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KAWASAKI STEEL TECHNICAL REPORT
No.11 ( March 1985 )

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Synopsis :
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# Properties of Microalloyed Medium Carbon Steel*

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*To develop microalloyed carbon steel bars for machine parts, the effects of microalloying elements and the hot working conditions on the strength and toughness of medium carbon steel were investigated.*

*The results obtained are as follows:*

*(1) Because of the effects of V or Nb for precipitation hardening and crystal grain refinement, addition of V and/or Nb is effective for producing microalloyed carbon steel bars.*

*(2) Strength, hardness and toughness are controlled by the heating temperature and the cooling rate from $Ar_3$ to $Ar_1$.*

*(3) The chemical component design should be based on the manufacturing conditions and required properties of each part.*

*(4) This steel is suitable to the connecting rod, crank shaft, pin, shaft and so on.*

## 1 Introduction

In the process of making machine parts which use machine structural steel as feedstock, heat treatment such as quenching, tempering and normalizing is generally performed to obtain strength and toughness necessary for parts and to ensure workability of the steel.

In view, however, of the energy saving needs due to the recent sharp rise in energy prices, steels which can bypass heat treatments in the parts manufacturing process have come to be demanded,[1,2] and various types of non-heat-treated steels have been put into practical use in the parts of automobiles and construction machinery, with the fields of their application ever widening.

This paper describes microalloyed medium carbon steel bars among non-heat-treated steels manufactured by the company.

## 2 Development Concept of Microalloyed Steel Bars

The manufacturing process of machine parts are broadly divided into:

(1) As-rolled steel–quenching and tempering–machining–parts

(2) As-rolled steel–hot forging–quenching and tempering–machining–parts.

Ordinary quenching and tempering are performed to obtain high strength and toughness, but medium carbon steel, which is usually used for machine parts of the 80 kgf/mm$^2$ tensile-strength class, has lower hardenability. Therefore, it is difficult for the center part of the member made of medium carbon steel to be sufficiently quenched except for parts of a smaller mass, and the structure of medium carbon steel also becomes fine-grain pearlite. For parts which are put into practical use in such a condition, non-heat-treated microalloyed steel will prove more effective.

Instead of quenching and tempering, methods of increasing the strength of medium carbon steel include the following:

(1) Precipitation hardening

(2) Solution hardening

(3) Transformation hardening

In the method (1), carbonitride forming elements are added to the steel, and microprecipitates are formed during natural cooling after hot-working, thereby enhancing strength, and in the methods (2) and (3), large amounts of alloy elements must be added, making these methods disadvantageous in terms of cost. Therefore, the method (1) has been used in developing the present new-type steel, on the basis of a fundamental experiment using medium carbon steel to be described later,

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* Originally published in *Kawasaki Steel Giho*, 16(198 )3, pp. 205–212.

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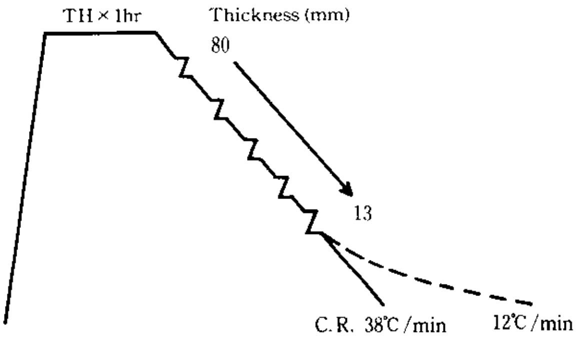


**Fig. 1** Hot-working conditions

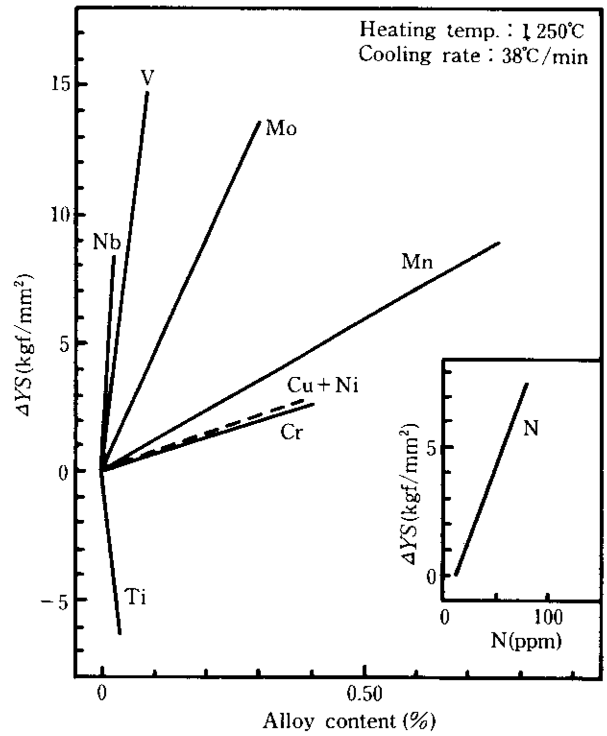


**Fig. 2** Effect of alloy contents on yield strength

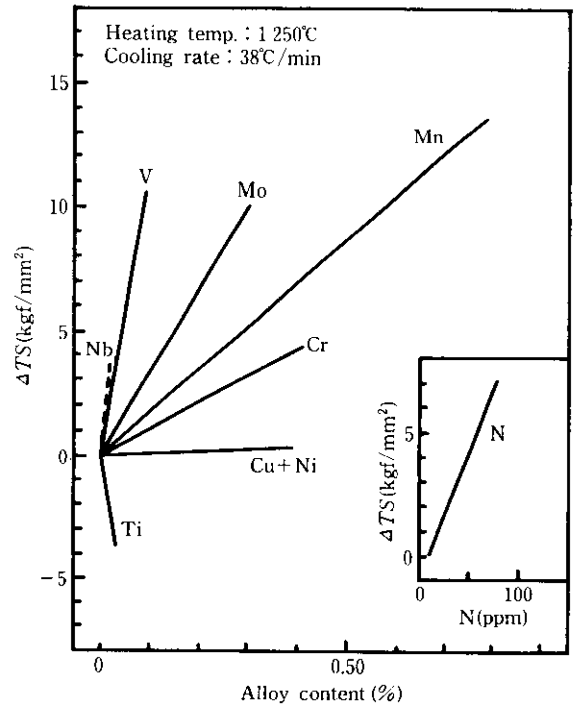


**Fig. 3** Effect of alloy contents on tensile strength

and for commercial grade steel, minute amounts of V, Nb, or V + Nb have been added to medium carbon steel to increase its strength in the ferrite-pearlite structure.

