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PROPERTIES OF LOW-CARBON AS-ROLLED STEEL BARS FOR MACHINE AND STRUCTURAL USE

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Abstract

New type of as-rolled steel bar products has been developed. They are characterized by an excellent combination of strength, toughness and ductility. The present paper describes a systematic study on the effect of alloying element on the mechanical properties of controlled rolled bars. Trial production test results, the processing and performance properties obtained are also described. The HSLA bars introduced herein can meet the requirements both of manufacturers and users for the complete elimination of the quenching and tempering process conventionally applied on the selected automotive components.

I. Introduction

Recently, as an alternative to the quenched and tempered steel, special attention has been given to as-rolled bar products to be directly machined and/or cold drawn for machine and structural use. The elimination of heat treatment leads to an appreciable cost-saving: energy-saving, shortening of stock period for semi-product and reduction of transportation expenses. For the above usage, medium-C (0.45%C) steels have mainly been applied. The demand, however, for improved toughness and ductility comparable to those of the conventional quenched and tempered steels has led to the recent development of the lower carbon steel bars. The present study describes the properties of low-C (0.25%C) bar products, in contrast with those of the medium-C versions.

II. Experimental Procedure

Table 1 shows chemical composition of the basal steel together with the contents of C, Si, Mn, Cr, V and N individually added to the basal steel. The 100-kg laboratory heats were prepared for each steel by air melting, and the ingots were forged to 68-mm dia. billets. They were heated to 1180°C and rolled to 22-mm dia. bars on a 15-pass schedule. The finishing temperature was controlled to 940°C. Cold drawing was given up to 33% cross-sectional reduction. Experimental flow chart is shown in Fig. 1.

Table 1. Chemical compositions of basal steel (JIS S25C)

(wt.%)

C	Si	Mn	P	S	V	sol.Al	N
0.25	0.23	0.75	0.013	0.006	0.091	0.031	0.0098

Variables C: 0.20 ∼ 0.36, Si: 0.23 ∼ 0.78
Mn: 0.45 ∼ 1.55, Cr: Tr. ∼ 0.94
V: Tr. ∼ 0.36, N: 0.0059 ∼ 0.0156

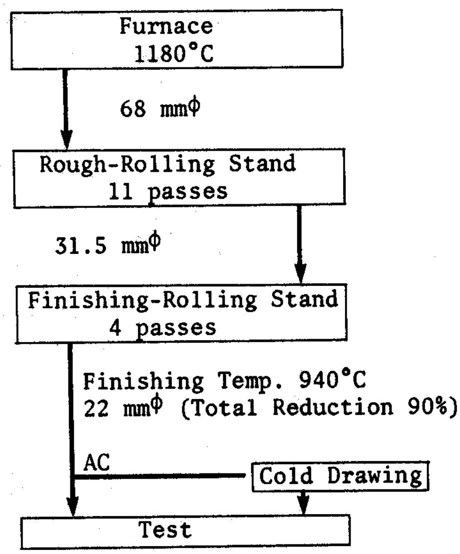


Fig. 1 Bar Rolling Layout

Solution temperatures of VC and VN for the basal steel shown in Table 1 were calculated using the following equations[1,2].

$$\log [V][C] = -\frac{9500}{T} + 6.72$$

$$\log [V][N] = -\frac{8330}{T} + 3.46$$

The values of 863°C and 1099°C were obtained for VC and VN, respectively. Strength and toughness properties were studied using JIS No. 4 tensile specimen and JIS No. 3 Charpy specimens, respectively.

Based on the above preliminary experiment, an alloy design was made to establish the chemical composition of as-rolled steel bars with the tensile strength of 640 MN/m^2 and 780 MN/m^2. Trial production of the above steel bars were carried out and the various processing and performance characteristics were studied: bending test, machinability test, friction welding test and soft-nitriding test, etc. Finally, the strength-toughness relationship obtained by the more sophisticated controlled rolling of 1050°C heating and 700°C finish-rolling was described.

Ⅲ. Results and Discussion

1. Effect of alloying elements on mechanical properties

Fig. 2 shows the effects of Mn, Cr and cold drawing on the strength and toughness. An addition of Mn up to 1.5% or Cr up to 0.5% increases the strength without deteriorating the toughness.

The above effects on Mn and Cr towards strengthening are interpreted to be due to the following individual or combined mechanism:

(1) Solution hardening.
(2) The shift of eutectoid point towards the lower carbon range with increasing Mn and Cr, resulting in an increase of the second-phase (pearlite) volume fraction
(3) Grain refinement due to the reduced Ar_3 temperature.

Photo. 1 shows the variation of microstructure with increasing Mn content. With a stepwise increment of Mn from 0.45 to 1.54%, the (ferrite + pearlite) microstructure becomes refined and the pearlite volume fraction increases. The similar trend is also recognized in Photo. 2, where the Cr content is varied. Photo. 3 shows electron micrographs of as-rolled bars with different Cr and Mn contents. With increasing Cr content, the pearlite inter-lamellar spacing tends to decrease, although Mn gives no remarkable effect on the inter-lamella spacing. An addition of Cr can therefore be effective to increase strength by an additional mechanism of refining the inter-lamella spacing.

As for the effects of alloying elements other than Mn and Cr, the strengthening effects by their addition were found to be always accompanied by an degradation in toughness. And, therefore, the detailed description of these results are not made here.

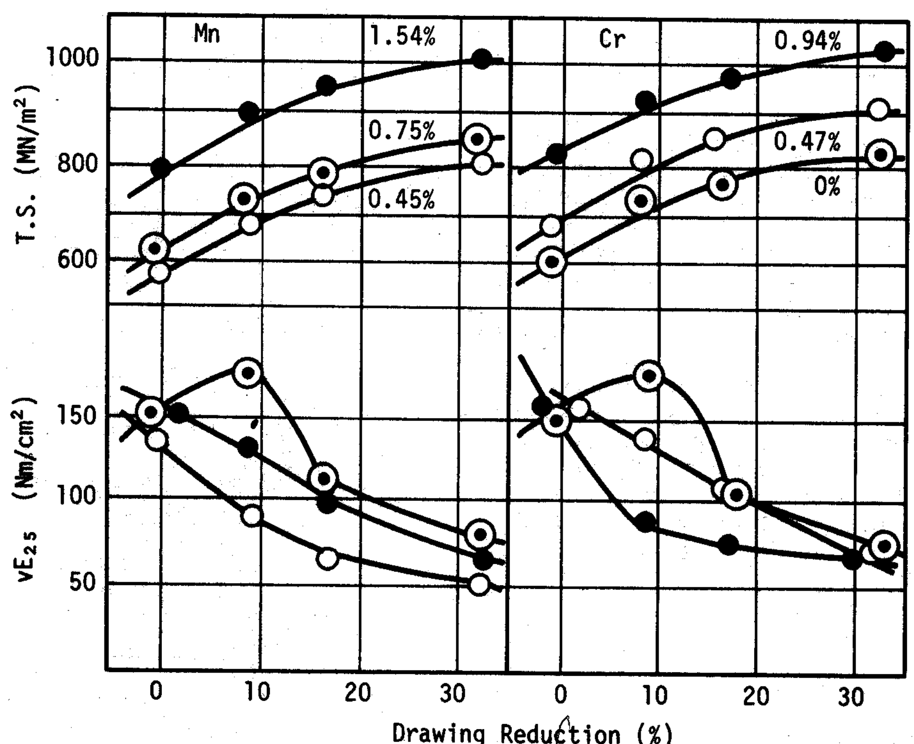


Fig. 2 Effect of Mn, Cr and cold drawing on strength and toughness.

