

Present Status and Future Outlook of Microalloyed Forging Steels

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Abstract:

Microalloyed hot-forging steels that are used in the hot-forged condition without subsequent quenching and tempering are applied in the automobile and industrial machinery industries. Their high strength and high toughness have expanded their field of application to include automobile undercarriage parts, resulting in a yearly increase in their consumption. The efforts Nippon Steel has expended in increasing the strength and toughness of microalloyed hot-forging steels as well as their future outlook are described.

1. Introduction

Since microalloyed hot-forging steels with vanadium additions to carbon steels were developed in Europe for machine structural use, they have been subjects of active research and development in Japan. They have yearly increased in production and are now used in amounts of over 10,000 tons per month.

Microalloyed steels not only save energy by eliminating heat treatment, but have advantages over conventional heat-treated steels in terms of processing time, inventory control, shape consistency and machinability, contributing to the enhancement of product quality.

The history of microalloyed hot-forging steels has been that of constant efforts at raising strength and toughness to increase the number of parts to which they can be applied. The efforts Nippon Steel has expended to increase the toughness of microalloyed hot-forging steels as well as their future outlook are described below.

2. Toughening of Ferrite-Pearlite Microalloyed Steel

2.1 Background

Microalloyed steels were produced initially by adding precipitation strengthening elements, such as vanadium and

niobium, to carbon steels or manganese steels. The initial microalloyed steel had a coarse ferrite-pearlite microstructure in the hot forged condition. This microstructure did not provide high toughness and, as a result, the steel had only a limited field of application.

High strength and high toughness can both be attained by reducing the carbon content and compensating for the resultant loss of strength by adding alloying elements. There is a limit to this low-carbon and high-alloy approach, however, because the resulting bainite or martensite microstructure is susceptible to transformation in the air-cooled condition, making the steel quality unstable, and, in addition, the method involves a steel cost increase.

The grain refinement of the microstructure is practically the only means available for increasing both strength and toughness without appreciably changing the chemical composition. As shown in Fig. 1, the steel microstructure must be refined through an optimum combination of chemistry control and forging process control in order to secure both high strength and high toughness in the steel.

When an attempt is made to refine the grain size by controlling the forging conditions, low-temperature working is inevitably resorted to. The low-temperature forging practice, however, often proves impractical because it increases the forging deformation resistance and shortens the die life.

To refine the ferrite-pearlite microstructure by controlling

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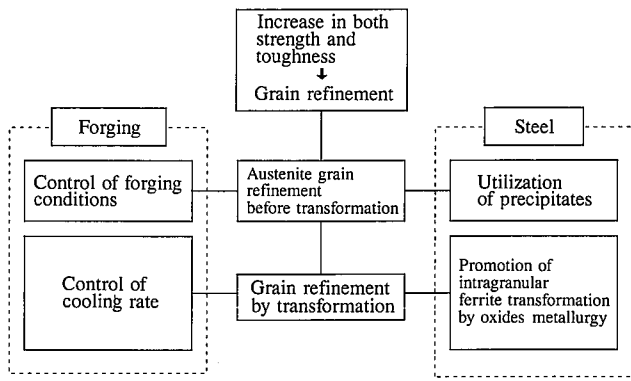


Fig. 1 Strengthening and toughening of ferrite-pearlite steel

steel quality, it is effective to utilize crystallized and precipitated particles for refining the transformed ferrite-pearlite structure. The particles are effective in refining reheated austenite grains and increasing the area of grain boundaries as a ferrite transformation site, and also in promoting intragranular ferrite transformation within prior austenite grains. Utilizing fine oxide and sulfide particles to improve the steel properties is being studied under the new concept "Oxides metallurgy in steels"¹⁾ suggested recently in Japan.

2.2 Prevention of coarsening of austenite grains

Preventing austenite grains from coarsening during reheating is essential to a fine transformed ferrite-pearlite structure. For this purpose, making use of crystallized and precipitated particles is effective. These particles pin the austenite grain boundaries and keep grains fine during reheating.