For improving toughness, grain-refinement of ferrite-pearlite structure has proved the most effective. The refinement of ferrite grains requires refinement of austenite grains before transformation, and it is said that control of the hot-working conditions is important.[3]

Effects of alloying elements and working conditions on the mechanical properties of medium carbon steel with a basic chemical composition of 0.45%C–0.25%Si–0.75% Mn are considered below. Under the working conditions shown in **Fig. 1**, 80 mm thick steel plate was hot-rolled into a 13 mm thick steel plate and investigations were made. Rolling schedules used were as follows:

(1) For hot rolling at 1 200°C, 5 pass continued rolling was performed at a reduction of 30% per pass.

(2) For hot rolling at 1 150°C, 3 pass continued hot rolling was performed at a rolling-start temperature of 1 050°C followed by air cooling to 850°C, and then 2 pass continued rolling was performed at 850°C or below.

Average cooling rates from 800 to 400°C after rolling were set to 38°C/min and 12°C/min for both the above-mentioned schedules (1) and (2). **Figures 2** to **4** show the relations of alloying elements added to strength and the Charpy impact value. These figures indicate that addition of minute quantities of V and Nb can increase strength, and addition of Mn, Cr and N to V-bearing steel increases not only strength but also toughness. **Figure 5** shows the effects of the cooling rate on strength and the Charpy impact value. When the characteristics

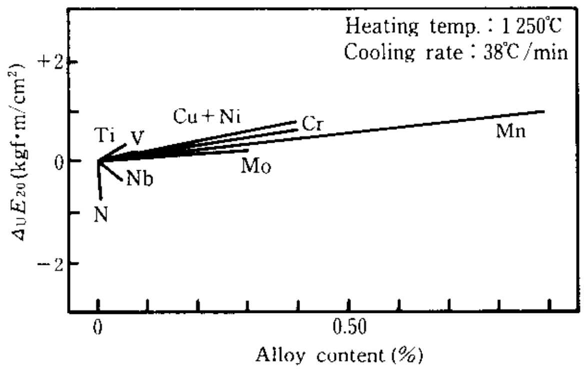


**Fig. 4** Effect of alloy contents on charpy impact value

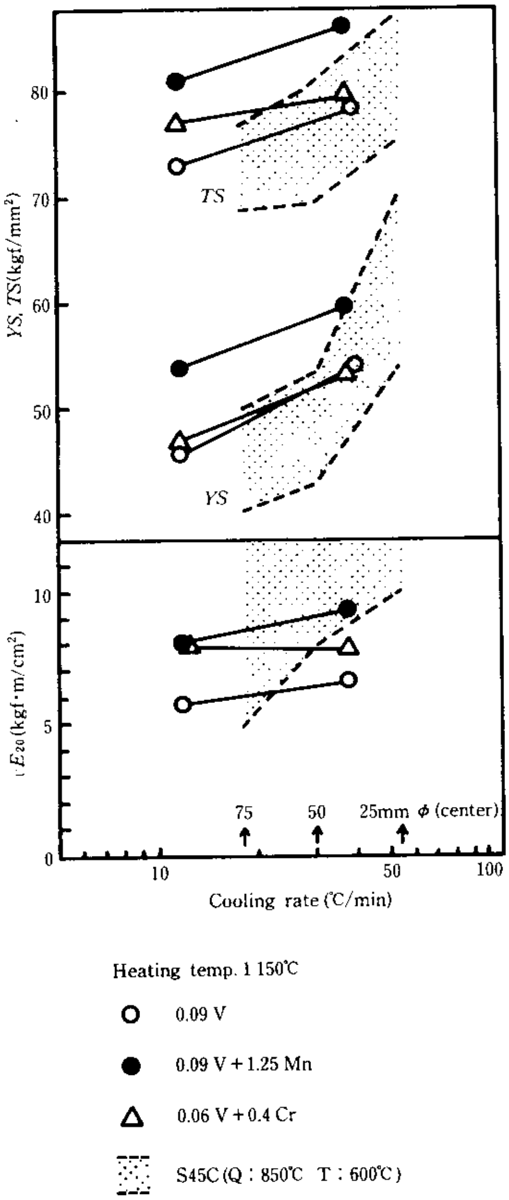


**Fig. 5** Effect of cooling rate on strength and charpy impact value

of the microalloyed carbon steel in this figure are compared with those of quenched and tempered S45C steel, the *YS* and *TS* values for the former are sufficiently high, and $_U E_{20}$ in the former is slightly lower than that of the latter when the cooling rate is faster, but is almost equal, when the cooling rate is slower. This indicates that application of microalloyed carbon steel to weighty parts is more advantageous in toughness than that of quenched and tempered steel.

As described above, it is necessary to design the chemical composition of the microalloyed carbon steel from the sizes of the target parts and necessary mechanical properties.

## 3 Characteristics of Microalloyed Carbon Steel Bar

**Table 1** shows chemical compositions of steel bars which have been developed with the aim of replacing quenched and tempered steel of the 0.45%C class which is mainly applied to parts used for machining or hot forging. Both NH45MV steel of the Mn + V type and NH45CV steel of the Cr + V type have chemical compositions for good toughness and are rolled into bars with diameters of 25, 50, 75 and 110 mm by controlling finishing temperatures after heating up to 1 150°C. Properties of parts made of microalloyed steel bars, namely, parts made only by machining of rolled steel, are determined by hot rolling conditions and cooling conditions. As-rolled characteristics of both NH45MV and NH45CV steels are described below.