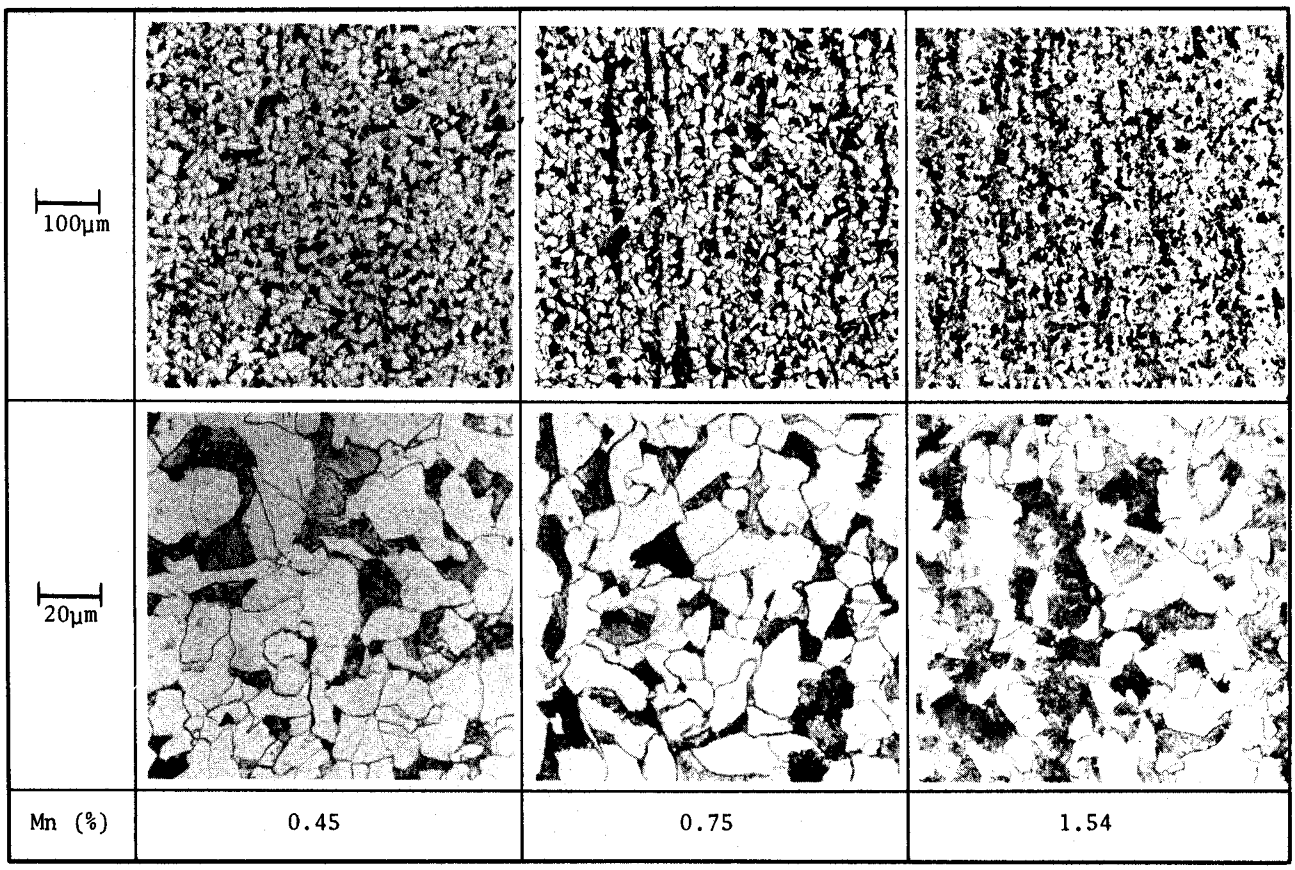


Photo. 1 Microstructures (variable: Mn content)

