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Special Steel Bars and Wire Rods Contribute to Eliminate Manufacturing Processes of Mechanical Parts

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Abstract

Many mechanical parts, such as those used in automobiles, are manufactured in a forging process of special steel bars and wire rods in hot and cold temperature regions. Ordinarily, in these manufacturing processes, secondary processing such as machining and drawing before or after forging, and various heat treatment processes such as annealing or quenching and tempering are necessary. Because of that, there is strong demand to eliminating processes such as heat treatment processing in order to achieve cost reduction and energy savings. This paper outlines the efforts of Nippon Steel Corporation with regard to eliminating manufacturing processes of mechanical parts that use the three types of special steel bars and wire rods of bolt steel, softened cold forging steel and high strength micro-alloyed steel for hot forging.

1. Introduction

Many mechanical parts, such as those used in automobiles, are manufactured in a hot and cold forging process of special steel bars and wire rods. One of the current large issues regarding the steel for forging for use in automobiles is the elimination of processes. Normally, before and after forging, secondary processing such as drawing, machining and various heat treatment processes such as annealing, quenching and tempering are necessary in the manufacturing of mechanical parts by forging. For that reason, there is a strong demand for eliminating heat treatment and machining from the viewpoint of reducing costs and conserving energy. The movement of eliminating machining is called "near-net shape" or "chip-less manufacturing".

This paper outlines the efforts of Nippon Steel Corporation aimed at eliminating manufacturing processes of mechanical parts using the three types of special steel bars and wire rods of bolt steel, softened cold forging steel and high strength microalloyed steel for hot forging.

2. Boron Additive Bolts Steel for Grain-coarsening Prevention – FIRST Steel

Generally, bolts are manufactured by hot rolling medium carbon alloy steel such as JIS SCM 435 and spheroidizing annealing, then bolt shapes are formed by cold forging and quenched and tempered. In recent years, in order to reduce the costs of manufacturing bolts, there has been some acceleration in the movement to replace alloy steel with boron steel. Boron steel is a steel which is softened even after hot rolling by reducing the amounts of carbon and alloy elements, and its accompanying reduced hardenability is supplemented by a boron addition. It can reduce the amount of alloy elements added and omit the spheroidization annealing process, so it is the steel that can greatly reduce material and manufacturing costs. However, in comparison to alloy steel, boron steel causes the abnormal growth of specific austenite grains easily during heating for quench-hardening. Because this grain-coarsening easily occurs, it was difficult to apply to higher strength bolts than 8T (tensile strength 800 to 1,000 MPa) in which delayed fracture occurs.

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This paper outlines boron steel "FIRST steel" (FIRST: Fine-grain Retaining and Softened Steel) for use on bolts that prevent grain-coarsening that was developed against the background described above.

2.1 Method of preventing grain-coarsening of the FIRST steel

Gladman[1)] proposed the following equation for the critical conditions of the abnormal grain-coarsening.

$$r_{crit} = \frac{6R_0 f}{\pi}\left(\frac{3}{2} - \frac{2}{Z}\right)^{-1}$$

Here, r_{crit} is the critical precipitate particle radius, R_0 is the matrix grain radii, f is the volume fraction of the precipitate and Z is the ratio of radii of growing and matrix grains (R/R_0). The above equation shows when precipitate particle size (r) that is pinning grain boundary exceeds r_{crit}, the abnormal grain-coarsening occurs. The generation of grain-coarsening in bolt steel is easy to appear because cold forging makes the initial austenite grains of when heating for quench-hardening (normally 870 to 900°C) finer (R_0 is small) and the critical value for grain-coarsening is reduced (r_{crit} is small). The point for prevention of grain-coarsening is the large amounts of precipitate particle in the matrix and finely dispersed (f is large, and r is small).

To make precipitate particle fine, 1) the precipitate particle is dissolved once; 2) and a precipitation treatment then given after that are effective. When applying this method to actual processing, it is considered that: 1) the precipitates are once dissolved by heating for hot rolling process and; 2) then give a precipitation treatment in controlled cooling after the hot rolling or annealing process. AlN is generally used for the above method, but AlN cannot be used in the case of boron additive steel. Because, in boron steel, N is fixed by a Ti addition to suppress generation of BN, in order to stabilize the effect of improving hardenability by solution B, but as a secondary effect, it is also to suppress the generation of AlN. On the one hand, the solubility of TiN is extremely small and because it is substantially impossible to completely dissolve when heating for hot rolling, it is difficult to make it fine. For the above reason, boron steel causes grain-coarsening easily in comparison to alloy steels.