When crystallized and precipitated particles are to be utilized in the hot forging temperature range, they must not dissolve in the steel at the high temperature. For this reason, TiN, NbN, and MnS have been selected as pinning particles^{2,3)}. It has been known that the more and finer the dispersed particles, the greater their capability of suppressing the growth of reheated austenite grains is. The size of these pinning particles is controlled together with the amounts of titanium, niobium, and sulfur to be added^{4,6)}. Fig. 2 shows the effects of titanium (TiN) and sulfur (MnS) on the austenite grain size during reheating. As evident from Fig. 2, the coarsening of austenite grains can be effectively prevented with fine TiN if the forging temperature is relatively

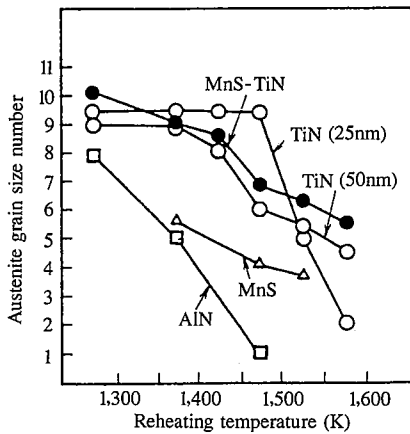


Fig. 2 Relationship of reheating temperature with austenite grain size

low, and with TiN of ordinary size or the combination of TiN and MnS if the forging temperature is relatively high.

The size and number of TiN particles in steel are influenced by cooling rates after casting that depend on the cast section size and by the subsequent rolling conditions^{5,6)}. Photo 1 shows the morphology of titanium carbonitrides. In large-section bloom casting for bars, the titanium carbonitrides in the bloom are almost equal in morphology to those in the bar. When the cast bloom is of a medium section, the titanium carbonitrides in the bloom are different in both morphology and size from those in the bar. As the large-section bloom is cooled after casting, titanium precipitates and grows as stable TiN at elevated temperatures. In medium-section bloom casting, on the other hand, the time for the cast bloom to pass through the TiN precipitation temperature range during cooling is too short for the complete precipitation of TiN. The remaining solute titanium angularly precipitates on TiN as stable TiC in a lower temperature range. TiC is considered to be dissolved again and finely precipitated as stabler TiN on heating during subsequent primary rolling and bar rolling. Finally, fine TiN is dispersed in the medium-section casted bar.

At present, TiN microalloyed steel bars rolled from medium-section blooms are applied to small parts with a relatively low forging temperature and provide good mechanical properties.

MnS (S = 0.06%) is large in particle size and when used singly, cannot be expected to prove as effective as TiN in inhibiting the grain coarsening of the austenite microstructure, as evident from Fig. 2. MnS, however, does not readily dissolve and is very stable in the forging temperature range, and serves also as intragranular ferrite transformation site as described below. On the whole, MnS is a very effective grain refiner.

2.3 Intragranular ferrite transformation

Intragranular ferrite (IGF) is an outcome of transformation that takes place within prior austenite grains. Transformation of many intragranular ferrite grains substantially refines the microstructure and improves the steel toughness. This effect is outstanding particularly in medium-carbon ferrite-pearlite microalloyed steel for which few toughening means are available.

Improving the toughness of vanadium-microalloyed steel by utilizing intragranular ferrite transformed at MnS sites is noted