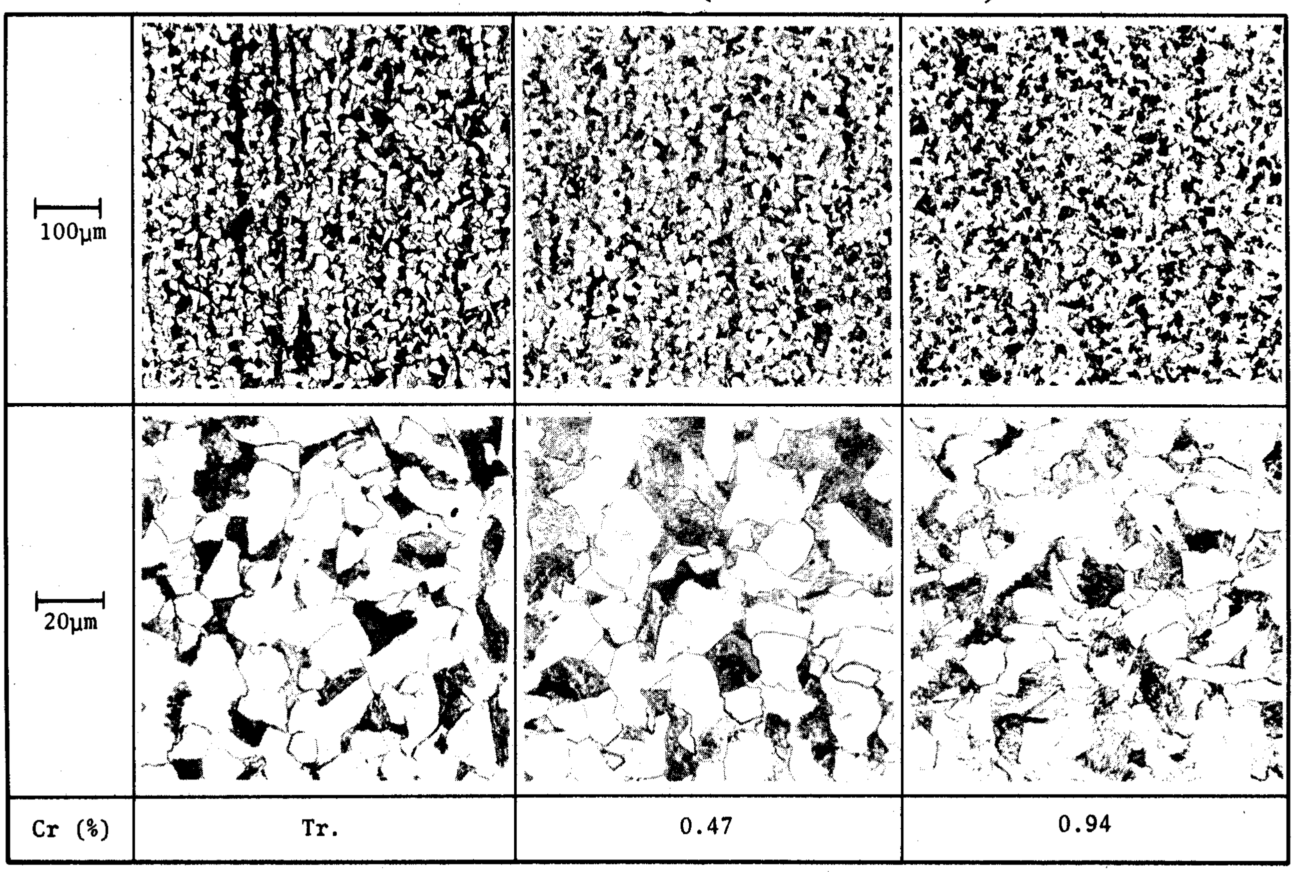


Photo. 2 Microstructures (variable: Cr content)

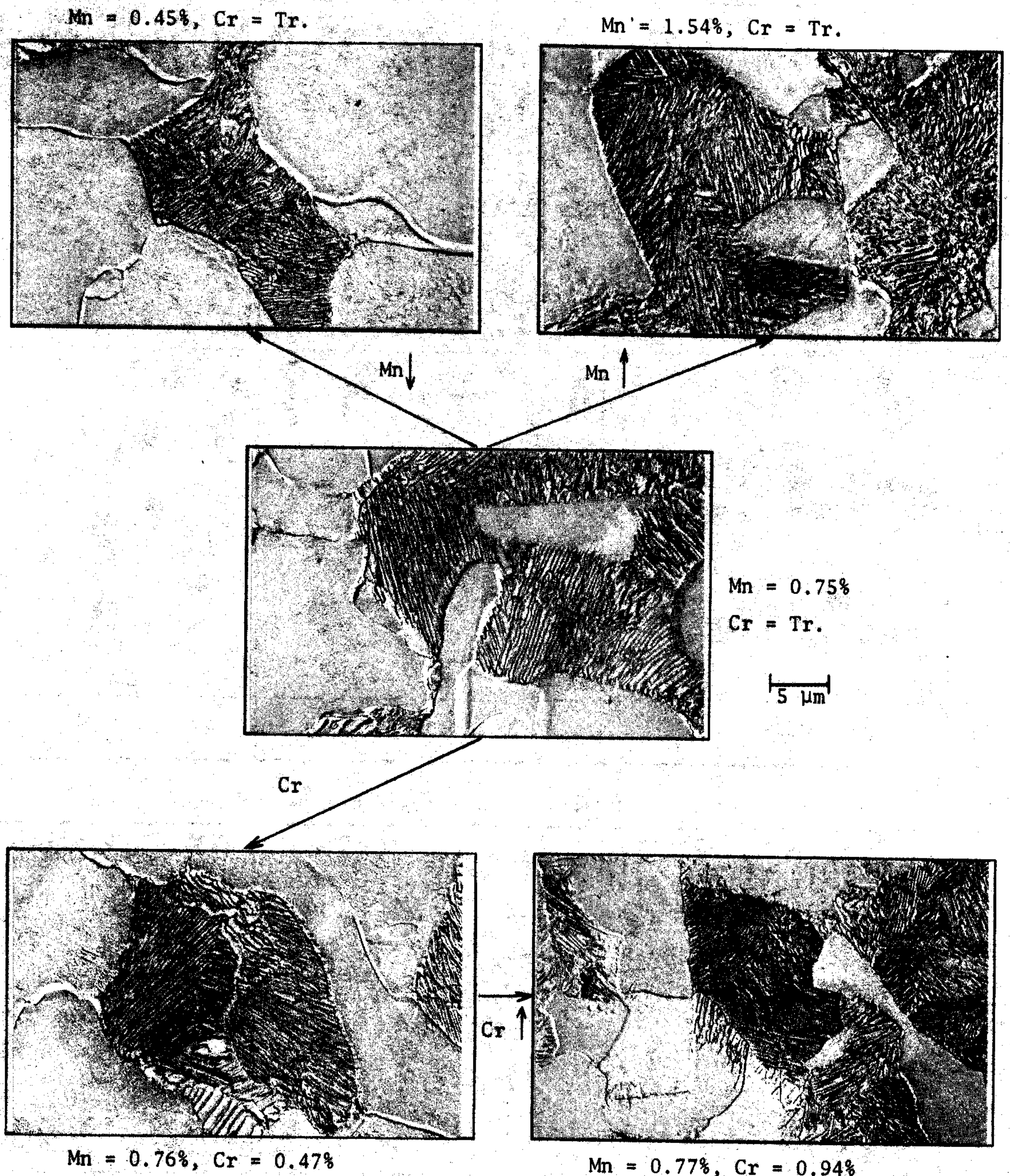


Photo. 3 Electron Micrographs (Two-Stage Replica)

Based on the above preliminary study, regression equations have been derived which can be used to predict yield strength (YP), tensile strength (TS) and hardness (H_RB).

YPcal (MN/m^2)

$$= 660(\%C) + 64.7(\%Si) + 159(\%Mn) + 60(\%V) + 1878(\%Nb) - 208(\%S) + 80.4$$

T.Scal (MN/m^2)

$$= 1046(\%C) + 49(\%Si) + 172(\%Mn) + 178(\%Cr) + 541(\%V) + 1204(\%Nb) - 335(\%S) + 167.$$

H_RBcal

$$= 69.1(\%C) + 4.7(\%Si) + 10.3(\%Mn) + 11.4(\%Cr) + 36.6(\%V) + 118.8(\%Nb) - 27.2(\%S) + 59.5$$

Fig. 3 indicates that the measured and calculated tensile strength are in an excellent agreement. Using these regression equations, chemical compositions corresponding to the 640 and 780 MN/m² tensile strength were determined, as shown in Table 2. The numbers attached to the designation LC or MC indicate specified minimum of tensile strength expressed in kgf/mm². LC and MC mean low carbon and medium-carbon versions, respectively. By adjusting the chemical composition together with applying a controlled rolling technique, predetermined as-rolled tensile strength is guaranteed for each steel.