This development tried the use of TiC. **Fig. 1** shows the example of a calculation result using the Thermo-Calc which is an equilibrium calculation program of the phase diagram. Using this, 1) to increace the amount of Ti as Tic, it is necessary to reduce N content and; 2) it is necessary to raise the heating temperature for hot rolling to dissolve the TiC once. Further, it is desirable to reduce N as much as possible because N raises the dissolution temperature of Ti (CN).

2.2 Influence of manufacturing conditions on grain-coarsening behavior of FIRST steel

Fig. 2 shows the results of testing using actual manufacturing process based on the above considerations. It is known that as the heating temperature for hot rolling increases, the grain-coarsening temperature increases. It is considered that fine TiC that precipitates after hot rolling increased because TiC dissolves sufficiently at high temperatures. **Photo 1** shows an example of precipitates observed with TEM. It cannot be determined whether the precipitate is TiC or Ti (CN), but it can be seen that the precipitate is made fine through the high temperature heating. Furthermore, the slow cooling after hot rolling also increases the grain-coarsening temperature. It is considered that precipitation of fine TiC is sufficient because of slow cooling.

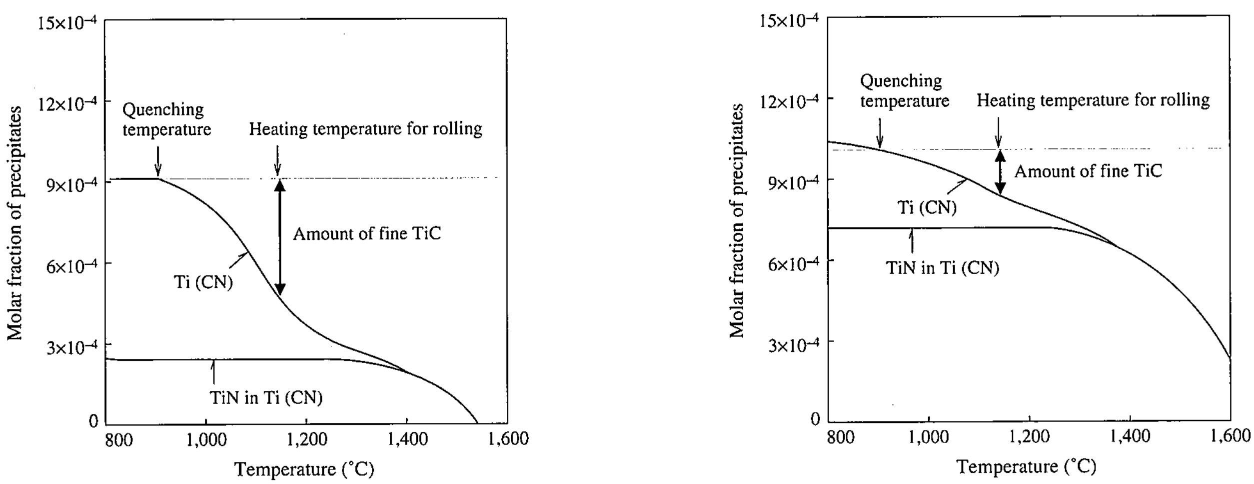
2.3 Cold forgeability of FIRST steel

Fig. 3 shows the relationship of the hardness of the rolled steel and its Ti content. As Ti content is increased, the hardness of the rolled steel increases due to the precipitation hardening of TiC and the cold forgeability degrades. Thus, in order to combine preventing grain-coarsening performance and cold forgeability, it is necessary to fully consider Ti and N content and their balance. **Fig. 4** shows the flow stress curve of FIRST steel. The cold forgeability of FIRST steel is equivalent to the spheroidized steel of SCM 435.

2.4 Delayed fracture resistance of FIRST steel

Table 1 shows an example of chemical composition of FIRST steel used in 10T class (tensile strength 1,000 to 1,200 MPa). Reducing P and S to increase grain boundary strength, increasing Cr content for improving the resistance of softening by tempering, and reducing Si and Mn to keep cold forgeability. **Fig. 5** shows the delayed fracture resistance of FIRST steel. As a delayed fracture test, we used a method that charged hydrogen to a notched specimen by electrolysis under constant load, creating a situation wherein hydrogen entered into the fastened bolt from the external environment. FIRST steel has better delayed fracture resistance than SCM 435.

As stated above, the application of FIRST steel is expanding not only from the 8T class but also to the 10T class, and it is considered that application to be expanded in the future because of its major economic effects.



