results of a Charpy impact test on 2 mm U-notched specimens are shown in **Fig. 7**. The developed steel has upper shelf impact values of 300 J/cm^2 or more and a fracture transition temperature of −40°C, showing excellent toughness.

S-*N* diagrams obtained by a rotating banding fatigue test are shown in **Fig. 8**. Because of high yield strength due to precipitation hardening the developed steel has

Table 2 Chemical compositions of steels examined

(mass%)

Steel	C	Si	Mn	P	S	Al	Cr	Mo	Others
TPCP steel	0.007	0.24	2.01	0.015	0.016	0.036	Tr.	Tr.	Cu, Ni, Nb, Ti, B
AISI 4137	0.34	0.22	0.80	0.016	0.014	0.026	1.08	0.21	—

Table 3 Mechanical properties of the TPCP steel bar and the quench-tempered AISI 4137

Steel	Position	0.2%PS (MPa)	TS (MPa)	YR (%)	El (%)	RA (%)
TPCP steel	Surface*	730	840	87	26	74
	1/4*D*	708	818	87	25	72
	1/2*D*	689	813	85	22	66
Quench-tempered AISI 4137	Surface*	644	820	79	23	62
	1/4*D*	638	811	79	22	59
	1/2*D*	636	807	79	20	52

*15 mm inside from surface

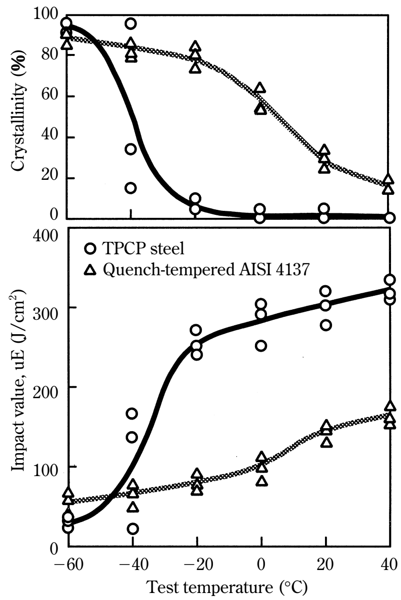


Fig. 7 Temperature dependence of Charpy impact value and crystallinity of the TPCP steel and the quench-tempered AISI 4137

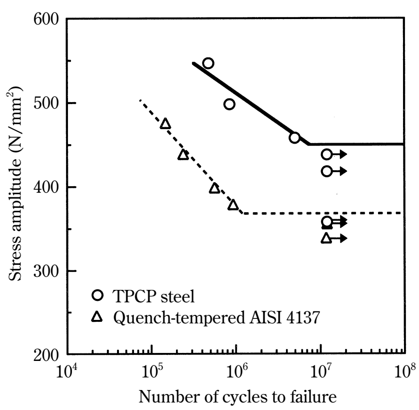


Fig. 8 *S-N* diagrams of the TPCP steel and the quench-tempered AISI 4137

higher fatigue strength than the quench-tempered AISI 4137. The relationship between tensile strength and the fatigue limit of the developed steel in the rotating banding fatigue test is compared in **Fig. 9** with that of the quench-tempered steel for machine structural use.[17] The data shows that the developed steel has higher fatigue limit.

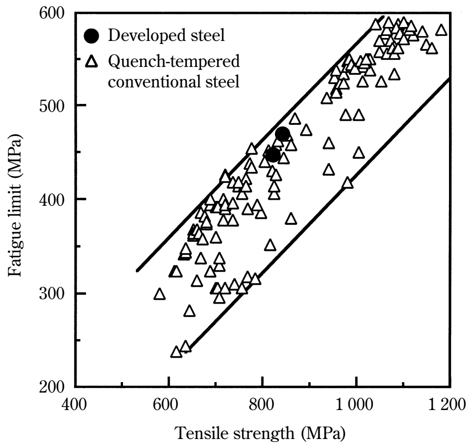


Fig. 9 Relationship between tensile strength and fatigue limit in a rotating bending fatigue test