**Table 1** Chemical composition

(wt.%)

| Steel | C | Si | Mn | P | S | Cr | V | N |
|---|---|---|---|---|---|---|---|---|
| NH45MV | 0.45 | 0.27 | 1.25 | 0.011 | 0.020 | 0.02 | 0.09 | 0.0071 |
| NH45CV | 0.45 | 0.25 | 0.96 | 0.010 | 0.020 | 0.20 | 0.09 | 0.0068 |

### 3.1 Characteristics of As-rolled Steel Bars

#### 3.1.1 Structures

As shown in **Photo 1**, as-rolled steel bar has a ferrite-pearlite structure. As the bar diameter becomes smaller, the structure becomes finer owing to the effects of the amounts of working and cooling rates. **Photo 2** is an electron-micrograph of a 50 mmϕ steel bar, and many fine precipitates of about 100 Å in size are dispersed in the matrix. These precipitates were found to consist mainly of V carbonates as shown in **Photo 3** and **Fig. 6**, as a result of analyzing by EDX (Energy-dispersive X-ray spectrometer) and EELS (Electron energy loss spectroscopy).

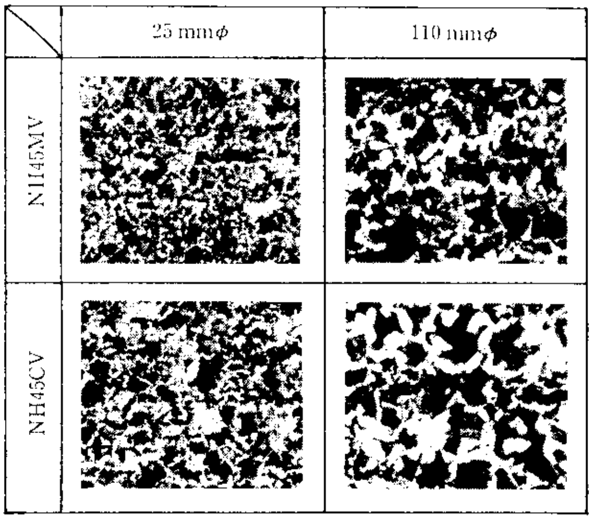


**Photo 1** Microstructures of hot-rolled steel bar

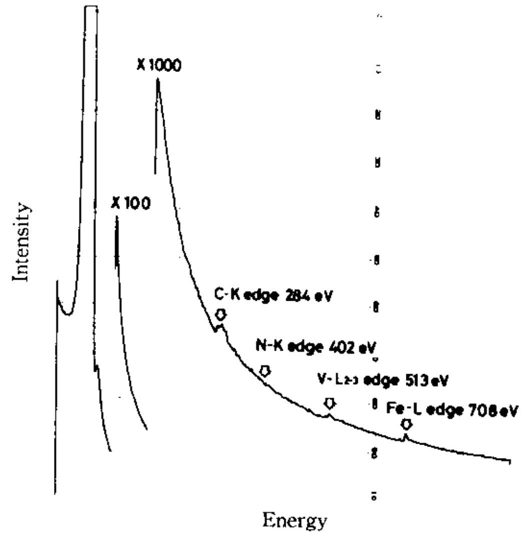


**Fig. 6** Results of EELS analysis of dispersed precipitate in the hot-rolled NH45MV 50 mmφ steel bar

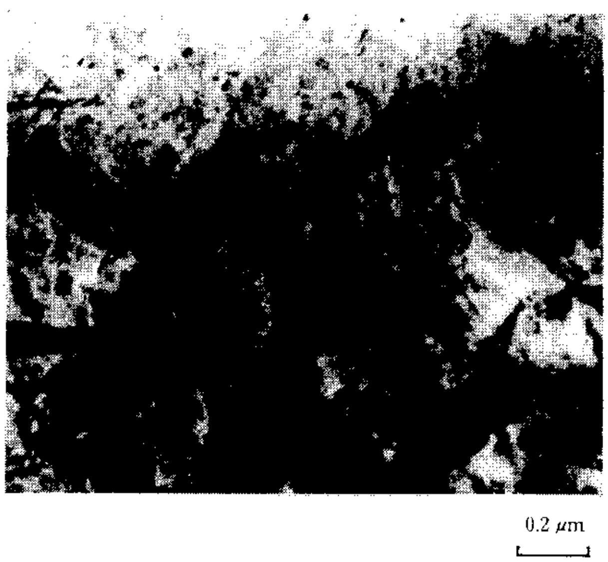


**Photo 2** Electron-micrograph of dispersed precipitate in the hot-rolled NH45MV 50 mmφ steel bar

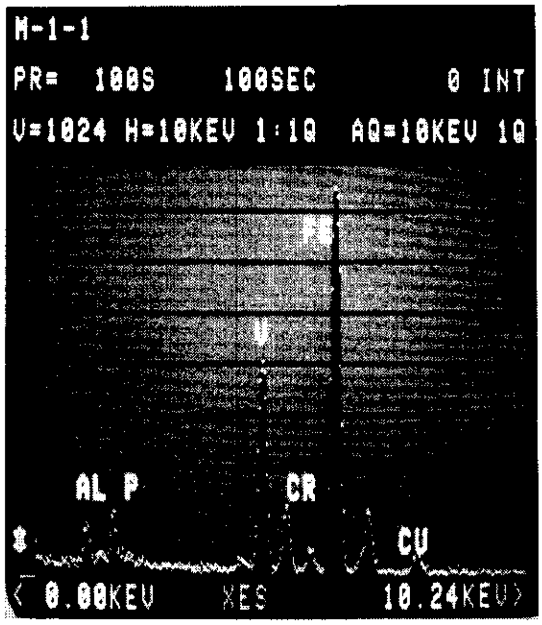


**Photo 3** Results of EDX analysis of dispersed precipitate in the hot-rolled NH45MV 50 mmφ steel bar

### 3.1.2 Mechanical properties

**Figure** 7 shows mechanical properties of hot-rolled steel bars of various sizes. Characteristics of two 25 mmφ steel bars are shown below:

NH45MV—*YS* 58 kgf/mm$^2$, *TS* 82 kgf/mm$^2$, *El* 26%, *RA* 58% and $_UE_{20}$ 10.0 kgf · m/cm$^2$

NH45CV—*YS* 55 kgf/mm$^2$, *TS* 81 kgf/mm$^2$, *El* 25%, *RA* 57% and $_UE_{20}$ 8.8 kgf · m/cm$^2$

The above values fully satisfy JIS reference values (25 mmφ) of S45C after quenching and tempering, namely, *YS* ≧ 50 kgf/mm$^2$, *TS* ≧ 70 kgf/mm$^2$, *El* ≧ 17%, *RA* ≧ 45% and $_UE_{20}$ ≧ 8 kgf · m/cm$^2$. Further, the decreases of strength and toughness of both steel bars due to increases in diameter are smaller than the actual values of quenched and tempered S45C steel bars.