(a) Low N steel (b) High N steel

Fig. 1 Influences of N content and temperature affecting solution behavior of Ti carbonitride (Presumed by Thermo-Calc)

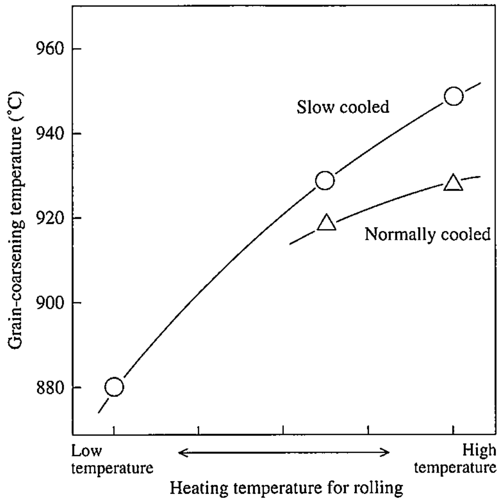


Fig. 2 Influence of rolling conditions affecting grain-coarsening temperature

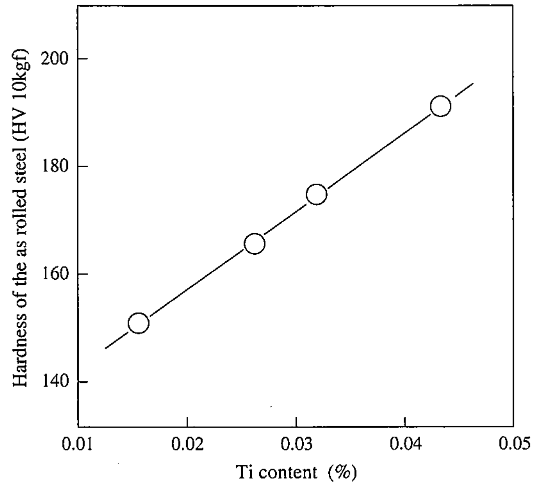
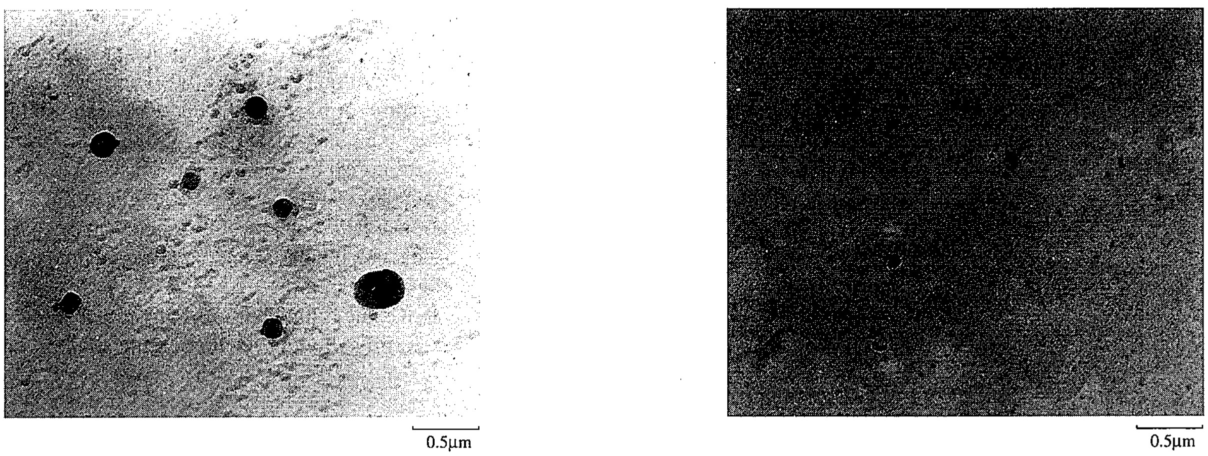


Fig. 3 Influence of Ti content affecting the hardness of the as-rolled steel



(a) Heating at low temperature **(b) Heating at high temperature**

Photo 1 Influence of heating temperature at hot rolling affecting dispersing of Ti (CN)