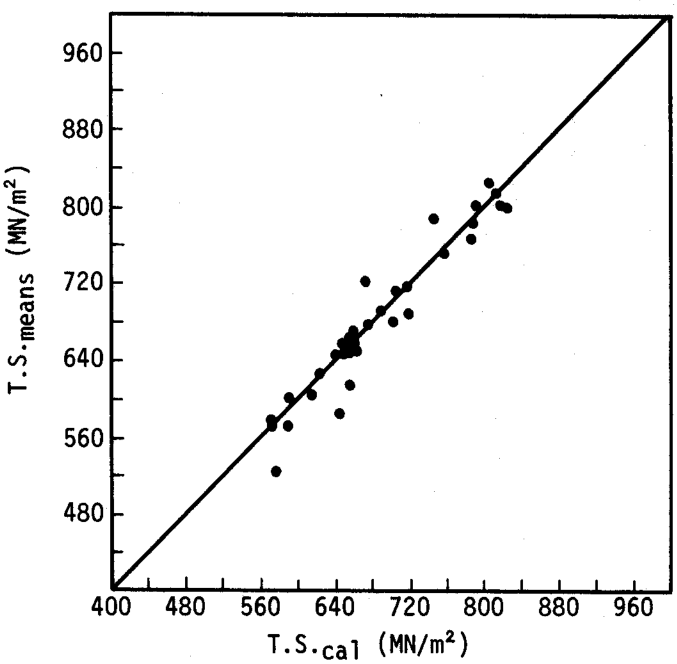


Fig. 3 Relationship between measured and calculated values of tensile strength.

Table 2 Chemical compositions of selected steels for further study.

Steel	C	Si	Mn	P	S	Cr	V	As-Rolled T.S. (MN/m²)
LC 65	0.24	0.21	1.14	0.016	0.016	0.05	0.10	640
LC 80	0.28	0.35	1.54	0.014	0.019	0.26	0.11	780
MC 65	0.31	0.28	0.86	0.011	0.029	0.09	0.10	640
MC 75	0.43	0.28	0.99	0.016	0.017	0.16	0.09	735
							(wt.%)	(Min.)

2. Properties of selected steels

Trial production on the steels shown in Table 2 has been made and diversified properties were studied. For comparison, medium-carbon versions with carbon content greater than 0.30% were also used.

2.1 Microstructures

Photo. 4 shows the microstructure of the as-rolled steel bars. Fine-grained (ferrite-pearlite) structures are obtained due to an application of controlled rolling. The average ferrite grain size was found to be 8.5, irrespective of the chemical composition.

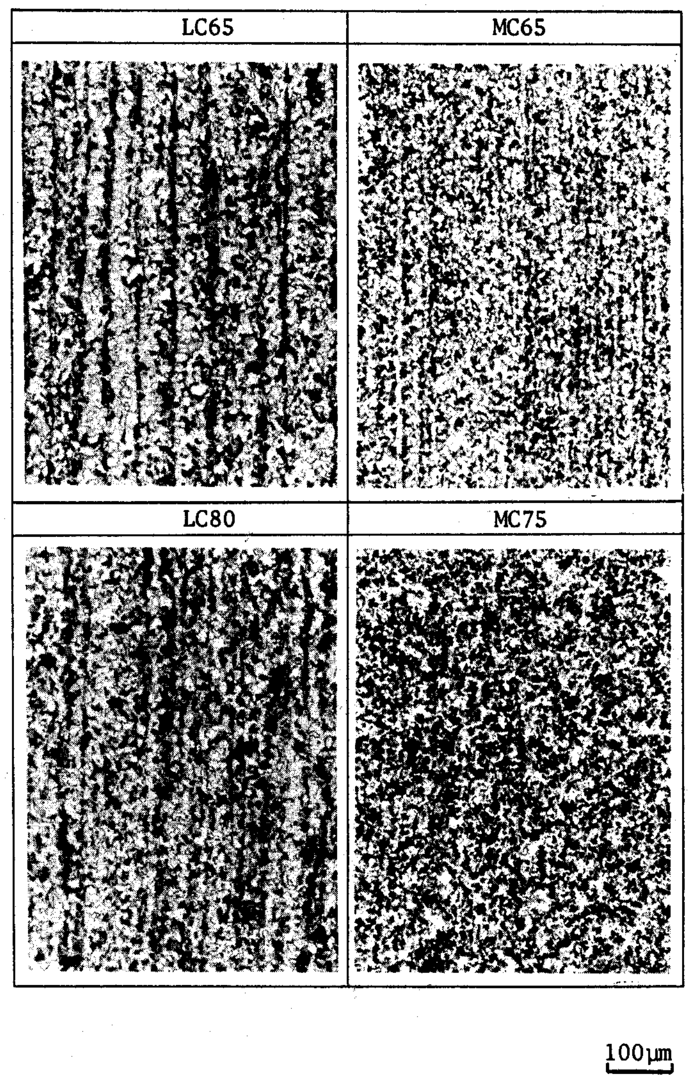


Photo. 4 Microstructures of as-rolled LC65, LC80, MC65 and MC75.

2.2 Mechanical properties

Fig. 4 gives mechanical properties as a function of the amount of cold drawing.

Drawing reduction up to 10% remarkedly increases the yield strength. With further increment in the amount of cold drawing, however, yield strength tends to saturate. On the other hand, tensile strength is seen to increase in proportion to the amount of cold drawing up to 25%.

Ductility expressed in terms of elongation (El) and reduction of area (RA) decreases with an increase in cold drawing. Charpy impact value at 20°C (vE_{20}) shows similar behavior to that of ductility. Fig. 5 depicts the variation of reduction of area with tensile strength. At the equivalent strength level, the low-carbon steels LC65 and LC80 show greater ductility that the

