Relation of Processing Variables in Thermomechanical Treatment to Strength, Ductility and Toughness of 280 kgf/mm² Grade Maraging Steel*

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Synopsis

In order to produce an ultrahigh strength maraging steel plate with excellent ductility and toughness, and free from mechanical anisotropy, the effects of processing variables in thermomechanical treatment on the mechanical properties of 13Ni-15Co-10Mo steel have been investigated. The relation between the prior austenite grain size and mechanical properties has also been investigated. The prior austenite grain size attainable is greatly affected by the degree of reduction in rolling. Grain refinement increases tensile strength and ductility, but does not improve fracture toughness. The anisotropy of strength and ductility is found to be related to the occurrence of the unrecrystallized austenite grain, whereas the anisotropy of fracture toughness is not observed in all conditions. Thus, the recrystallized and fine grained structure is found to be favorable to produce an excellent combination of strength, ductility and highly isotropic nature in mechanical properties. Such a microstructure is produced by choosing the optimum condition in thermomechanical treatment, which involves the rolling temperature and reduction.

I. Introduction

The experiment on the effect of microstructure on mechanical properties in a 280 kgf/mm² grade steel, has shown that the application of thermomechanical treatments is highly effective to obtain an excellent combination of strength, ductility and toughness in ultrahigh strength steels.¹⁾ Various ways of thermomechanical treatments have been tested and it has been elucidated that the most excellent combination of strength, ductility and toughness can be achieved with the multiple-pass rolling method for the square bar.²⁾ In addition, it has shown that the effect of the multiple-pass rolling during cooling on the tensile properties is not identical on the square bar and plate. It has been concluded that this is attributable to the difference in the austenite grain sizes attained in both rollings because of the difference in the degree of reduction and the distribution of the reduction during rolling. However, on practical applications of high strength steels,¹⁾ plates are very useful as well as bars, and the anisotropy in mechanical properties of the plate to the rolling direction will become an important problem.³⁻⁵⁾

The purpose of this study is to investigate the effects of processing variables in the thermomechanical

treatment by the multiple-pass rolling on mechanical properties with special reference to the relation with the austenite grain size and to understand the optimum condition for producing an ultrahigh strength steel plate with excellent ductility and toughness, and with highly isotropic nature in mechanical properties.

II. Experimental Procedure

1. Steels

The two steels, 13Ni-15Co-10Mo steel and 12Ni-16Co-11Mo steel having a slightly higher strength than the former steel, were prepared for the present investigation. These were melted as 17.5 kg ingots in a vacuum induction furnace. In the experiment described in Section III. 1, the three heats having the same nominal composition were prepared for both steels. In the experiments described in Sections III. 2, III. 3 and III. 4, one heat of 13Ni-15Co-10Mo steel was prepared respectively. After all, six heats of 13Ni-15Co-10Mo steel and three heats of 12Ni-16Co-11Mo steel were prepared for the present investigation. However, it is considered that there is no essential difference in heats having the same nominal composition, as all the heats are highly pure, as shown in Table 1, and were melted in accordance with the nominal composition. The ingots were hot rolled down into the plate with 40, 50 and 60 mm thicknesses, 60 mm width and 100 mm length and these rolling blanks were used as the starting material for thermomechanical treatment.

2. Thermomechanical Treatment

The rolling blanks were homogenized at 1 200°C for 24 h in hydrogen and reheated at 1 250°C for 1 h in air. These were subsequently deformed during the cooling period according to the schedule of rolling pass shown in Table 2, and quenched into water within 6 s after the final pass. The starting temperature of rolling (hereafter referred to simply as starting temperature) for all the cases of total reduction was

Table 1. Chemical composition of alloys used. (%)

	C	Si	Mn	P	S	Ni	Co	Mo	Ti	Al	Mg	Fe
13Ni-15Co-10Mo	0.004	0.005	0.003	0.004	0.004	12.65	14.61	9.62	0.18	0.006	0.001	Bal.
12Ni-16Co-11Mo	0.003	0.006	0.003	0.004	0.005	12.09	15.21	10.45	0.17	0.005	0.001	Bal.

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Table 2. Schedule of rolling pass in thermomechanical treatment.