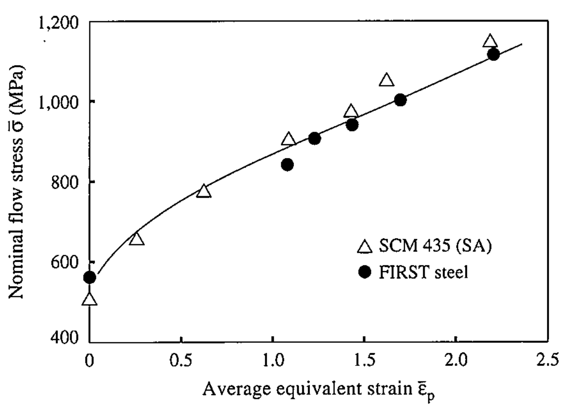


Fig. 4 Stress-strain curve of FIRST steel

3. "Super-mild Steel" for Softened Cold Forging

There is a strong demand for the omission of annealing before cold forging for cold forging parts such as case hardened parts other than bolts. For example, alloy steel equivalent to JIS SCM 420 is used for case hardened parts, but the normal microstructure of the rolling steel contains bainite and is extremely hard and it is difficult, not to mention cold forging, and to even cut as rolled. For that reason, ordinary annealing before processing is performed. With regard to that, Nippon Steel Corporation first applied TMCP (Thermo Mechanical Control Process) technology to bar steel and wire rod rolling processes and developed[2, 3] a softened steel "mild-alloy" that prevents the content of bainite as it is rolled. And they have already put it to use. However, there is a limit to the level of softening among the range of existing components and even though it was possible to omit ordinary annealing, it is currently difficult to omit spheroidizing annealing. Against such a background, a "super mild steel" for cold forging developed to respond to the needs of further softening is outlined.

Table 1 Components of FIRST steel (mass %)

	C	Si	Mn	P	S	Cr	B	Ti, N
8T	0.23	0.20	1.10	0.015	0.015	0.30	Additive	Adjusted
10T	0.23	0.05	0.50	0.010	0.005	Increased amount	Additive	Adjusted

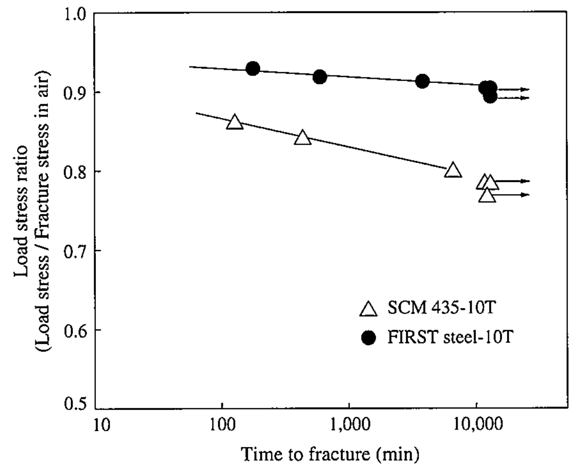


Fig. 5 Delayed fracture resistance of FIRST steel

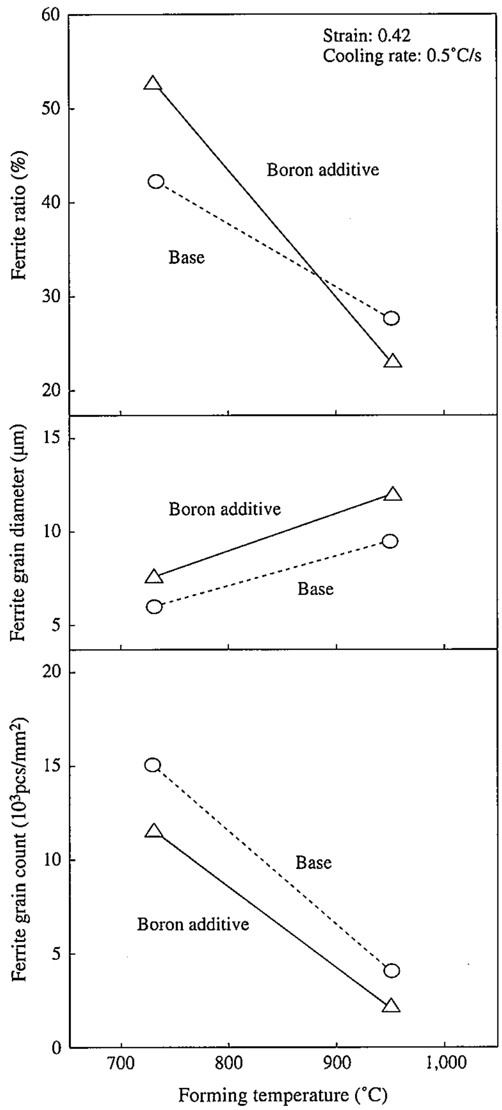


Fig. 6 Influence of forming temperature and boron additive affecting the generating behavior of ferrite

3.1 Basic technology of softening cold forging steel

The technologies to suppress the generation of bainite as rolled and make it a ferrite-pearlite microstructure, as mentioned above, have already been established. In the ferrite-pearlite microstructure, in order to attain further softening, it is important to increase the ratio of ferrite. For that purpose, it is effective to make the steel boron steel in the same way as the steel for bolts.