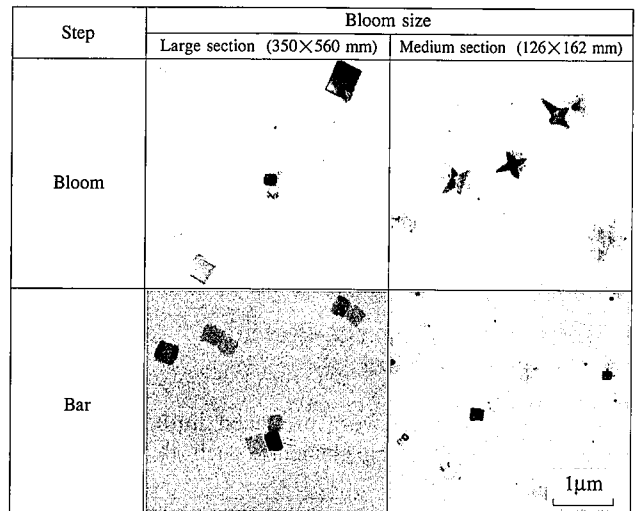


Photo 1 Morphology of titanium carbonitrides

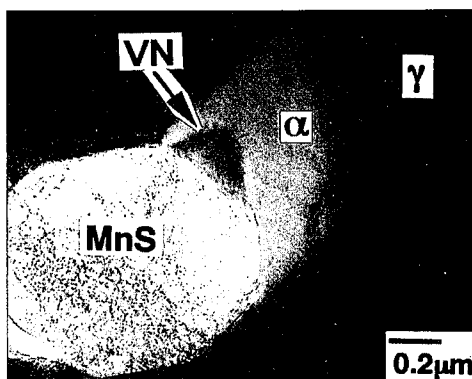


Photo 2 TEM image of intragranular ferrite transformed at VN on MnS

already in a Japanese patent applied in 1980⁷⁾. The intragranular ferrite transformation sites were later identified as vanadium carbonitride [V(C,N)] or vanadium nitride [VN] precipitated on MnS^{8,9)}. Vanadium carbonitride has very high lattice coherency with ferrite and reduces the energy required for ferrite transformation. This is the reason why vanadium carbonitride plays its role as intragranular ferrite transformation sites. Photo 2 shows a TEM image of intragranular ferrite transformed at the sites of VN on MnS¹⁰⁾. Transformation of many intragranular ferrite grains calls for dispersion of many MnS particles as vanadium carbonitride precipitation sites. Control of the MnS particle dispersion is described next.

Sulfur is necessary for improving the machinability of steel. When a sulfur addition of 0.05% or more, for example, is made to the steel, MnS crystallizes in the initial stage of solidification following casting. Observation of the inside of crystallized or precipitated MnS reveals the presence of complex oxides in almost all cases, as shown in Photo 3. This means that oxides are used as preferential crystallization and precipitation sites. It follows then that when oxide particles that facilitate the crystallization and precipitation of MnS are dispersed in a large number, MnS particles can be dispersed in a large number as vanadium carbonitride and intragranular ferrite transformation sites^{11,12)}. Microalloyed hot-forging steels of the same composition ($S = 0.06\%$) were melted in a laboratory vacuum furnace, cast by changing the addition of aluminum or the degree of aluminum deoxidation, and examined for the number and size of MnS particles after solidification. The results are shown in Fig. 3. It is evident from the figure that if the steel is deoxidized to some appropriate degree, many fine MnS particles can be crystallized and precipitated. Takamura et al.¹⁾ indicated the