Initial thickness (mm)	Number of pass							Final thickness (mm)	Total reduction (%)
	1	2	3	4	5	6	7		
40	28 mm*	19	12	9	7			12	70
	30%**	32	37	42%				7	82
50	35 mm	28	19	12	9	7		12	76
	30%	20	32	37	42%			7	86
60	42 mm	35	28	19	12	9	7	12	80
	30%	17	20	32	37	42%		7	88

* Thickness of plate

** Reduction per one pass

maintained at a constant temperature of 1 200°C and the finishing temperature of rolling (finishing temperature) was adjusted to a constant temperature of 900°C by varying the interval of rolling pass. When applying the multiple-pass rolling, the design of the reduction in each pass is also of importance as well as the total reduction, which is measured from the difference between the initial and final thicknesses. Therefore, the reduction in each pass shown in Table 2 was decided from the following standpoint. Firstly, it was aimed to supply the reduction above 30% in each pass, because the reduction of about 30% was supplied for the square bar rolling by which the most excellent result was obtained in the previous work.²⁾ Secondly, it was aimed that the reduction increased in the order of the rolling pass and, particularly, the reduction of about 50%⁶⁾ was supplied at the final pass because the critical reduction required for recrystallization increases with decreasing the rolling temperature.^{7,8)} The result of the preliminary experiment clearly indicates that supplying the reduction of 50% at the final pass at about 900°C is impossible due to the limitation in capacity of rolling machine. Hence, when rolled from 12 mm to 7 mm at the final pass, the rolling blanks were rolled down to 9 mm and then immediately to 7 mm thickness without interval. Due to the above mentioned situation, the pass of 12→9→7 mm is indicated in Table 2 as the reduction of 42%.

3. Measurement of Prior Austenite Grain Size

The microstructural observation was made on the change of the size and shape of the austenite grain. In order to make clear the prior austenite grain boundary, the specimen was aged at 500°C for 30 min and electrolytically etched in a 10% chromic acid solution.

The prior austenite grain size was measured on both the longitudinal and transverse sections to the rolling direction as shown in Fig. 1. The transverse section is hereafter referred to as L section because the average grain size of this section is mainly responsible for mechanical properties on the specimen taken from the longitudinal direction to the rolling direction, and the longitudinal section is referred to as T section. The prior austenite grain size was

Section	Average prior grain size	Grain aspect ratio
L	$1.78 \left(\frac{\bar{a} + \bar{b}}{2} \right)$	$a_L = \frac{\bar{b}}{\bar{a}}$
T	$1.78 \left(\frac{\bar{a} + \bar{c}}{2} \right)$	$a_T = \frac{\bar{c}}{\bar{a}}$

Fig. 1. Schematic representation of measurement of the prior austenite grain size and grain shape in the rolled plate.

measured by linear intercept method. In the case of elongated grain, the grain size and the degree of deformation were indicated by the average grain size and the grain aspect ratio, as shown in Fig. 1.

4. Tensile and Fracture Toughness Testing

Tensile test specimens were machined to orient the specimen axes parallel and perpendicular to the rolling direction and the fracture toughness test specimen was machined from L-T and T-L directions (hereafter referred simply as L and T directions, respectively), which are specified in the ASTM specification.⁹⁾ All the specimens were subjected to the aging treatment at 500°C for 4 h to produce the maximum hardness condition.

Tensile tests were carried out on the specimen of 3.5 mm diameter and 25 mm gauge length in a strain rate of $3.3 \times 10^{-3} \text{ s}^{-1}$. Fracture toughness tests were carried out in accordance with the ASTM specification,⁹⁾ using the three point bending specimen with 10 or 5 mm thickness, 10 mm width and 40 mm span for loading. These tests were conducted at room temperature and the experimental value under a testing condition was indicated as the average of two or three measurements.

III. Experimental Result and Discussion

1. Effect of Reduction

Figure 2 shows the effect of total reduction on the average prior austenite grain size and grain aspect ratio on L and T sections, showing the grain refinement with increasing the reduction. The grain size of 12Ni-16Co-11Mo steel is slightly finer than that of 13Ni-15Co-10Mo steel. For both steels, the observed grain size is finer in L section than in T section. This is attributed to the elongated grain in the rolling direction (the unrecrystallized grain) after the final pass as is evident from grain aspect ratio. There is no systematic change of grain aspect ratio for both steels as a function of total reduction.

Fig. 2. Effect of total reduction on the prior austenite grain size and grain aspect ratio.

Open marks refer to the longitudinal properties and full marks to the transverse properties.