Fig. 6 investigates the influences of boron additives and forming temperature that affect ferrite transformation behavior. The base material was 0.4 C-Cr steel and the cooling rate was 0.5°C/s. By forming boron additive steel at low temperatures, the ferrite ratio increased and ferrite grains were refined. Because the effect of the ferrite ratio on hardness was larger than that of grain size, softening was attained by forming boron additive steel at low temperatures.

Fig. 7 shows the investigative results of the ferrite generating behavior by quenching during the cooling process after forming. Low temperature forming promoted the growth of ferrite and the behavior was particularly remarkable with the boron additive. Boron additives lowered the starting temperature of ferrite generation without being dependent on the forming temperature, but on the other hand, the growth rate of ferrite increased remarkably at low temperature forming and the ratio of ferrite in the cooling process was reversed. **Fig. 8** shows a model of a mechanism for this promoting the ferrite transformation when rolling boron additive steel at low temperatures. The low temperature formed boron additive steel showed $Fe_{23}(CB)_6$ precipitate at the boundary of α/γ. The growth rate of ferrite was thought to be determined by the diffusion of carbon to the austenite from the α/γ boundary. The growth promotion of ferrite as described above in the boron additive steel was presumed[4] to be caused by the fact that $Fe_{23}(CB)_6$ precipitates at the α/γ boundary and becomes the sinking site of excess carbon.

From the above, the rolling boron additive steel at low temperature was affective in softening ferrite-pearlite steel by raising the

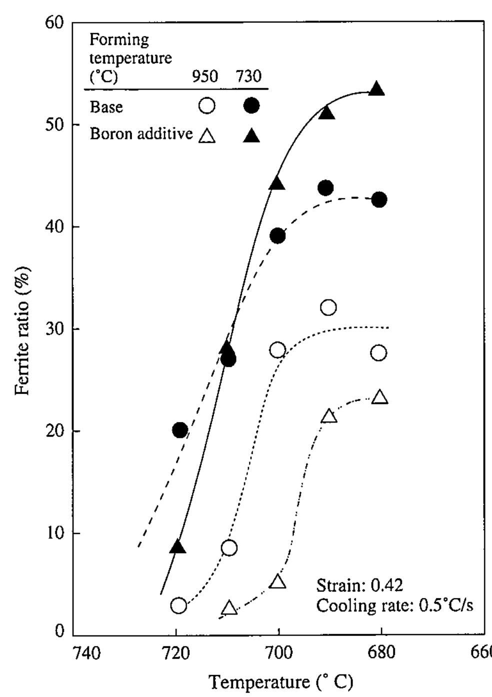


Fig. 7 Influence of forming temperature and boron additive affecting ferrite transformation ratio in the cooling process

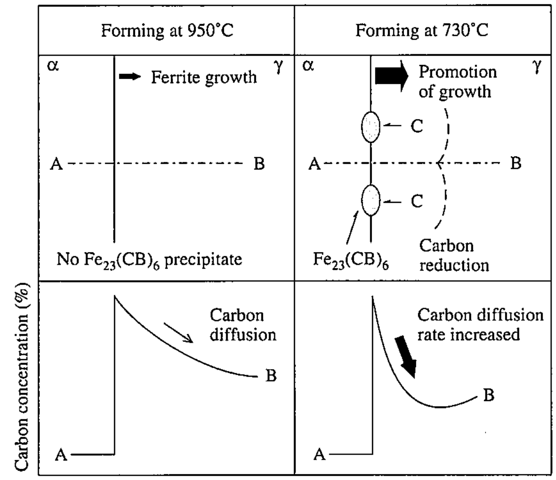


Fig. 8 Promotion mechanism of the ferrite transformation by boron additive and low temperature forming (Schematic illustration)

ferrite ratio. Furthermore, the boron additive (1) contributes to ensuring hardenability as described before and; (2) contributes to improving fatigue strength in the final product through increasing the grain strength, as the authors have recently made clear. Based on the above fundamental considerations, through composition control and TMCP technology applications in the rolling of bar and wire rod steel, a "super-mild steel" that attains softness to the level that it is possible to omit spheroidizing annealing as rolled has been developed. Below outlines the characteristics of alloy steel and carbon steel.