Figure 7 also shows mechanical properties of control-rolled bar steel in which steel having the same chemical composition as that of S45C has been given the same characteristics as those of normalized steel bars by controlling its heating and rolling temperatures. Figure 7 in-

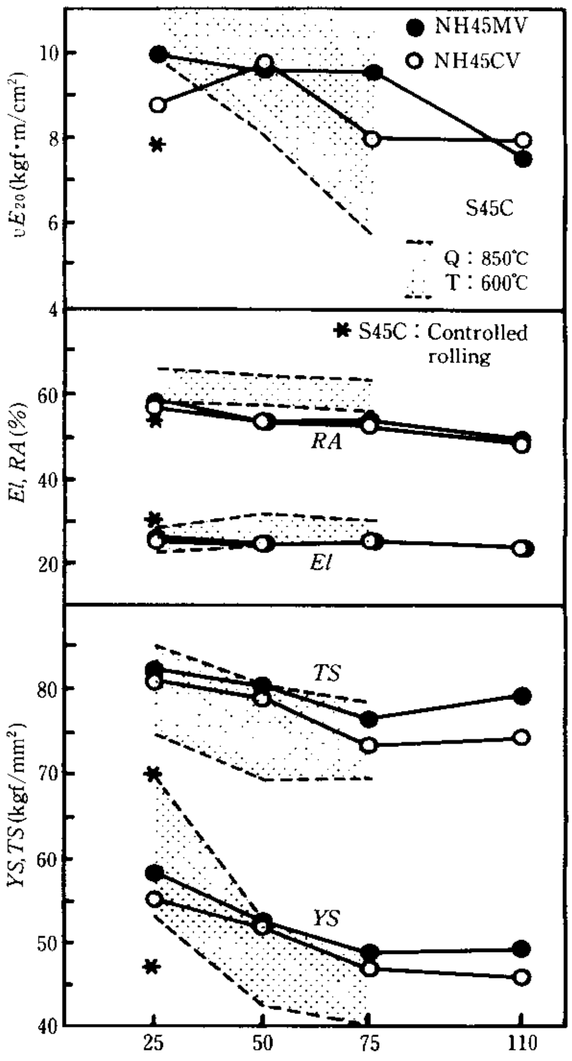


**Fig. 7** Mechanical properties of hot-rolled steel bar

dicates that microalloyed medium carbon steel, in which Mn and Cr contents are adjusted, with V added and heating and rolling temperatures controlled, has its strength and toughness improved compared with the control-rolled S45C steel bar.

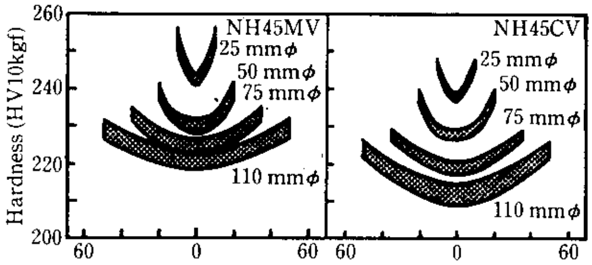


**Fig. 8** Hardness distribution in diameter of hot-rolled steel bar

### 3.1.3 Sectional hardness

**Figure 8** shows the hardness distribution in sector, indicating that as the diameter increases, hardness tends to decrease. It is also found that for all sizes, the surface of the bar is harder than its center part, but this difference in hardness is as small as 20 or below in Vickers hardness, and the larger the diameter, the gentler and the more homogenized is the hardness distribution.

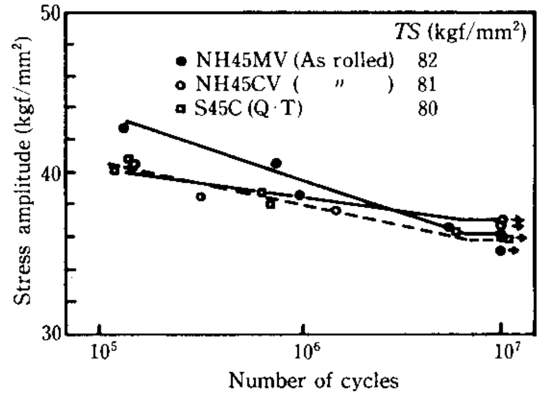


**Fig. 9** Results of rotating bending fatigue test

### 3.1.4 Fatigue characteristics

**Figure 9** shows the results of Ono's rotating bending fatigue test. Both NH45MV and NH45CV show nearly the same fatigue strength as that of quenched and tempered S45C.

### 3.1.5 Machinability

**Figure 10** shows the results of the machinability test using cemented carbide tools. Since both NH45MV and NH45CV have a ferrite-pearlite structure, they have better machinability than has the quenched and tempered S45C. If still higher machinability is required, their machinability can be enhanced by adding a free-cutting element. As an example, the characteristics of S-added steel are shown in **Fig. 11**.