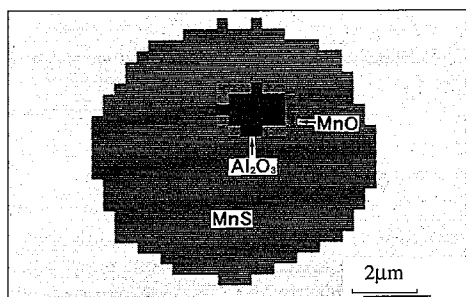


Photo 3 MnS particles in aluminum-killed steel

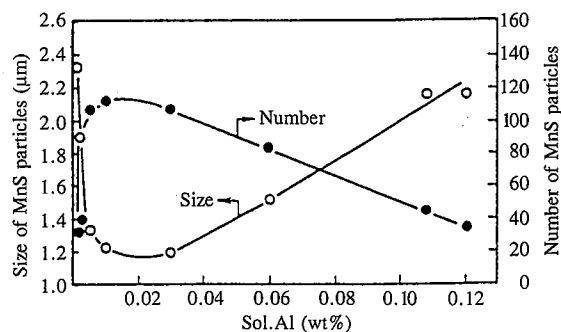


Fig. 3 Effect of deoxidation degree on size and number of MnS particles

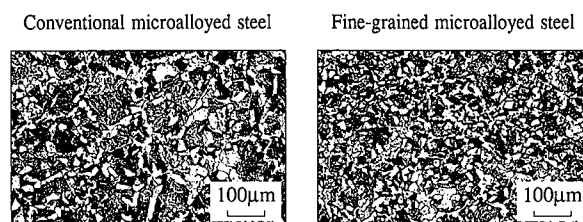


Photo 4 Optical microstructures of conventional microalloyed steel and fine-grained microalloyed steel

ability of oxides of the cation vacancy type to serve as crystallization and precipitation sites. Appropriate deoxidation is believed to have formed many particles of a complex oxide having alumina, an oxide of the strong deoxidizer aluminum, surrounded by MnO, a cation vacancy-type oxide of the weak deoxidizer manganese (see Photo 3).

Photo 4 shows the optical microstructures of a fine-grained microalloyed steel with a tensile strength of 800 MPa and produced by utilizing oxides metallurgy, as compared with a conventional microalloyed steel of the same tensile strength. The impact values of the two steels are shown in Fig. 4, and their -50°C impact fracture surfaces are shown in Photo 5. The fine-grained microalloyed steel exhibits larger impact values, because intragranular ferrite acted to retard crack propagation during failure and refined the fracture facets.

Fatigue strength is an important property for machine structural parts. Fig. 5 shows the rotational bending endurance

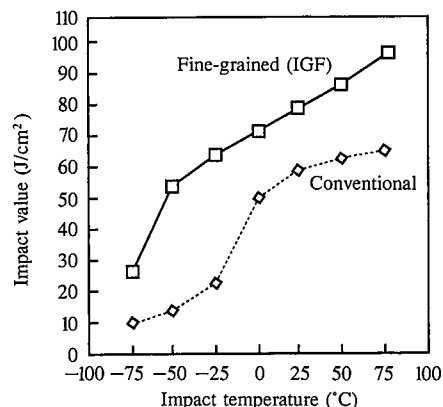


Fig. 4 Impact properties of conventional microalloyed steel and fine-grained microalloyed steel (IGF) (tested with JIS No. 3 specimens)

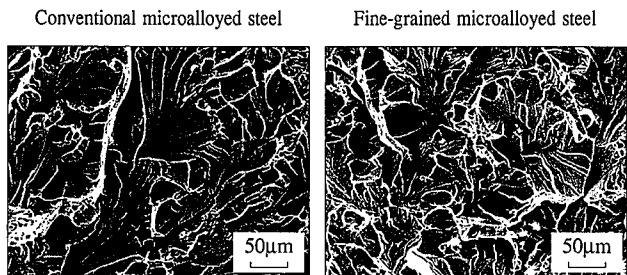


Photo 5 —50°C impact fracture surfaces of conventional microalloyed steel and fine-grained microalloyed steel

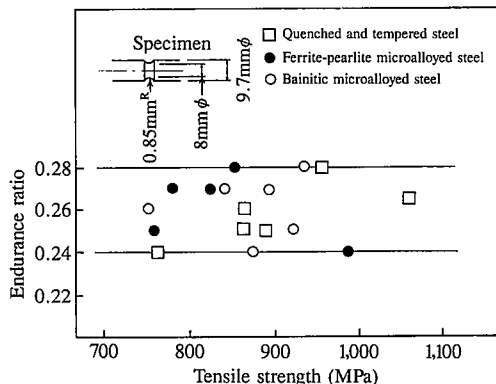


Fig. 5 Endurance ratio of fine-grained microalloyed steel

ratio (fatigue strength/tensile strength) of a conventional quenched and tempered steel and the fine-grained microalloyed steel. The endurance ratio of the fine-grained microalloyed steel falls in the same range as the conventional quenched and tempered steel.