3.2 Softened alloy steel "Super-mild alloy"

Fig. 9 shows the flow stress to cold upsetting of super-mild alloy that is equivalent to JIS SCr 420 steel. The super-mild alloy was manufactured by controlled rolling and controlled cooling. The flow stress of the as-rolled super-mild alloy was less than the equivalent to the spheroidizing annealed (SA) SCr 420. Also, the component of super-mild alloy is optimized for a soft microstructure and that effect continues after SA. Among the same SA steels, the flow stress of the super-mild alloy is about 10% lower than the others. Therefore, in some manufacturing processes of cold forging parts, SA is performed before cold forging and it is possible to omit intermediate annealing.

Next, **Fig.10** shows the hardness distribution after carburizing. The conditions of the carburization was 940°C for 4 hours. The hardenability of the super-mild alloy was adjusted to the equivalent of SCr 420, so the hardness distribution was the same for both. Bending fatigue strength also had the same characteristics. Furthermore, with boron steel, the generation of coarse grains during carburization has been a problem in the past. But with super-mild alloy, the technology application that prevents coarse grains in the FIRST steel discussed in the earlier sections, it was possible to prevent the generation of coarse grains in the carburization process of cold forged steel in which it is easiest for coarse grains to be generated.

3.3 Softened carbon steel "Super-mild SC"

Super-mild SC is one of the menus of mild steel that corresponds to JIS SC carbon steel. **Fig. 11** shows the flow stress to cold upsetting of super-mild SC that is equivalent to S 45 C steel. In the same way as super-mild alloy, the flow stress of the as-rolled super-mild SC is less than the equivalent to the SA material of S 45 C. Furthermore, the hardness level after annealing is low in comparison to SC

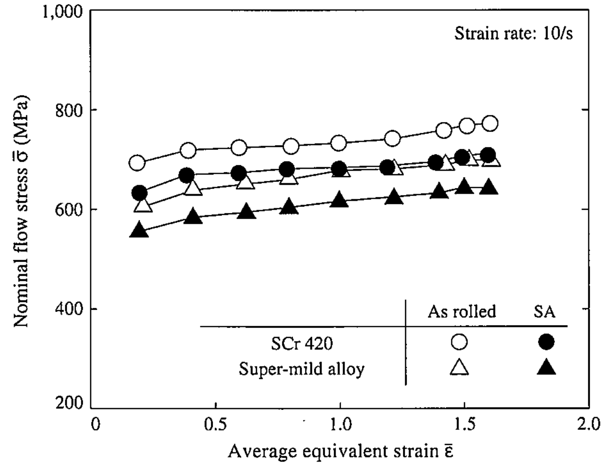


Fig. 9 Stress-strain curves of super-mild alloy corresponding to SCr 420

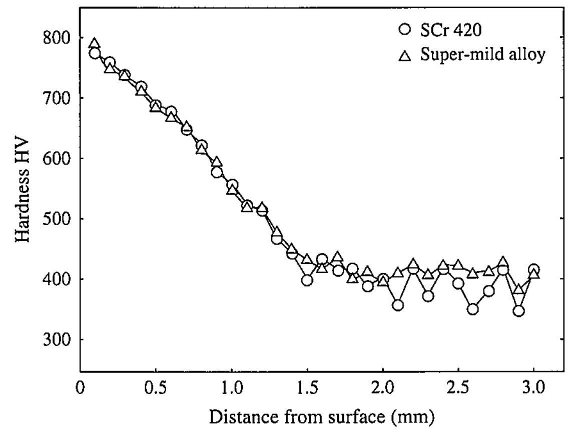


Fig. 10 Hardness distribution of the carburized super-mild alloy corresponding to SCr 420

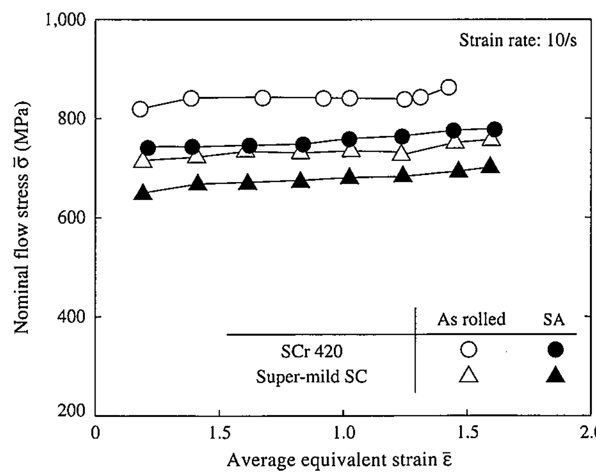


Fig. 11 Stress-strain curves of super-mild SC corresponding to S 45 C

steels and it is effective in simplification or omission of intermediate annealing and improving formability after annealing.