Fig. 3. Effect of total reduction on the tensile properties and plane strain fracture toughness for a) 13Ni-15Co-10Mo steel and b) 12Ni-16Co-11Mo steel.

As stated above, the finishing temperature adopted in the present experiment was 900°C, because the recrystallization temperature of these steels was expected to be about 900°C from the result of the previous work.²⁾ However, the result in Fig. 2 shows that this finishing temperature is too low to obtain the recrystallized grain structure. It is necessary to examine the stage of formation of the elongated grain during multiple-pass rolling and the appropriate finishing temperature to obtain the recrystallized grain structure. These will be discussed in detail.

Figure 3 shows the effect of total reduction on tensile properties and plane strain fracture toughness (K_{Ic}). With increasing the degree of total reduction, the tensile strength increases slightly and the reduction of area is greatly improved. These steels, however, have the marked anisotropy to the rolling direction in both properties. The tensile strength is higher and the reduction of area is lower in T direction than in L direction. In contrast, K_{Ic} is scarcely affected by the degree of reduction and by the direc-

Open marks refer to the longitudinal properties and full marks to the transverse properties.

Fig. 4. Relationship between the tensile properties and average prior austenite grain size for a) 13Ni-15Co-10Mo steel and b) 12Ni-16Co-11Mo steel.

tion of the specimen. In 12Ni-16Co-11Mo steel, the strength is higher by 10~20 kgf/mm² and, the reduction of area and K_{Ic} are lower than in 13Ni-15Co-10Mo steel.

Figure 4 shows the effect of the average prior austenite grain size on the tensile strength and the reduction of area. The properties in each direction are shown as a function of average grain size of the corresponding section, which is mainly responsible for the properties. Both the tensile strength and the reduction of area exhibit the linear relationship with reciprocal square root of average prior austenite grain size d , and the slopes are identical, irrespective of the kind of steels and the specimen directions. It can be seen that the reduction of area is effectively improved by the grain refinement. As shown above, the reduction of area still exhibits the anisotropy when rearranged as a function of $d^{-1/2}$. That means that the anisotropy of reduction of area is not solely caused by the difference in the effective grain size for the corresponding sections.

Figures 5 and 6 show the tensile strength *vs.* K_{Ic} plot, and the tensile strength *vs.* the reduction of area plot from the results of both steels shown in Fig. 3. K_{Ic} is highly isotropic and scarcely shows the scatter. With increasing the tensile strength, K_{Ic} slightly decreases. On the other hand, the relation between the reduction of area and tensile strength shows considerable scatter. This is not so surprising because the reduction of area is strongly dependent on the prior austenite grain size. However, as shown in Fig. 6 by the solid and broken lines, the linear relationships in the identical direction can be obtained if one selects only the value with fine grained structure. Therefore, the anisotropy of the reduction of area can not be explained solely by the difference of the strength in both directions. As the result, the anisotropy of tensile ductility is mainly caused by the anisotropy in strength (the anisotropy in the plastic flow behavior) and by the difference in the prior austenite grain size. It is usually said that the anisotropy in ductility is strongly related to the con-

Fig. 5. Relationship between tensile strength and plane strain fracture toughness.

Double marks show the result of the specimen with fine grained structure.

Fig. 6. Relationship between tensile strength and reduction of area.

figuration of nonmetallic inclusions for high tensile strength steels.^{10,11)} However, this is not the case for the anisotropy in ductility in the present steels because the amount of impurity elements is extremely reduced.

2. Behavior during Multiple-pass Rolling

Figure 7 shows the change of austenite grain size and mechanical properties of 13Ni-15Co-10Mo steel during multiple-pass rolling in the case of 82% total reduction. The initial grain size of 850 μm is refined with successive rolling passes to 20 μm after the third pass. The recrystallized grain structure is obtained up to the third pass, but after the fourth pass the elongated grain structure is formed. After the fifth pass the grain is further elongated to the rolling direction, so the apparent average grain size on T section is increased. An unstable fracture in a low stress level occurs on the specimen with coarse grain size after the first and the second passes, but after the third pass the reduction of area above 20% and the isotropy in tensile strength and in reduction of area are obtained. With a further increase in the number of pass, the tensile strength increases rapidly and the reduction of area decreases in T direction, so that the anisotropy in strength and ductility begins to appear. K_{Ic} is slightly higher after the first and the second passes, but K_{Ic} does not change very much and is also isotropic.