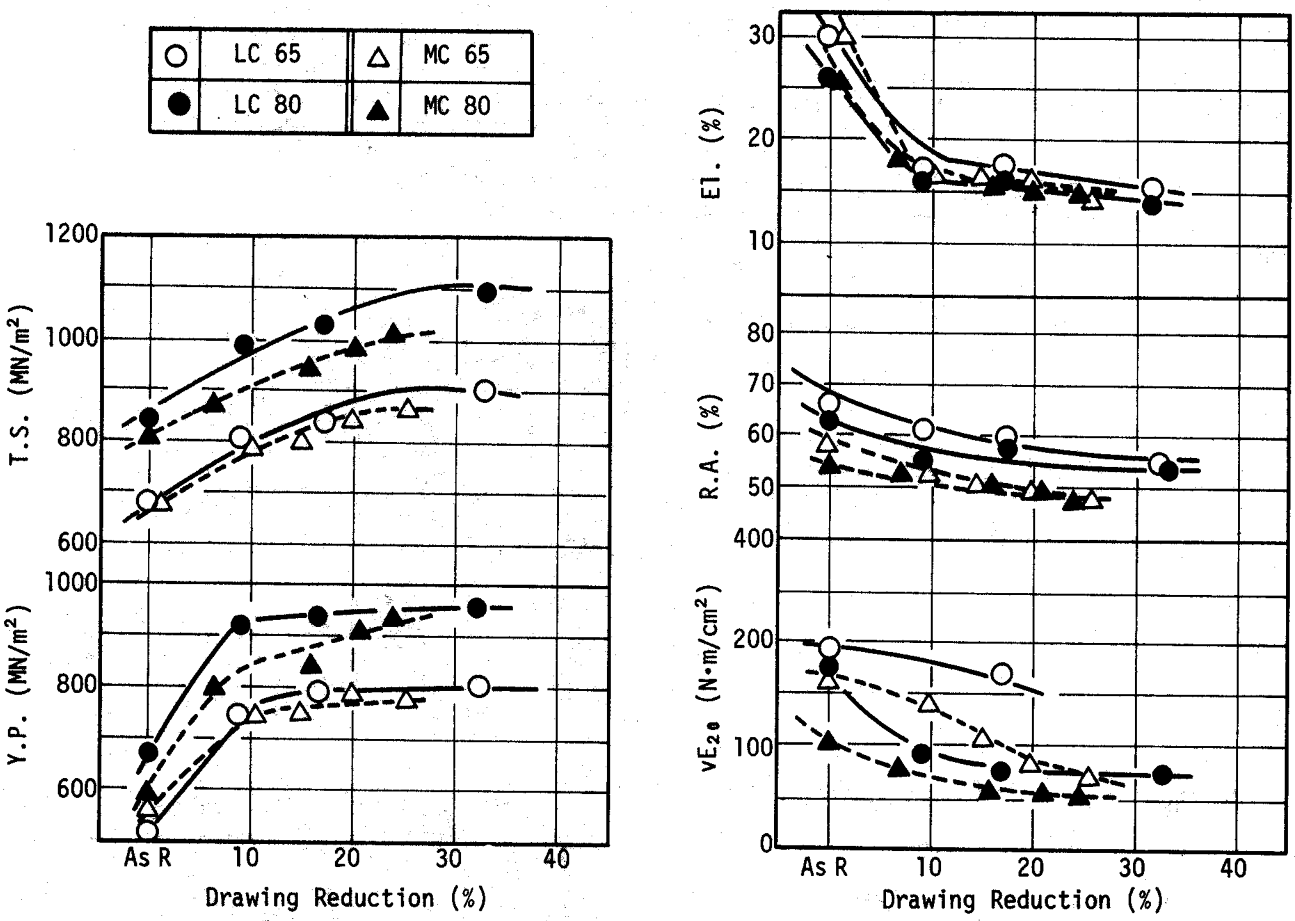


Fig. 4 Variation of mechanical properties with amount of cold-drawing.

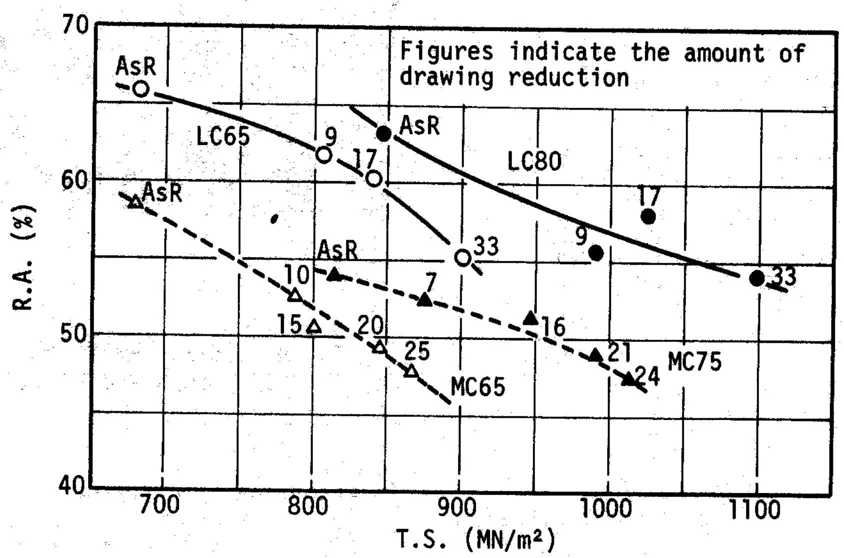


Fig. 5 Strength/ductility relationships (TS vs. RA)

medium-carbon versions, MC65 and MC75. Thus, reduced carbon content is confirmed to improve strength-ductility relationships of as-rolled and/or cold-drawn steel bars. At the tensile strength level ranging from 650 to 1050 MN/m^2, reduction of area equal to or greater than 55% could be obtained. Fig. 6 indicates the Charpy impact value as function of tensile strength. Impact values attained in the low-carbon steels, LC, are distinctly greater than those of the medium-carbon versions, MC. For high tensile strength level of 1000 MN/m^2, the impact value of 70 $N{\cdot}m/cm^2$ can be attained on the steels LC, in contrast with 50 $N{\cdot}m/cm^2$ obtained on MC.

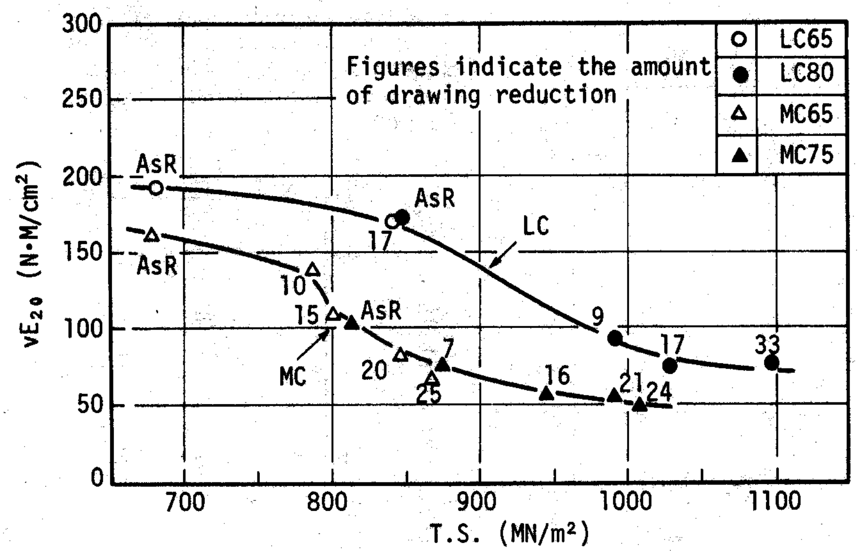


Fig. 6 Strength/toughness relationships (TS vs. vE_{20})

2.3 Bending properties

Bending test result is shown in Photo. 5. The steel bar, LC80, cold-drawn to 33% with the resultant tensile strength of 1080 MN/m^2 was tested under the 180° flat bending condition. No surface cracking was detected, indicating an outstanding bendability of LC80.