Fig. 12 shows the hardness distribution after induction hardening. Super-mild SC attains the hardness distribution equivalent to S 45 C. Super-mild SC is effective steel material for near-net shapes

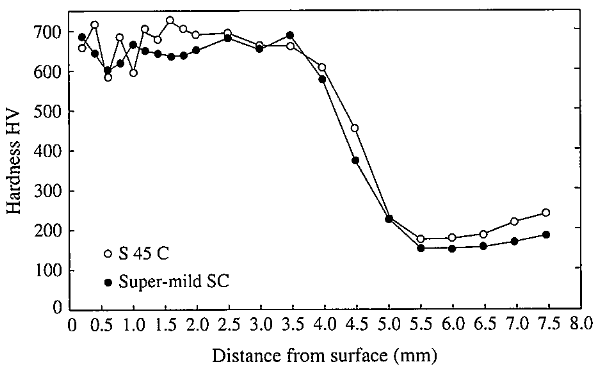


Fig. 12 Hardness distribution of the induction hardened super-mild SC corresponding to S 45 C

and chip-less work. The major part of the mechanical parts of high carbon steel that exceed 0.5% is currently manufactured in a hot forging process. From the viewpoint of improving productivity, there is a strong demand to switch from hot forging to cold forging. Softening by spheroidizing annealing of high carbon steel is insufficient and it is difficult to perform cold forging of high carbon steel. In this regard, by applying the super-mild SC, switching to cold forging shows promise.

4. High Strength Bainite Type Microalloyed Steel

Quenching and tempering are extremely good heat treatments giving superior strength and ductility to steel, and have been applied to mechanical parts. On the other hand, in the 1970s, a method to attain prescribed strength only by adjusting the cooling after hot forging of a microalloyed steel for hot forging(called MA steel below) was developed in Europe. The initial MA steel was a carbon steel and a Mn steel precipitation hardened by small amount of V. These MA steels were low in ductility and toughness. In regard to this, after the 1980s in Japan, high ductility MA steel having finer microstructures was developed and applied to steering systems of automobiles[5].

High ductility type MA steel is classified into a ferrite-pearlite type, bainite type and martensite type. Particularly, bainite type and martensite type have high toughness. The martensite type has difficulty to make any merits in terms of costs, since they are high in alloy amount, and strain during quenching is easily generated and straightening is necessary. In regard to the bainite type, it is easily made to a high strength and it has the feature of not requiring quenching. Here, medium carbon bainite MA steel that was developed for high strength parts is described.

4.1 Features of medium carbon bainite MA steel

It is possible, from the industrial use, to separate bainite MA steel into the two types in **Table 2**. When induction hardening is unnecessary, by making it a low carbon - high alloy composition, it is possible to increase the ductility and impact values and furthermore a uniform bainite microstructure can be attained in a comparatively wide cooling speed. On the other hand, if it is necessary for induction hardening to increase quenching hardness, normally it is necessary to have more than 0.3 % carbon. Increasing carbon, however, narrows the region of proper cooling speed for transforming to full bainite. For that reason, it contains ferrite, martensite and residual γ and has a tendency to have an unstable impact value and yield stress. Particularly, when it contains residual γ, there is a martensite transformation induced by strain during deformation and there is a decrease in yield ratio and ductility[6].

Table 3 shows the guidelines for designing bainite MA steel. The decrease of material quality by residual γ can be prevented quite a lot by slightly adding elements that make the γ microstructure fine during heating for forging. By making the γ microstructure fine during heating for forging[7], the size of the residual γ microstructure after hot forging is finer. An example of that kind of steel is shown in **Table 4** as steel A. Furthermore, **Table 5** shows the mechanical prop-

Table 2 Bainite microalloyed steels classified by induction hardenability

Induction hardening	Necessary carbon amount	Impact value	Features
Yes	≥ 0.3%	Normal	Midium carbon, low alloy
No	≤ 0.3%	Good	Low carbon, high alloy

Table 3 Designs of Bainite Steel

Target	Designing of steel
Uniform bainite structure	Low carbon (+ high alloy) and proper cooling conditions
Adjusting tensile strength	Adjust carbon equivalent Ceq Ceq(%) = (%C) + 1/10(%Si) + 2/11(%Mn) + 1/5(%Cr) + 1/3(%V)
Improved yield strength	Fine dispersing and reduction of residual γ by addition of microalloyed elements
Improved impact value	Reduction of carbide and inclusion Refining bainite lath structure by low temperature transformation Refining prior g microstructure by addition of microalloyed elements