As a result of the above observations, the following two facts can be made clear. Firstly, an unstable

Open marks refer to the longitudinal properties and full marks to the transverse properties.

Fig. 7. Change of austenite grain and the mechanical properties during multiple-pass rolling of 13Ni-15Co-10Mo steel. Initial grain size is 850 μm , the starting temperature of rolling 1 200°C, the finishing temperature of rolling 900°C and total reduction 82%.

fracture in a low stress level occurs at more than 40 μm of grain size and does not at 35 μm as reported previously,²⁾ so that the critical grain size above which an unstable fracture in a low stress level occurs is about 40 μm for 13Ni-15Co-10Mo steel. Secondly, the anisotropy in strength and ductility is not observed in the recrystallized grain structure and the appearance of the anisotropy well corresponds to the formation of the elongated grain.

3. Effect of Warm Working below Recrystallization Temperature

In order to confirm the effect of the elongated grain on mechanical properties observed in the previous section, the effect of warm working below the recrystallization temperature, or ausforming was examined. In the previous experiment, the starting material for thermomechanical treatment was obtained by the homogenization treatment in hydrogen and air after deformation, so that the initial grain size became extremely coarse. This is remarkably unfavorable to grain refinement by utilizing the recrystallization behavior.⁷⁾ Accordingly, in the experiments hereafter, the homogenization treatment was conducted on the ingots, followed by the rolling it down into the plate to 40 mm thickness and 60 mm width. By this procedure, the initial grain size of the starting materials for the thermomechanical treatment was greatly refined.

The starting materials which were solution treated at both temperatures of 1 250°C and 1 050°C, were rolled down into the plate of 12 mm thickness by three passes, subsequently air cooled to 800°C, and given the reduction (ausformed). The recrystallized grain size obtained was 30 and 16 μm , respectively. Figures 8 and 9 show the effect of the degree of reduction at 800°C on the prior austenite grain size and the mechanical properties. The elongated grain structure is formed by the warm working below the recrystal-

Fig. 8. Effect of the reduction below recrystallization temperature of austenite phase (at 800°C) on the average prior austenite grain size and grain aspect ratio in 13Ni-15Co-10Mo steel. Initial grain size is 30 μm for a) and 16 μm for b).

Fig. 9. Effect of the reduction below recrystallization temperature of austenite phase (at 800°C) on the mechanical properties in 13Ni-15Co-10Mo steel. Initial grain size is 30 μm for a) and 16 μm for b).

lized temperature for both the initial grain sizes. With increasing the reduction, the tensile strength increases and the increasing rate of the strength is faster in T direction than that in L direction. As the result, the anisotropy in the strength begins to appear. Such an anisotropy in the strength has been frequently observed in high tensile strength steels rolled at lower temperatures. This has been explained by the formation of texture structure in martensite due to preferred orientation of the unrecrystallized austenite phase.^{12,13)} The reduction of area scarcely changes in L direction but is slightly reduced in T direction, so that the marked anisotropy appears when heavy reduction is given. On the other hand, K_{Ic} is scarcely affected by the degree of reduction and by the direction of the specimen. Although there is no possibility to improve K_{Ic} , one can expect to improve the strength by applying ausforming without

Fig. 10. Effect of a) the starting temperature and b) the finishing temperature of rolling on the prior austenite grain size and grain aspect ratio in 13Ni-15Co-10Mo steel.

any loss of K_{Ic} . Thus, ausforming is effective for improving the strength and ductility in L direction but has a weak point to promote the mechanical anisotropy.

4. Effect of Starting and Finishing Temperatures of Rolling

The results described in the previous sections clearly indicate that the excellent combination of strength, ductility and toughness and the isotropic nature can be obtained in the recrystallized and fine grained structure. In order to get the optimum condition for obtaining such a microstructure, the effects of starting and finishing temperatures on the structure and mechanical properties were investigated on 13Ni-15Co-10Mo steel in the case of 82% total reduction. For the examination of the effect of starting temperature, the starting plate was heated for 1 h at the temperature 50°C higher than the starting temperature, and was rolled down and roll-finished at 900°C for all the specimens. Thus, when varying the starting temperature, the initial grain size was also varied as 350, 220 and 100 μm at 1 200°, 1 100° and 1 000°C, respectively. For the examination of the effect of finishing temperature, the starting temperature was maintained at a constant temperature of 1 200°C.