The fine-grained microalloyed steel and the conventional quenched and tempered steel were tested for machinability by turning with a cemented carbide tool and drilling with a high-speed steel drill. The test results are given in Figs. 6 and 7. When compared at approximately the same hardness, the fine-grained microalloyed steel performed better than the quenched and tempered steel in terms of both cemented carbide tool wear and high-speed steel drill life. This may be explained as follows. While the quenched and tempered steel has a tempered martensite microstructure in which carbides are uniformly dispersed, the ferrite-pearlite microalloyed steel has a dual-phase microstructure and the stress applied to the point of cut is concentrated in soft

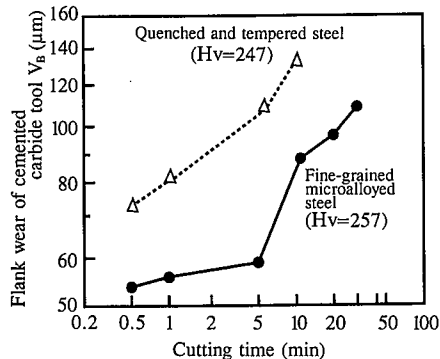


Fig. 6 Wear of cemented carbide tool used to turn fine-grained microalloyed steel

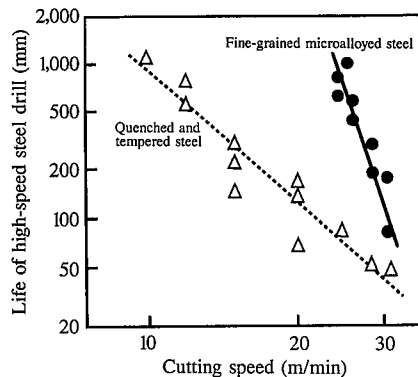


Fig. 7 Life of high-speed steel drill used to drill fine-grained microalloyed steel

Table 1 Chemical compositions of ferrite-pearlite microalloyed steels with tensile strength of 900 to 1,000 MPa

(wt%)						
C	Si	Mn	S	Cr	V	Ti
0.23	0.20	1.40	0.02	0.20	0.05	0
0.40	1.30	1.70	0.07	0.40	0.25	0.02

ferrite, reducing the cutting force¹³⁾.

As a result of the technological progress discussed above, ferrite-pearlite microalloyed steels have rapidly increased in strength and toughness in the past decade. Ferrite-pearlite microalloyed steels with a tensile strength of as high as 900 to 1,000 MPa (see Table 1) are now used for automotive undercarriage parts¹⁴⁻¹⁶⁾.

3. Toughening of Bainitic Microalloyed Steel

It is difficult for steel with a ferrite-pearlite microstructure to stably achieve a tensile strength of over 1,000 MPa. Steels with a bainite or martensite microstructure are studied for application in the tensile strength range of over 1,000 MPa^{17,18)}. Since bainitic microalloyed steels are stable in hardness, do not need quenching and are therefore free from quenching distortion, they are looked upon as the next-generation of high-strength microalloyed steels, and some are already in commercial use.

Bainitic microalloyed steel has higher manganese and chromium contents than ferrite-pearlite microalloyed steel and has molybdenum or boron added as required, so that bainitic transformation can take place in the air-cooled condition. Fig. 8 shows the chemical composition of a bainitic microalloyed steel with a tensile strength of 1,200 MPa, and its continuous cooling transformation (CCT) curves. The bainitic microstructure is stably obtained at cooling rates of 1.0 °C/s or less in the air cooling range. The bainitic microstructure is generally known to form when the steel is rapidly cooled from the austenite temperature range and isothermally treated. When left in the air-cooled condition after hot forging, the steel is continuously cooled. As the air cooling proceeds down from the austenite temperature range, some of the austenite transform not to a bainitic microstructure but to a martensitic microstructure, or remain as retained austenite down to room temperature. Since the soft retained austenite reduces its yield strength, the steel is used after transforming austenite to ferrite and carbides by