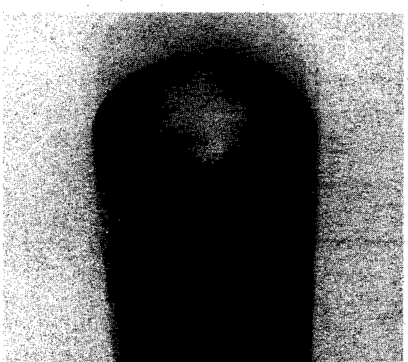


Photo. 5 Flat bend test on LC80
Drawing reduction 33%
(22mmϕ → 18mmϕ) TS 1080 MN/m^2

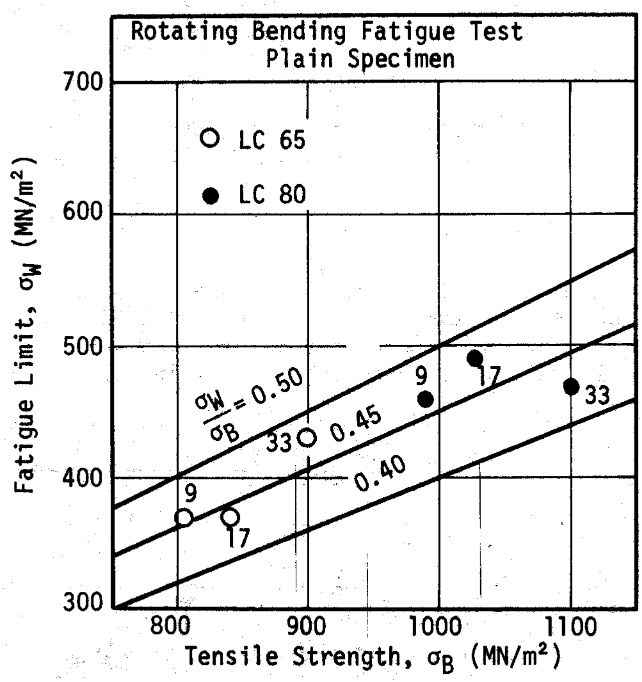


Fig. 7 Fatigue properties
(TS vs. fatigue limit)

2.4 Fatigue properties

One-type rotating bending fatigue test was performed, and the fatigue limits are presented in Fig. 7. Endurance ratios thus obtained fall within the range of 0.43 to 0.48, which are the well-established values for conventional structural steels now in common use.

2.5 Machinability

Fig. 8 demonstrates the machinability test results. Cutting force during the lathe turning test using carbide tools is plotted against cutting speed. Cold drawing applied on the as-rolled steel bars is found to reduce cutting force, thus leading to the improvement in machinability. In Fig. 8, it is also demonstrated that no substantial difference in machinability arises from reducing the carbon content.

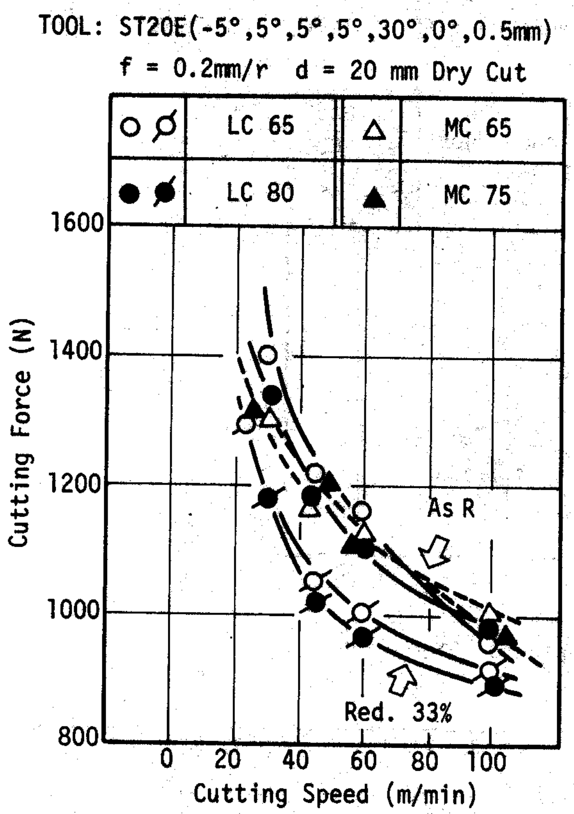


Fig. 8 Machinability test results (Cutting force vs. cutting speed)

2.6 Cold formability

Cold formability test was made on the steels LC and MC, and the results are given in Fig. 9 and 10. Static compressive deformation was given to the cylindrical specimen (8.5mm in dia. x 20mm in length) in the longitudinal direction. Fig. 9 compares cold formability of as-rolled low-carbon and medium-carbon steels. Steels LC show the improved cold-formability, as compared with medium-carbon steels MC. Critical compressive strain obtained on LC is greater than 80%, in contrast with that less than 80% for MC. Cold formability of cold-drawn bars is shown in Fig. 10, together with data for as rolled bars. With the cold-drawing of 33% cross-sectional reduction, tensile strength increases by approximately 200 MN/m^2. Even with this increment in strength, cold formability is found to suffer no sacrifice.

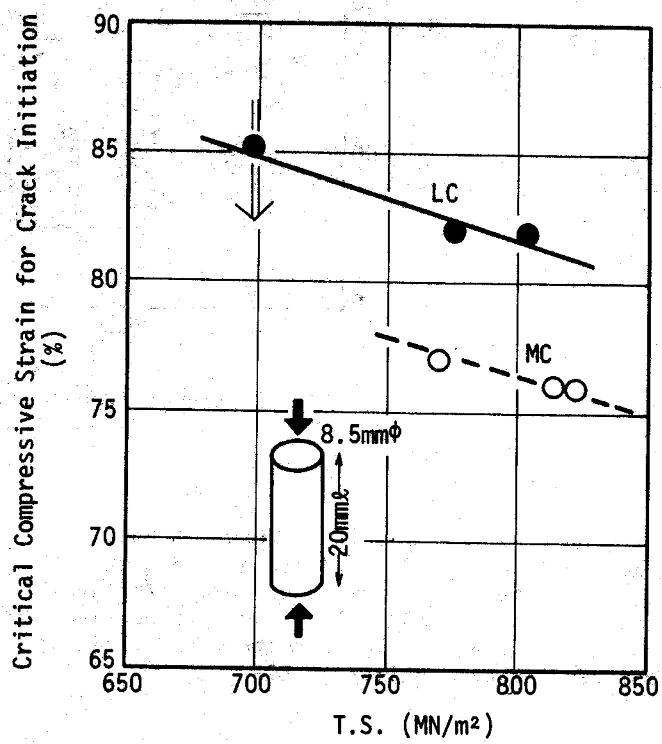


Fig. 9 Cold formability of as-rolled steel bars, LC and MC.