### 3.2 Effect of Hot-forging Conditions on Mechanical Properties

The properties of hot-forged parts using microalloyed carbon steel bars are determined by the hot-forging conditions and cooling conditions after hot-forging. Since $\gamma$ grain size before transformation and the cooling rate are important control factors, a hot forging test and a heating and cooling test, which simulates hot-forging, were conducted to investigate the effects of the hot-forg-

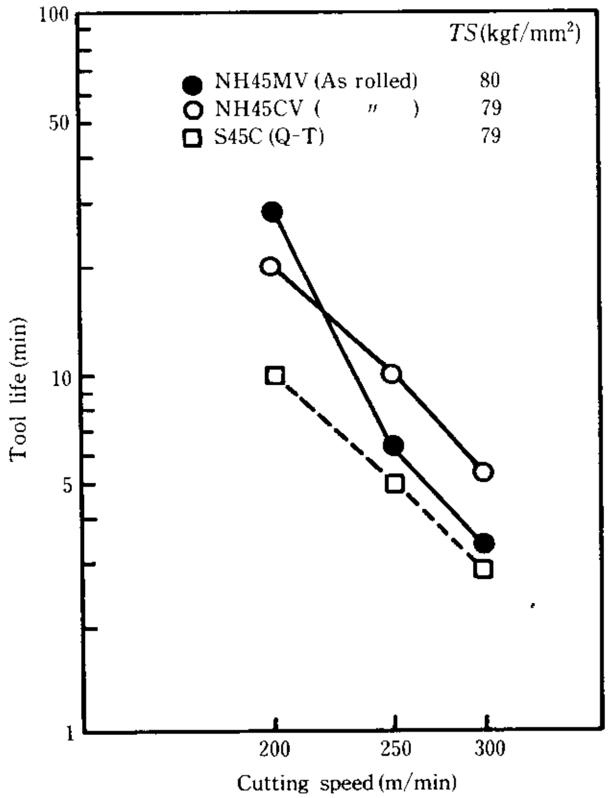


**Fig. 10** Results of machinability test

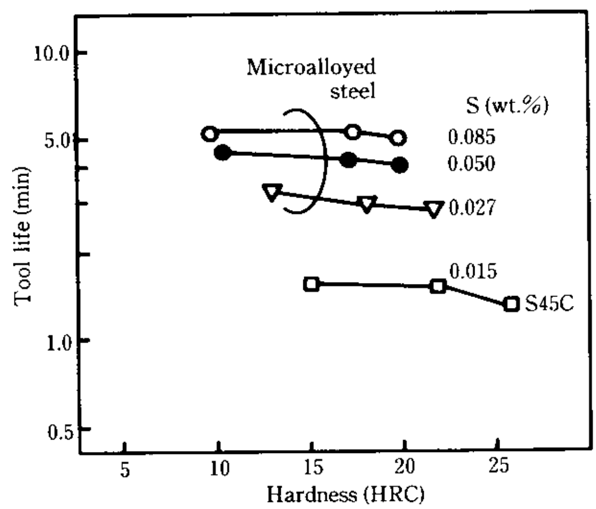


**Fig. 11** Effect of hardness and sulphur contents on machinability

**Table 2** Hot forging conditions

| Steel | Heat temp. (℃) | Initial dia. (mm$\phi$) | Final dia (mm$\phi$) |
|---|---|---|---|
| NH45MV | 1 000～1 300 | 50 | 15, 20, 25, 30 |
| NH45CV | | | |

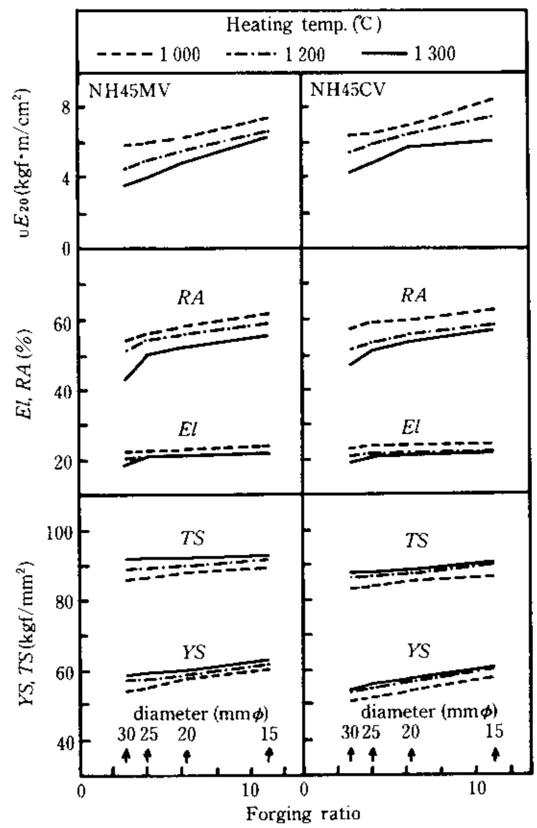


**Fig. 12** Effect of hot-forging conditions on mechanical properties

ing conditions on the mechanical properties of microalloyed carbon steel bars.

### 3.2.1 Mechanical properties after hot forging

Rolled bars of NH45MV and NH45CV were hot forged under the conditions shown in **Table 2**, air-cooled, and used as test pieces. Their mechanical properties are shown in **Fig. 12**. Both types of steel bars show the trend of increasing strength and toughness in proportion to the forging ratio. The forging ratio being equal, the higher the heating temperature, the higher will be strength and the lower will be toughness. Both steel bars have the ferrite-pearlite structure as shown in **Photo 4**, and when heating temperatures are equal, the greater the forging rate, the finer the structure.

### 3.2.2 Effects of heating temperature

**Figure 13** shows the mechanical properties of NH45MV and NH45CV steel bars which were held at an austenitizing temperature of 1 000 to 1 300°C for 15 min and cooled at a rate of about 55°C/min. Under the same cooling conditions, the higher heating temperature gives higher strength, but lower ductility and toughness. This is due to the fact that pearlite grain sizes