Table 4 Conditions of turning test

Item	Condition
Tool	Sintered carbide, JIS-P10
Cutting speed (m/min)	200, 250, 300
Cutting depth (mm)	2
Feed (mm/rev)	0.25
Lubricant	Dry
Criterion for tool life	Flank wear (V_B) = 0.1 mm

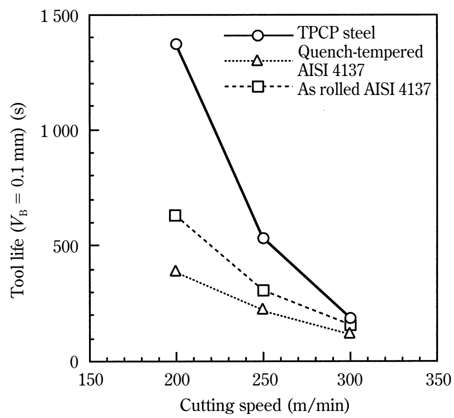


Fig. 10 Relationship between tool life in turning test and cutting speed of TPCP steel, as rolled AISI 4137, and quench-tempered AISI 4137

3.3 Machinability

In order to evaluate the machinability of the developed steel, a turning test was conducted using a lathe under the conditions shown in **Table 4**, in which a sintered carbide tool was used. Tool life was defined as the time it took for the flank wear of the tool tip to reach 0.1 mm.

Fig. 10 shows the effect of cutting speed on the tool life of the developed steel, quench-tempered AISI 4137 and as-rolled AISI 4137. The developed steel showed a very long tool life and had, in an as-rolled state, strength and toughness equal to or better than the quench-tempered AISI 4137. **Photo 3** shows the microstructures of these steels under a scanning electron microscope. Because hard cementite that promotes the abrasive wear of tools does not exist in the developed steel the developed steel shows excellent tool wear characteristics.

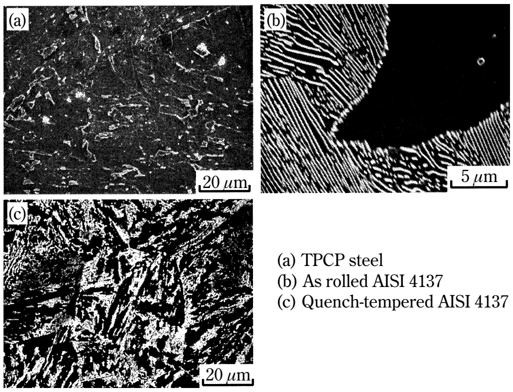


Photo 3 SEM micrographs of TPCP steel, as rolled AISI 4137, and quench-tempered AISI 4137

3.4 Repair Weldability

A maximum hardness test (JIS Z 3101) of heat affected zone (HAZ) was conducted in order to compare the hardenability of base steel after the welding repair of dents on bar surfaces. The welding conditions used in the test are shown in **Table 5**. The hardness distributions of the HAZ of the developed steel and quench-tempered AISI 4137 are shown in **Fig. 11.** In AISI 4137 the maximum hardness of HAZ is more than twice that of the base steel, whereas in the developed steel the HAZ did not harden at all. Therefore, in the case of the developed steel, it is unnecessary to conduct preheating before repair welding or special heat treatment after welding, thus providing the advantage that cutting can be performed without modifying the steel.

Table 5 Conditions of maximum hardness test

Item	Condition
Method	Bead on plate
Shield gas	Ar + 20%CO_2, 20 /min
Welding wire	JIS Z 3313 YGW23 (KM-60)
Current (A)	300
Voltage (V)	34
Welding speed (mm/s)	5
Heat input (kJ/mm)	2

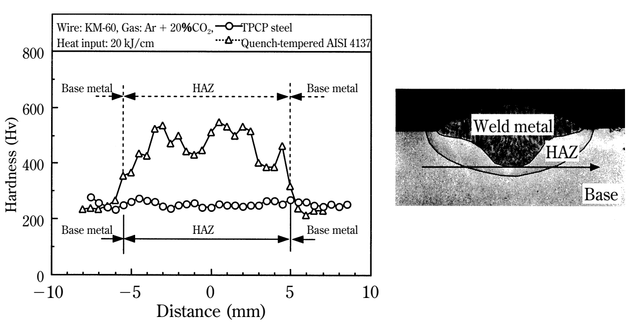


Fig. 11 Hardness distributions of the heat affected zone of the TPCP steel and quench-tempered AISI 4137