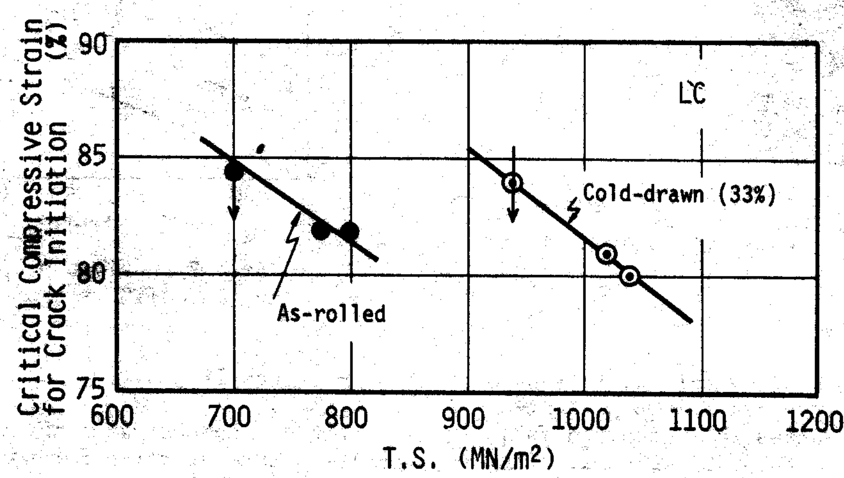


Fig. 10 Cold formability of as-rolled and cold drawn steel bars.

2.7 Mechanical properties of the friction-weld welded zone

Friction-welding test was conducted under the condition shown in Fig. 11, and the mechanical properties of friction-welded zone were investigated.

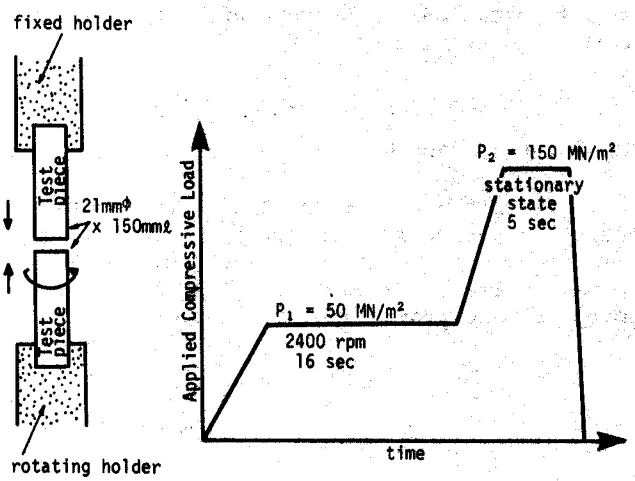


Fig. 11 Test condition of friction-welding.

Fig. 12 gives the change in impact value with tensile strength. Tensile test performed on the specimens containing the friction-welded zone in the center of gauge length indicated fracture originating at the position off the welded zone. Hence the values on the abscissa of Fig. 12 represents the tensile strength of the base metal. Charpy impact value obtained on the low-carbon steels LC show a marked contrast with those of the medium-carbon versions MC; in case of the steels MC, impact values of about 20 N·m/cm^2 are obtained for all strength levels studied. On other hand, the steels LC exhibit greater impact values inversely proportional to the tensile strength. The 180° flat bend test made on the welded zone of the steels LC gave no sign of cracking.

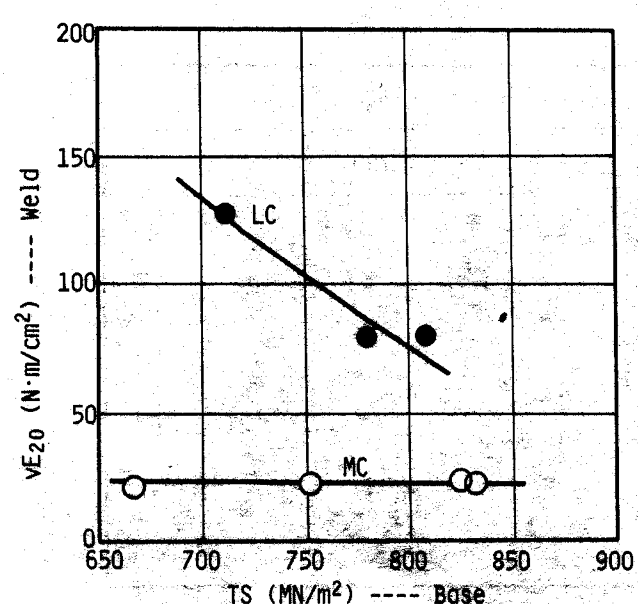


Fig. 12 Strength-toughness relationship of the friction welded zone

2.8 Soft-nitriding properties

As shown in Table 2, LC65 and LC80 are low-carbon, V-containing steels and hence their soft-nitriding characteristics are unique and attractive. Fig. 13 shows the hardness profile measured after soft-nitriding. Among S25C, S25C + 0.1%V, MC75 and LC80, the low-carbon steel modified by the combined addition of Cr and V (LC80) shows the best soft-nitriding behavior in terms of the surface hardness and the effective case depth: Surface hardness MHv 650, effective case depth 0.2mm, and core hardness MHv 260. LC80 meets the following compositional requirements to enhance the soft-nitriding response[3]:

(i) low-carbon content (< 0.30%)
(ii) Cr and V addition
(iii) Al-killed steel

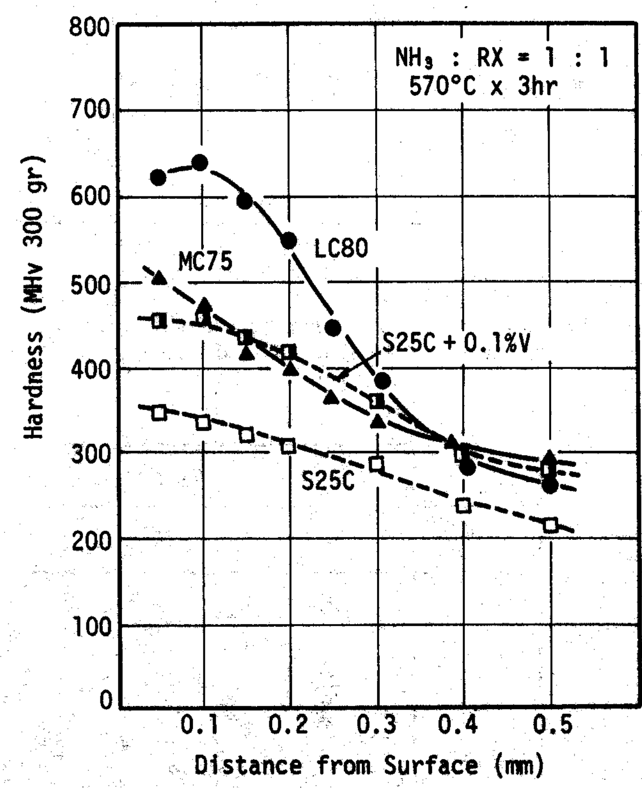


Fig. 13 Soft-nitriding response.