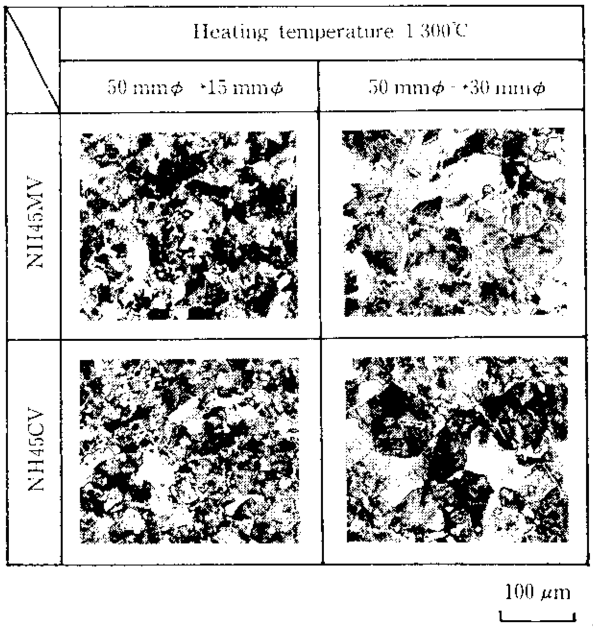


**Photo 4** Microstructure of hot-forged steel bar

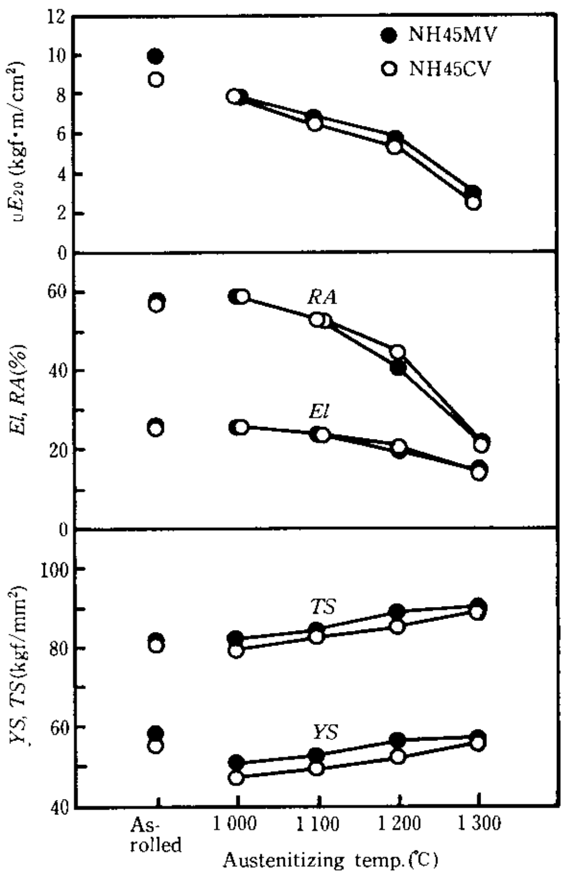


**Fig. 13** Effect of austenitizing temperature on mechanical properties

in the ferrite-pearlite structure become coarser and the fractional factor of pearlite becomes greater.

### 3.2.3 Effects of cooling conditions

**Figure 14** shows the mechanical properties of NH45MV and NH45CV steel bars which were held at an austenitizing temperature of 1 200°C for 15 min and cooled from 800 to 600°C at a cooling rate of about 1.5 to 55°C/min. Strength, ductility, and toughness all became higher as the cooling rate became faster.

**Figure 15** shows the mechanical properties of the above-mentioned steel bars which were slowly cooled at a rate of about 1.5°C/min and whose cooling rate was increased to about 50°C/min starting from the prescribed temperature, to find out the temperature range which affects the mechanical properties. The values of *YS* and *TS* began to drop at 700°C or below for NH45MV and at 800°C or below for NH45CV. This was due to the fact that transformation began during the slow cooling. In the test, in which the steel bars were cooled at a rate of about 50°C/min after being heated up to 1 200°C and slowly cooled at a rate of about 1.5°C/min from the respective temperatures, lowering of strength was