Figure 10 shows the effect of the starting and finishing temperatures on the prior austenite grain size and the grain aspect ratio. In this figure, the grain sizes in the thickness direction ($\bar{a}$), in rolling transverse direction ($\bar{b}$) and in rolling direction ($\bar{c}$), which are shown in Fig. 1, are presented in addition to average grain size. This kind of presentation is essential to understand general features, because the average grain size is relatively insensitive to the processing variables but the grain sizes along the elon-

gated grain axes seem to be very sensitive, as is evident in Fig. 10. The prior austenite grain size on both sections is greatly refined with decreasing the starting temperature, but the grain aspect ratio is scarcely dependent on the starting temperature. With respect to the effect of the finishing temperature, the prior austenite grain size is slightly refined when the finishing temperature is lowered from 1050° to 1000°C, but with a further decrease to 900°C the grain size is coarsened. The recrystallized grain structure is obtained at the finishing temperature of 1050°C, and the elongated grain structure is obtained at 1000° and 900°C. Since the relation between grain aspect ratio on L section (a_L) and the degree of reduction (r) is given by the formula $r = (\bar{b} - \bar{a})/\bar{b} = 1 - 1/a_L$, the elongated grain is considered to be formed at the stage of the final pass (9 mm → 7 mm) in the case of the finishing temperature of 1000°C and at the stage from the previous pass in the case of 900°C.

The changes of mechanical properties due to processing variables are shown in Fig. 11. As the starting temperature is lowered, the strength increases gradually, and the reduction of area is greatly improved in L direction and is reduced in T direction in the case of the finishing temperature of 1000°C. The improvement of strength and ductility well correspond to the refinement of the prior austenite grain size with an exception of the behavior in T direction. K_{Ic} does not change by the change in the starting temperature and is also isotropic. With respect to the effect of the finishing temperature, the anisotropy in the strength is not observed at 1050°C, and the reduction of area is relatively inferior. The reduction of area is improved at 1000°C and the slight anisotropy in strength appears. The anisotropy in strength increases further at 900°C and the reduction of area is reduced less than that at 1000°C. Such changes in tensile properties well correspond to the refinement of the prior austenite grain size as mentioned above. K_{Ic} is also independent of the finishing

temperatures.

In the case of the finishing temperature of 1000°C, the additional experiment that the starting temperature was lowered to 1100°C, was carried out and its results are shown as double marks on the axis of 1000°C in Fig. 11 (b). This treatment is expected to obtain the recrystallized grain structure even at the finishing temperature of 1000°C, because the initial grain size is refined and so the critical reduction required to recrystallization may be reduced. When applying this treatment, the prior austenite grain is slightly finer than that at 1200°C of starting temperature, but the elongated grain structure is still obtained, and tensile properties and K_{Ic} scarcely change. In order to obtain the recrystallized grain structure, it is necessary to raise the finishing temperature above 1050°C but it becomes difficult to obtain the extremely refined grain structure. Accordingly, to obtain the recrystallized and extremely fine grained structure, the following two methods can be considered. Firstly, the finishing temperature is selected at 1050°C and the degree of total reduction is increased more than 82%. Secondly, the finishing temperature is selected at 1000°C but the reduction from 12 mm to 7 mm at the final pass has to be supplied directly, or by one pass. Whenever applying any methods, the finishing temperature of 900°C mainly supplied in the present work is too low to obtain the recrystallized grain structure and the finishing temperature has to be elevated to 1000° ~ 1050°C. This is in agreement with the result reported by Ishihara *et al.*¹⁴⁾

The fact will be lastly discussed that the pronounced anisotropy in tensile ductility is observed and its change does not correspond to the change in average grain size when the starting temperature is 1000°C. As is evident in Photos. 1 (a) and (b), the average grain size is finer at 1000°C than at 1100°C of the starting temperature, but the coarse elongated grains are partially observed as shown in Photos. 1 (c) and (d). This mixed grain structure is apt to be formed when 1) the starting temperature is low and 2) the initial grain size is coarse. As the recrystallization is difficult to occur under these two conditions,⁷⁾ the coarse elongated grain may be formed as the result that the unrecrystallized grain formed in the early stage in rolling schedule is retained by being prevented to recrystallize. However, if the ductility loss is only caused by the formation of mixed grain structure, it has to be explained why the ductility in L direction is not reduced but that in T direction is solely reduced. These coarse elongated grains are scarcely observed in the center of the rolled plate and frequently observed near the surface as shown in Photo. 2. In addition, the elongated grain is more elongated on T section than on L section. A round specimen of 3.5 mm diameter cut from the rolled plate of 7 mm thickness exhibits more elongated grains on T section than on L section. The difference may reflect the anisotropy in ductility.