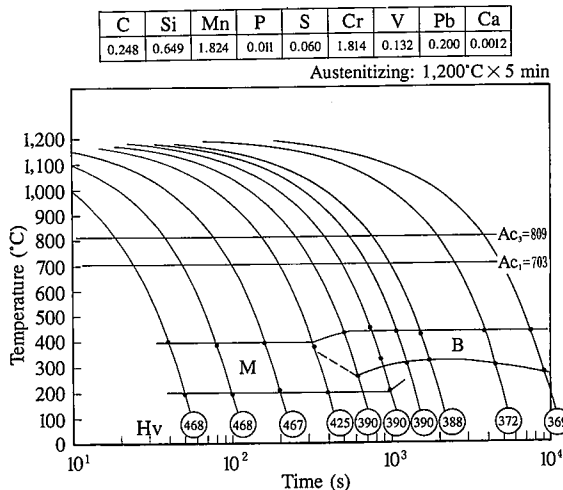


Fig. 8 CCT curves of bainitic microalloyed steel with tensile strength of 1,200 MPa

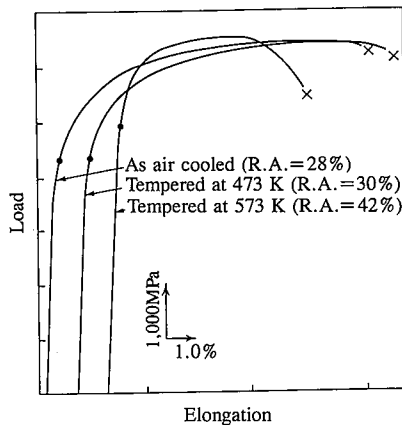


Fig. 9 Load-elongation curves of bainitic microalloyed steel with tensile strength of 1,100 MPa

Table 2 Chemical compositions of 1,100-MPa tensile strength bainitic microalloyed steels

Steel	(wt%)						
	C	Si	Mn	S	Cr	V	Ti
A	0.23	0.51	2.98	0.05	0.15	0.121	tr.
B	0.21	1.51	2.50	0.05	0.30	0.151	0.018

tempering at relatively low temperatures¹⁸⁾. Fig. 9 compares the tensile properties of microalloyed steel in the air-cooled condition with those of tempered. The as-air cooled steel has relatively low yield strength and large elongation compared with tempered steel. This is because of the strain-induced Transformation of retained austenite.

The mechanical properties of bainitic microalloyed steel are considered to depend not only on the amount of retained austenite, but also on the size of bainite packets, the grain size of the martensite-austenite microstructure, and the spheroidization degree of carbide particles when the steel is tempered. Table 2 gives the chemical compositions of steel A and steel B, the latter being microalloyed with titanium and having a higher silicon content. Photo 6 shows the microstructures of the two steels

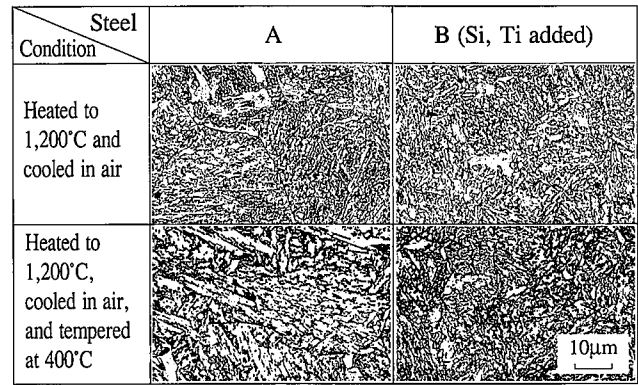


Photo 6 Effects of silicon and titanium on microstructures of bainitic microalloyed steels

Table 3 Mechanical properties of 1,100-MPa tensile strength bainitic microalloyed steels