4 Conclusions

By applying the TPCP technology, Kawasaki Steel succeeded in manufacturing a high strength, high toughness, highly machinable non heat-treated bar steel and put it into practical application. The characteristics of the developed steel are as follows:

(1) The developed steel has a yield strength of 680 MPa or more and tensile strength of 810 MPa or more when it is formed into large steel bars with a diameter of 190 mm.
(2) The developed steel has upper shelf impact values of 300 J/cm^2 or more and a fracture transition temperature of −40°C, providing excellent toughness.
(3) The rotating bending fatigue strength of the developed steel is 450 MPa, better than that of quench-tempered AISI 4137.
(4) Because the microstructure of the developed steel does not contain hard cementite that promotes tool wear, the life of tools made of this steel is longer than as-rolled AISI 4137 and quench-tempered AISI 4137.
(5) The developed steel has excellent welding preperties in that no increase of hardness in HAZ is observed.

The developed steel can replace quench-tempered AISI 4137 and has made it possible to reduce energy consumption and costs in the manufacturing process of machine structural components. Furthermore, because the developed steel has excellent toughness, it was given a certificate of classification by the Japan Marine Surveyors and Sworn Measurers' Association.

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References

1) H. Kojima: *CAMP-ISIJ*, **5**(1992), 772–776, (in Japanese)
2) Y. Otani and F. Nakazato: *Tetsu-to-Hagané*, **68**(1982), S1279, (in Japanese)
3) T. Yamamoto, T. Aizawa, Y. Yokomizo, and K. Fukui: *Tetsu-to-Hagané*, **70**(1984), S512, (in Japanese)
4) K. Takada, T. Ochi, Y. Koyasu, and Y. Ishikawa: *CAMP-ISIJ*, **5**(1992), 777–780, (in Japanese)
5) N. Iwama, T. Tsuzaki, T. Maki, I. Nomura, Y. Hanai, and T. Yamamoto: *CAMP-ISIJ*, **5**(1992), 801–804, (in Japanese)
6) T. Ishizaki, T. Shiraga, T. Sanpei, and K. Matsumoto: *CAMP-ISIJ*, **5**(1992), 793–796, (in Japanese)
7) M. Katsumata, O. Matsumoto, O. Ishiyama, A. Inoue, M. Nakamura, Y. Matsushima, and Y. Nakatani: *CAMP-ISIJ*, **5**(1992), 805–808, (in Japanese)
8) M. Okatsu, T. Hayashi, and K. Amano: *Kawasaki Steel Giho*, **30**(1998)3, 131–138, (in Japanese)
9) K. Amano, F. Kawabata, T. Hoshino, O. Tanigawa, and H. Imamura: *Materia*, **39**(2000), 184–186, (in Japanese)
10) "Atlas for Bainitic Microstructures Vol. 1", Bainite Committee of Iron & Steel Institute of Japan, Tokyo(1992), 4, (in

Japanese)
11) K. Hase, T. Hoshino, and K. Amano: *CAMP-ISIJ*, **12**(1999), 478, (in Japanese)
12) E. A. Wilson: *J. of Iron and Steel Inst*., **206**(1968), 164–168
13) K. Osamura, H. Okuda, S. Ochiai, M. Takashima, K. Asano, M. Furusaka, K. Kishida, and F. Kurosawa: *ISIJ Int.*, **34** (1994), 359–365
14) Iain Le May and L. McDonald Schetky: "Cu in Iron and Steel", A Wiley-Interscience Publication, Canada(1982), 23–32
15) De Hai Ping, K. Hono, K. Hase, and K. Amano: *CAMP-ISIJ*, **14**(2001), 1230, (in Japanese)
16) K. Hase, T. Hoshino, A. Matsuzaki, and K. Amano: *CAMP-ISIJ*, **14**(2001), 1229, (in Japanese)
17) "Fatigue of Metals I (2nd Edition)", The Japan Society of Mechanical Engineers, Tokyo(1982), (in Japanese)