The above explanation is too simple to be accepted. However, the similar mixed grain structure

Fig. 11. Effect of a) the starting temperature and b) the finishing temperature of rolling on the mechanical properties of 13Ni-15Co-10Mo steel.

- (a) STR 1 100°C, T section
- (b) STR 1 000°C, T section
- (c) STR 1 000°C, L section
- (d) STR 1 000°C, T section

Photo. 1.

Optical micrographs of the rolled plate of 13Ni-15Co-10Mo steel, showing the effect of the starting temperature of rolling (STR) and the occurrence of the coarse unrecrystallized grain.

- (a) STR 1 000°C, L section
- (b) STR 1 000°C, T section

Photo. 2. Optical micrographs of the rolled plate of 13Ni-15Co-10Mo steel, showing the occurrence of the coarse unrecrystallized grain along thickness direction.

has been observed in the control-rolled high tensile strength steel¹⁵⁾ and has been pointed out to have the detrimental effect on notch toughness.¹⁶⁾ Accordingly, it is the subject for future study to investigate the condition and mechanism for the formation of the coarse elongated grain and to make clear its effect on mechanical properties.

5. Effect of Testing Condition on Fracture Toughness

The fatigue cracking was conducted before aging in the fracture toughness testing for 280 kgf/mm² grade steel reported previously^{1,2)} because of the difficulty to control the crack length after aging. However, as the ASTM specification⁹⁾ recommends to fatigue crack the specimen after whole heat treatment, the specimen was cracked after aging in the present study. Therefore, in order to make clear the relation with the experimental values reported previously, the fatigue cracking was conducted for all specimens before and after aging.

Figure 12 shows both relationships, showing that apparent K_{Ic} measured with the specimen fatigue cracked before aging is always higher than valid K_{Ic} measured with the specimen fatigue cracked after aging. Apparent K_{Ic} is about 10% higher than valid K_{Ic} and scarcely shows the scatter when valid K_{Ic} is below 90 kg/mm^{3/2}. Therefore, the higher the fracture toughness, the more sensitive the experimental value becomes to conduct the conditions for fatigue cracking. However, when valid K_{Ic} is about 110 kg/mm^{3/2}, four experimental values are present which are identical in both conditions. These experimental values are the results after the first and the second passes in rolling schedule and therefore, are obtained in the extremely coarse grained structure. However,

Fig. 12. Relationship between valid K_{Ic} obtained from the specimen precracked after aging and apparent K_{Ic} obtained from the specimen precracked prior to aging.

it is not clear why K_{Ic} is not affected with the condition for fatigue cracking if the specimen has the coarse grained structure, so this is a subject for a future study.

IV. Conclusion

In order to produce an ultrahigh strength maraging steel plate with excellent ductility and toughness and free from mechanical anisotropy, the effects of processing variables in the thermomechanical treatment on mechanical properties of 13Ni-15Co-10Mo steel have been investigated with special reference to the relation with grain size. The results are summarized as follows:

(1) When applying thermomechanical treatment by multiple-pass rolling, grain refinement proceeds by the repetition of working-recrystallization and the austenite grain size attainable is strongly dependent on the degree of reduction. The heavier the degree of reduction is, the finer the austenite grain size is.

(2) Tensile strength and reduction of area can be improved by austenite grain refinement, whereas K_{Ic} is independent of grain size.

(3) The anisotropy of strength and ductility to the rolling directions is observed when the unrecrystallized grain is formed during rolling. The strength is higher and ductility is lower in T direction than in L direction. When the degree of reduction increases below the recrystallization temperature, the strength increases and the ductility decreases further in T direc-

tion, so that the anisotropy of both properties becomes remarkably.

(4) K_{Ic} is scarcely affected by warm working below the recrystallization temperature and its anisotropy to the rolling direction is not observed.

(5) Thus, the recrystallized and fine grained structure is found favorable to produce the excellent combination of strength, ductility and highly isotropic nature in mechanical properties.

(6) As a result of investigating the optimum condition to produce such a microstructure, the starting temperature at 1100°~1200°C, the finishing temperature at 1000°~1050°C and the total reduction above 82% can be recommended.

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