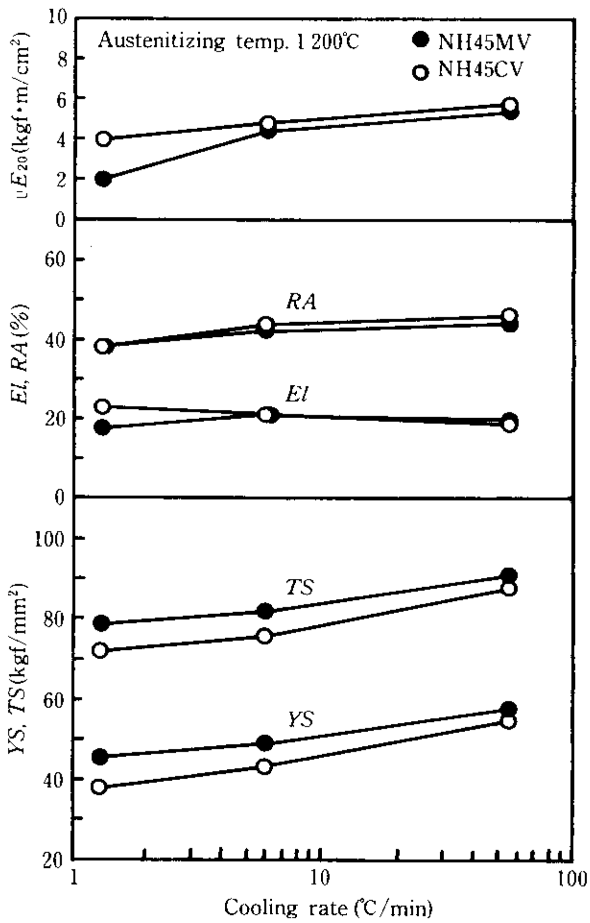


**Fig. 14** Effect of cooling rate on mechanical properties

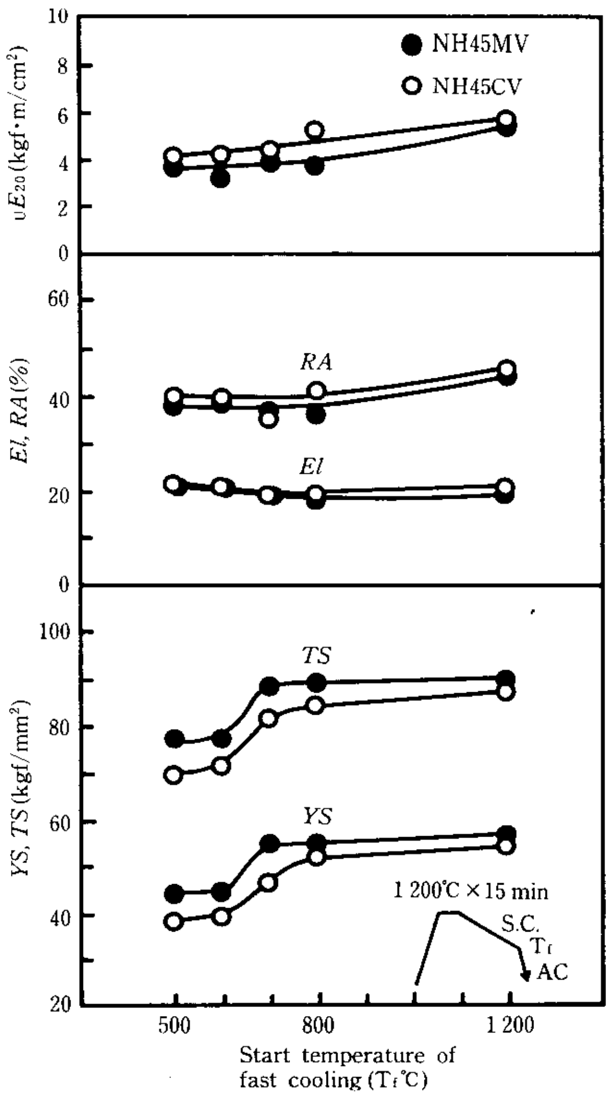


**Fig. 15** Effect of start temperature of fast cooling on mechanical properties

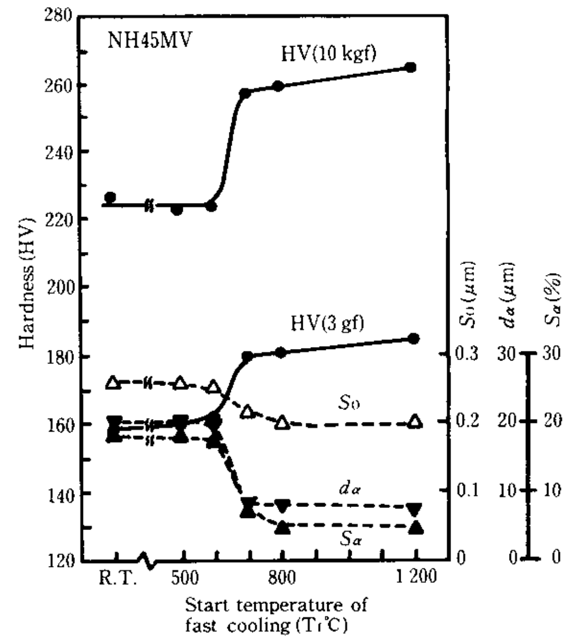


**Fig. 16** Influence of start temperature of fast cooling on hardness and structure factor

observed, when the $Ar_3$-$Ar_1$ transformation points passing rate was slower.

**Figure 16** summarizes the relation between the start temperature of fast cooling, hardness and the structure factor. The figure indicates the relation between the cooling rate, the temperature of fast cooling, mean hardness (HV 10 kgf), pro-eutectoid ferrite hardness (HV 3 gf), pearlite lamellar interval ($S_0$), ferrite grain size ($d_\alpha$) and ferrite area factor ($S_\alpha$). These mesured values have changes within the temperature range of 700 to 600°C in which $Ar_3$-$Ar_1$ transformation occurred. At 700°C or above, the values of $S_0$, $d_\alpha$, and $S_\alpha$ were small and ferrite hardness was high.

The cooling conditions also have a great effect on the precipitate distribution. In this chemical composition of NH45MV, fine precipitates were observed in pro eutectoid ferrite. When cooling started at a rate of about 50°C/min from the temperature of $Ar_3$ or above, precipitates with sizes of 100 Å or below were mainly found, but when slow cooling at a rate of about 1.5°C/min was performed down to $Ar_1$ point or below, sizes grew larger to about 300 Å. For the effects of the sizes of precipitates upon ferrite hardness, it is known that when precipitate sizes decrease to 100 Å or below, hardness was improved.[4] Therefore, it can be said that a start of cooling at a temperature of $Ar_3$ point or above improves ferrite hardness.

As described above, strength and toughness of hot-forged steel are affected, other than by the chemical composition adjustment, by heating temperatures and the cooling rate between $Ar_3$ to $Ar_1$ points. Therefore, heating and cooling conditions constitute important control items.

## 4 Application to Actual Machine Parts

The NH45MV and NH45CV steel bars were used to manufacture automobile connecting rods and crank shafts by hot forging and air cooling, and the characteristics of the products were investigated. Unit weight of parts after forging was 0.5 kg for the connecting rod and 9.5 kg for the crank shaft. **Table 3** shows the mechanical properties of the connecting rods. Both strength and the impact value were equal or superior to the characteristic values of quenched and tempered S40C steel. For crank-

**Table 3** Mechanical properties of connecting rod

| Steel | $YS$ (kgf/mm²) | $TS$ (kgf/mm²) | $El$*1 (%) | $RA$ (%) | $uE_{20}$*2 (kgf·m/cm²) | HV (10 kgf) | | Note |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\bar{x}$ | σ | |
| NH45MV | 66 | 93 | 16 | 56 | 8.2 | 265 | 3.3 | As hot-forged |
| NH45CV | 64 | 89 | 16 | 57 | 9.3 | 252 | 3.9 | |
| S40C | 53 | 77 | 17 | 63 | 8.3 | 253 | 1.5 | Q-T |

**Table 4** Mechanical properties of crank shaft

| Steel | $YS$ (kgf/mm²) | $TS$ (kgf/mm²) | $El$*1 (%) | $RA$ (%) | $UE_{20}$*2 (kgf·m/cm²) | HRC | | Note |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\bar{x}$ | σ | |
| NH45MV | 57 | 86 | 16 | 31 | 3.1 | 22.6 | 0.4 | As hot-forged |
| NH45CV | 52 | 85 | 16 | 29 | 3.1 | 21.2 | 0.7 | |
| S45C | 59 | 84 | 13 | 32 | 3.9 | 22.3 | 0.8 | Q-T |

*1 JIS No.14A G.L.$=5.65\sqrt{A}=25$ mm
*2 JIS No.3

shafts, **Table 4** also shows that the strength and the impact values of NH45MV and NH45CV are nearly equal to those of quenched and tempered S45C. Heavy weight parts for construction machinery (unit weight: 12 kg) were produced by hot forging and air cooling of NH38V of which chemical composition is shown in **Table 5**. The mechanical properties of the products were slightly lower in the impact value than those of the hot-forged and heat-treated S45C product as shown in **Table 6**, but it was confirmed by the actual machine test that the former products have no problems in their mechanical properties including machinability, induction hardenability and wear resistance.