2.9 Variation of toughness with a change in rolling condition

To further improve the toughness of low-carbon as-rolled steel bars developed herein, the more sophisticated controlled rolling has been applied: 1050°C heating followed by 700°C finish rolling. Photo. 6 shows the microstructures encountered. It should be noted that, with a decrease in heating and finish-rolling temperatures, the resultant microstructure is remarkably refined. Fig. 14 demonstrates the improvement of toughness achieved by the lower-temperature hot rolling. An increment in impact value of 50 to 100 MN/m^2 could be obtained by a change in the hot rolling condition. Tensile strength, in contrast, does not seem to be increased by a reduction in the hot rolling temperature. The heating temperature applied here is 1050°C, and the precipitation strengthening effect of vanadium carbonitride is interpreted to be explored only to a limited extent. Thus, the positive effect of grain refinement towards strengthening is counteracted by the negative one of an imcomplete solution of vanadium carbonitride during heating at 1050°C. Note that, by an application of the lower-temperature controlled rolling coupled with a cold drawing of 17 to 33%, tensile strength and Charpy impact energy of greater than 1000 MN/m^2 and 100 N•m/cm^2 respectively, can be achieved. The above strength-toughness relationship is equivalent to that usually obtained on quenched and tempered standard Cr-Mo steels.

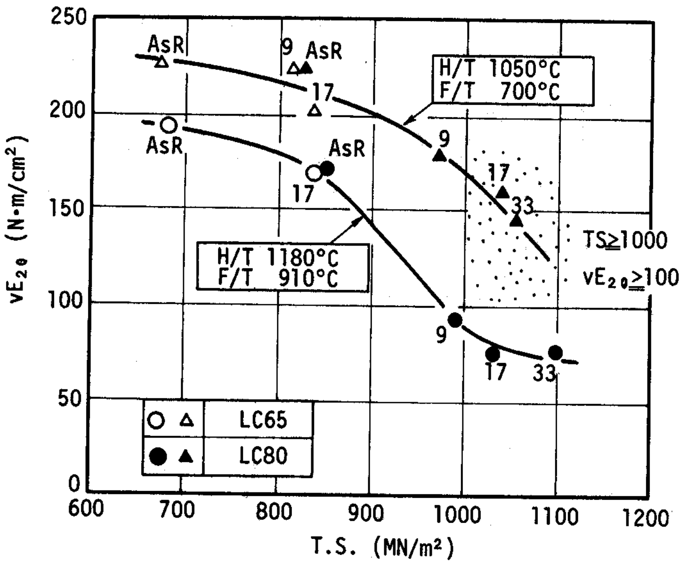


Fig. 14 Comparison of strength-toughness relationships obtained for different hot rolling condition.

IV. Potential and Proven Applications

Low-carbon as-rolled steel bars developed herein have already been getting a lot of publicity because of their excellent strength-toughness-ductility relationship. Fig. 15 gives potential and proven applications.

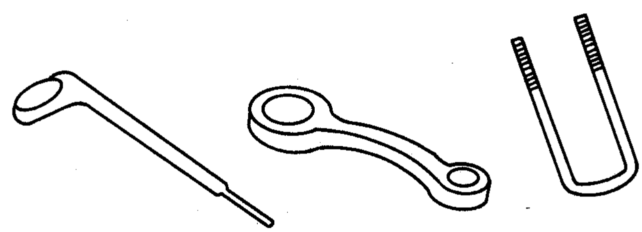
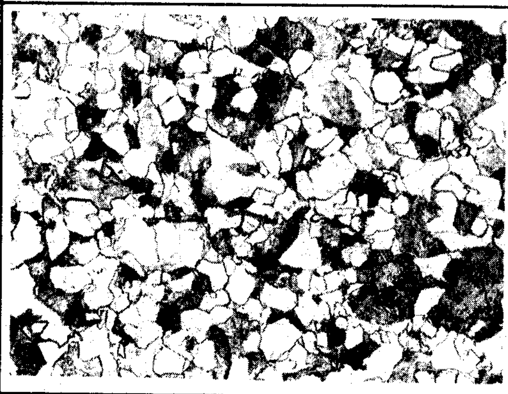


Fig. 15 Examples of current applications (potential and proven)

H/T	1180°C	1050°C
F/T	910°C	700°C
LC80		

68 mmΦ 22 mmΦ (15 pass-rolling) 20 μm

Photo. 6 Effect of heating and finish-rolling temperatures on the microstructure.

V. Summary

New type of low-carbon as-rolled high-strength low-alloy steel bars has been developed. They exhibit excellent strength-toughness-ductility relationships, as compared with the conventional medium-carbon versions. Their features are summarized in Table 4. With an appropriate amount of cold-drawing, tensile strength of 1000 MN/m^2 can be obtained together with the toughness of Charpy impact value of 70 $N \cdot m/cm^2$. With the more sophisticated controlled rolling, the impact value can be increased to 100 $N \cdot m/cm^2$, maintaining the equivalent tensile strength. The newly developed steel bars shows outstanding soft-nitriding characteristics and friction-welding properties. They are applicable to various machine and structural parts in the as-rolled, as-cold-drawn or as-soft-nitrided conditions.

Table 4 Features of low-carbon as-rolled steel bars.

1	Controlled Rolling	Grain Refinement
	Micro-Alloying	Precipitation Strengthening
2	Cold Drawing	Cold Work Hardening
	≈ 0.25% C	Excellent Strength / Ductility / Toughness Relationship
3	Cr, V, (Al)	Outstanding Soft-Nitriding Response

Acknowledgement

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Appendix

Among steels so far developed to eliminate the quenching and tempering process, low-carbon as-rolled HSLA bars described in the present paper lie in the relative position shown in the table below.

Table Classification of steels for the elimination of the quench and temper heat treatment

Carbon Level	Hot Forging	Direct Machining Drawing	Cold Forging
≈0.45%	0.45%C + V IH PPT	0.45%C + V IH 20~50mmφ Max. 130mmφ {GR by CR, PPT, CR}	—
≈0.25%	—	0.25%C + V {GR by CR, PPT, CW}	Materials for Bolts M6 ~ M12 {FP, LTTP (Bainite), CW}

IH: Induction Hardening
Strengthening Mechanism
- PPT : Precipitation
- GR by CR : Grain Refinement by Controlled Rolling
- CW : Cold Work
- FP : Fine Pearlite
- LTTP : Low-Temperature Transformation Products