Steel	Condition	Tensile strength (MPa)	Yield strength (MPa)	Yield ratio	Room temperature impact value μE_{23} (J/cm ²)	Low-temperature impact value μE_{30} (J/cm ²)
A	Heated and cooled in air	1,131	728	0.64	10	6
	Tempered at 400°C	1,033	831	0.80	26	11
B	Heated and cooled in air	1,141	730	0.64	54	29
	Tempered at 400°C	1,066	857	0.80	78	50

when cooled in air after heating to 1,200°C (to simulate the as-forged, non-heat treated condition) and when cooled in air and tempered at 673 K for 1 h. Steel B reveals shorter bainite laths and smaller bainite packets. This is a result of the austenite microstructure from being prevented from coarsening during reheating. Inhibition of carbide coarsening during tempering is attributable to the effect of silicon in suppressing the diffusion of carbon. Consequently, steel B achieves better impact values than steel A in both the air-cooled condition and the tempered condition (see Table 3).

The machining cost accounts for a very large percentage of the manufacturing cost of machine parts. The decrease in machinability with the increase in strength directly leads to an increase in cost.

The machinability of ferrite-pearlite microalloyed steel with a tensile strength of 1,000 MPa or less is superior to that of quenched and tempered steel of the same tensile strength as already described. However, since steels with tensile strength in excess of 1,000 MPa are seldom used in automotive parts, the machinability of bainitic microalloyed steel in the actual automotive parts production process is not known yet. So, sulfur, lead, and calcium were investigated for their effect on the machinability of high-strength microalloyed steel in the laboratory. Fig. 10 shows the change with cutting time in the wear of cemented carbide tools used to turn the outside of bars of bainitic high-strength microalloyed steel of 1,200-MPa tensile strength. When the machinability of the high-strength microalloyed steel is improved through the combined addition of sulfur, lead, and calcium¹⁹⁾, the steel can obtain a cemented carbide tool wear generally comparable to the conventional 900-MPa tensile strength ferrite-pearlite microalloyed steel.

The development of bainitic microalloyed steel that requires no tempering will proceed further, and the steel will find usage in an increasing number of applications.

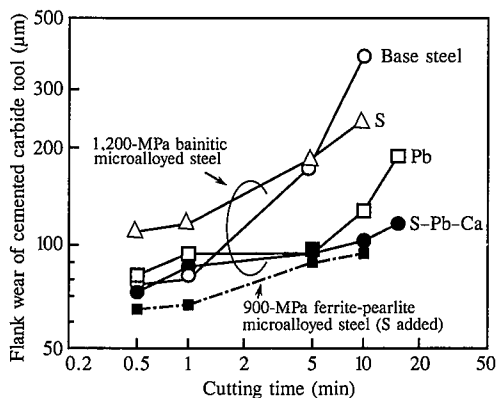


Fig. 10 Wear of cemented carbide tools used to turn 1,200-MPa tensile strength bainitic microalloyed steels

4. Future Outlooks and Conclusions

As a result of strengthening and toughening up to a tensile strength of 1,000 MPa, microalloyed steels centered on the ferrite-pearlite type²⁰⁻²³⁾ have come to be used in automotive undercarriage parts¹⁴⁻¹⁶⁾ with growing consumption year after year. This trend is expected to continue in the future in response to the need of the times for reducing the weight of automobile parts for higher fuel mileage.

Forged automotive parts are assuming more complex shapes in consequence of the current consolidation of parts. Such complex-shaped parts will become more difficult to make by the conventional quenching and tempering process because of the distortion problem accompanying rapid cooling. This translates into the high possibility of microalloyed steels solidifying their position as new high toughness steels for auto parts of complex shapes.

Thus, microalloyed steels are expected to grow further in consumption through their use in new applications. When their tensile strength exceeds 1,000 MPa, however, such problems are expected to come to the surface as the cuttability of bar stock, life of hot-forging dies and machinability of forged blanks. These problems will call upon forging manufacturers and steel manufacturers to cooperate more closely than ever in their development work.

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