Table 4 Chemical composition of microalloyed medium carbon bainite steel (wt %)

Steel	C	Si	Mn	Cr	Other
Steel A	0.36	0.25	2.0	0.32	Addition of microalloyed elements such as V and Ti
Steel B (compared steel)	0.32	0.48	2.0	0.23	Slight addition of V

Table 5 Mechanical properties of microalloyed medium carbon bainite steel after heating and air cooling

Steel	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio	Elongation (%)	Reduction of area (%)	$_{U}E_{20}$ (J/cm²)	Residual γ (%)
Steel A	750	1,071	0.70	19.3	42.7	53	1
Steel B (compared steel)	608	1,078	0.56	15.3	20.6	36	9
Steel B (after tempering)	760	999	0.76	13.5	44.1	42	6

erties of steel A after hot-forging simulation, reheated at 1,200°C and air cooled. The amount of residual γ in steel A was substantially near 0%, and 9% for comparison of steel B. The results were that there were great differences particularly in reduction, yield ratio and elongation.

Tempering is an effective means for achieving high toughness in bainite steel that contains residual γ and martensite. Tempering takes cost, but just by tempering for a short time at higher than 400°C, the yield strength and the impact value improve because residual γ transforms to ferrite and carbide, and the martensite is tempered. Table 5 shows an example of 400°C tempering of steel B.

4.2 Issues of bainite MA steel to be examined

Fig. 13 shows the relationship of tensile strength and impact value of MA steels. In order to attain high toughness, it is effective to reduce the carbon and make the microstructure bainite or martensite. As forged bainite MA steel and martensite MA steel that was self-tempered during cooling after hot forging has the constituent of ferrite and Fe_3C that is same as ferrite-pearlite, because the amount of carbide is small and the size of carbide is finer than ferrite-pearlite, ductility and impact value are improved.

However, since induction hardening is now widely applied to mechanical parts, it is necessary to contain medium amount of carbon to be a general purpose MA steel. Consequently, some method for getting finer carbide particles must be found to improve ductility. Furthermore, not only the controlling of the microstructure by adjusting the chemical composition of the steel, but also getting fine grains in the microstructure by controlling the forging process are considered to be issues that should be studied in the future.

Also, there is a problem in reduced machinability with regard to high strength. Some of MA steel parts which are processed by machining are those near the Vickers hardness of 320 (tensile strength is approximately 1,000 MPa), and it is presumed that it is the maximum hardness that can maintain machining efficiency and cost when it is produced industrially. In order to attain a hardness higher than that, it is necessary to add large amounts of free-cutting elements such as sulfur, but solving the problems of increased anisotropy of the mechanical properties and decreased forgeability is at issue. Among the free-cutting elements, lead has little influence on mechanical properties, but there is a movement now to review additives to protect the earth's environment and lead cannot be added in great amounts. In other words, MA steels have major issue of consistency in high strength with machinability.

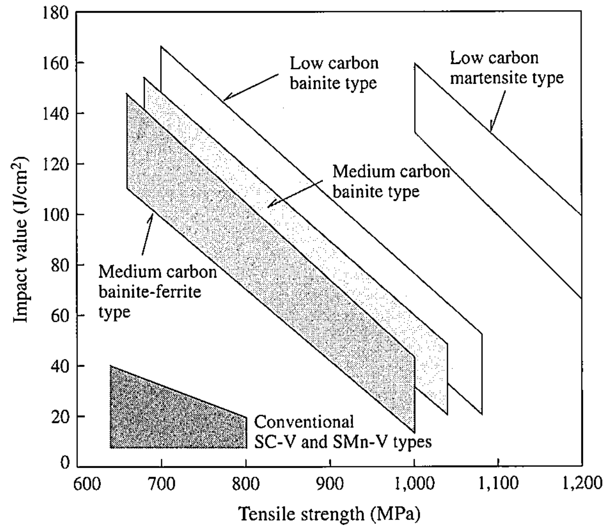


Fig. 13 Tensile strength and impact value of microalloyed steel for hot forging

5. Conclusion

To realize cost reductions and energy conservation in the manufacturing processes of mechanical parts, efforts toward simplifying the manufacturing processes of parts have been outlined. There are strong needs for omission of heat treatments and for moving to being chip-less, and the demand levels on steel materials are becoming higher year after year. In integrated processes from the manufacturing of steel materials to the manufacturing of the final products, simplifying the processes by drawing out the maximum characteristics of steel materials is considered to be of ever-increasing importance.

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