**Table 5** Chemical composition

(wt.%)

| Steel | C | Si | Mn | P | S | V | N |
|---|---|---|---|---|---|---|---|
| NH38V | 0.38 | 0.26 | 0.96 | 0.010 | 0.013 | 0.09 | 0.0068 |

For parts which are used by machining rolled steel, microalloyed medium carbon steel has the same mechanical properties as those of normalized steel as mentioned earlier and have no problem, and therefore investigation was made on drawing operation. **Figure 17** shows mechanical properties of NH45MV and NH45CV when they were cold-drawn. As the degree of drawing increases, strength also increases, but toughness decreases. The demerit of microalloyed steel lies in that its yield strength is lower than its tensile strength, but its yield strength greatly increases at drawing of about 8%. This indicates that if microalloyed steel is used after being subjected to light drawing, high yield strength can be obtained.

As mentioned above, V-bearing microalloyed steel bars have excellent characteristics and can replace quenched and tempered steel. They can be used for

**Table 6** Mechanical properties of powershovel part

| Steel | $YS$ (kgf/mm²) | $TS$ (kgf/mm²) | $El$*1 (%) | $RA$ (%) | $UE_{20}$*2 (kgf·m/cm²) | HV (10 kgf) | | Note |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\bar{x}$ | σ | |
| NH38V | 45 | 74 | 25 | 51 | 5.8 | 221 | 6.7 | As hot-forged |
| S45C | 41 | 70 | 24 | 51 | 7.1 | 189 | 8.0 | Heat-treatment |

*1 JIS No.14A G.L.$=5.65\sqrt{A}=25$ mm
*2 JIS No.3

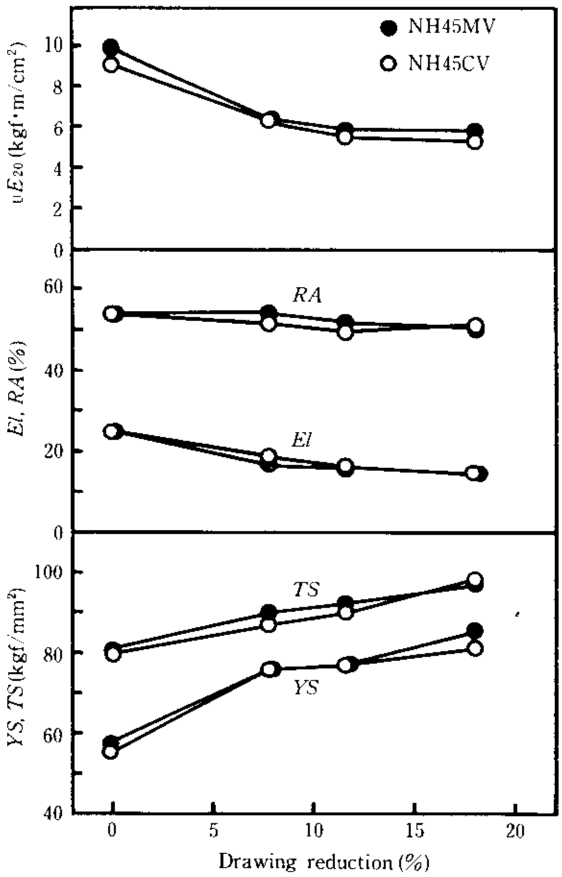


**Fig. 17** Effect of drawing reduction on mechanical properties

various machine parts, as rolled and air-cooled or as hot-forged and air-cooled.

## 5 Conclusions

To develop microalloyed steel bars which can bypass heat treatments in the process of manufacturing machine parts, investigation was made on the effects of minute elements and hot-working conditions on the strength and toughness of medium carbon steel bars. The main results of the investigation are given below.

(1) It is effective to add minute amounts of V, Nb, or V + Nb to microalloyed steel bars to bring about precipitation hardening and crystal grain refinement, thereby improving strength and toughness.

(2) Strength, hardness and toughness can be controlled by the heating temperature and the cooling rate within the $Ar_3$-$Ar_1$ transformation temperatures after hot-working.

(3) To enable microalloyed steel bars to demonstrate their full performance, it is necessary to design chemical composition based on the manufacturing process of applicable parts and required characteristics.

(4) Mechanical properties of microalloyed carbon steel NH45MV and NH45CV rolled bars (25 mm$\phi$) satisfy all the JIS reference values of quenched and tempered S45C. Further, a decrease of strength and toughness due to an increases in diameter is small. Both steel bars can be used for connecting rods, crankshafts, pins and shafts.

Microalloyed medium carbon steel bars are effective not only in cost saving due to energy saving but also in preventing defects due to heat treatment such as quenching deformation, quenching cracks, variation in material quality owing to uneven heat treatment and decarbonization, and process rationalization such as omission of straightening and transporting processes and shortening of the period of construction schedules, and their applicable ranges will be increased in the future.


**References**

1) S. Kimura: *Denki Seiko (Electric Furnace Steel)*, **51**(1980)1, 43–50
2) M. Ōsawa: *J. of Society of Automotive Engineers of Japan*, **36**(1982)8, 846–853
3) T. Tanaka: *J. of Japan Institute of Metals*, **17**(1978)2, 104–110
4) M. Tanino, T. Nishida, K. Ooka, K. Yoshikawa: *J. of Japan Institute of Metals*, **29**(1965)7, 734–741