Determination of Hot Sizing Conditions for Bar Rolling to Suppress the Grain Coarsening Phenomenon

by
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Synopsis

An experimental investigation was carried out using a hot deformation simulator on the grain coarsening phenomenon in hot metal working for a typical medium-carbon steel for cold forging of AISI 1045. The occurrence criterion regarding the grain coarsening phenomenon is expressed by a narrow band in the temperature-equivalent plastic strain domain. A prediction of grain size after sizing rolling by a single stand was given using the criterion and 3D FEM, and its validity was checked experimentally on a production line. A further experiment was carried out to confirm that the accumulation effect of equivalent plastic strain throughout sizing rolling by tandem stands is valid as far as the grain coarsening phenomenon is concerned in normal speed sizing. The grain coarsening criterion obtained in a laboratory test was found to be valid and crucial also for tandem sizing. A new draft schedule for tandem sizing of a rod and bar was then proposed to prevent the grain coarsening phenomenon from occurring.

1. Introduction

Installation of sizing technology to the hot finishing line of bar mill is one of the hot technological topics in the field of bar rolling[1)-3)]. At the back of this trend, there is an increasing demand of higher precision to the products from the market. There are various methods in sizing technology, but, in principle, slight reduction by tandem stands is given to the bar at the finishing line. However, it is qualitatively well known, especially in the field of hot strip rolling of a extra low carbon steel, that slight reduction sometimes causes "grain coarsening phenomenon"[4)-7)]. In cold forging, to which many of the bar products are subjected, existence of coarse grain is one of the causes of troubles in the final products. Examples are the problem of malformed deformation after heat treatment due to localized residual stress and problem of straightness of products after cold drawing and so on. Even if highest precision of the product geometry is achieved by the installation of sizing technology, it is no solution to the market demands unless grain coarsening phenomenon is suppressed at the same time.

In the present research work, attention is focused on a typical medium carbon steel for cold forging AISI 1045 and fundamental research work is first carried out in the laboratory on the grain coarsening behavior. Namely, influence of temperature and plastic strain on the grain size after plastic metal working was investigated by using a hot deformation simulator. Numerical analyses are then carried out to specify the optimum rolling condition for hot sizing of a AISI 1045 bar. The new rolling condition was tried out on the production line to verify the validity.

2. Fundamental Investigation

2.1 Experimental Approach by Hot Deformation Simulator

In order to understand quantitatively the grain coarsening phenomenon of AISI 1045, a set of compression tests were carried out using a hot deformation simulator by changing both testing temperature and plastic strain. An illustration of the bar rolling line is shown in **Fig. 1**. A sample of a rolled bar is taken after the set of intermediate stands. The sample size is 25 mm in diameter. Chemical compositions of the test piece are given in **Table 1**. The rolling condition is given in **Table 2**. The test pieces were taken from the middle portion of the sample, which is illustrated in **Fig. 2** together with the geometry of the test piece for hot deformation simulator testing. Testing conditions are shown in **Table 3** and testing in operation is shown in **Photo 1**. Heat pattern in the testing is illustrated in **Fig. 3**. There were consecutive two stages in the hot deformation simulator testing. At the first stage, the grain size was made fine and uniform for the preparation of the second stage. At the second stage, both the temperature and reduction in height of the test piece were taken as two variable parameters and the prepared test piece was subjected to the compression test. At the first stage, the test piece is heated to 1 323K and kept for 300 seconds to make the structure completely austenitic. Then height reduction of 30% was given to the test piece under the strain rate of 10/sec. The temperature of the test piece was kept unchanged for 10 seconds after compression for the completion of recrystallization and the final grain size number fell within the number of 7.5 and 8.0.

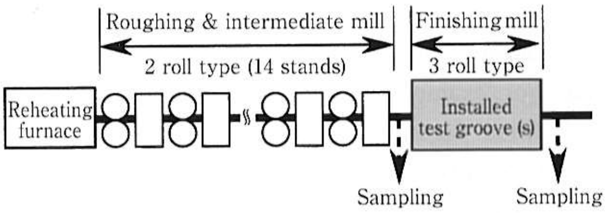


Fig. 1 Schematic illustration of bar rolling line

Table 1 Chemical composition of rolled samples

wt.%

C	Si	Mn	P	S	Cu	Ni	Cr	Mo
.44	.20	.70	.024	.025	.02	.02	.13	.02

Table 2 Conditions of bar rolling

Billet size	180mm sq.
Sample size	φ25
Material	AISI 1045
Sampling temperature	1 173K

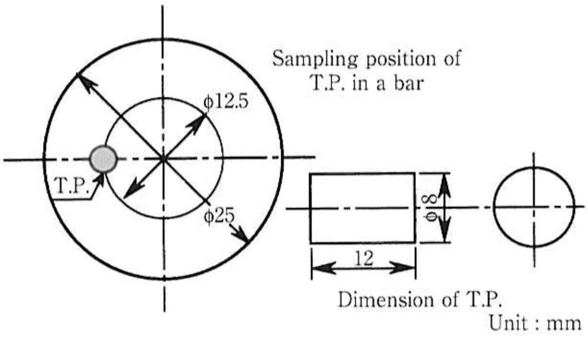


Fig. 2 Sampling position and dimensions of a test piece

Table 3 Conditions of hot compression test

Austenitization	1 223K
Keeping time for recrystallization	10sec
Working temperature	1 023K to 1 173K
Height reduction	0 to 40%
Strain rate	10/sec
Cooling rate after defomation	1K/sec

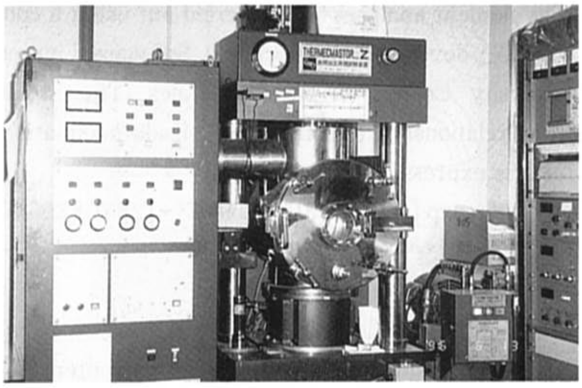


Photo 1 Hot deformation simulator

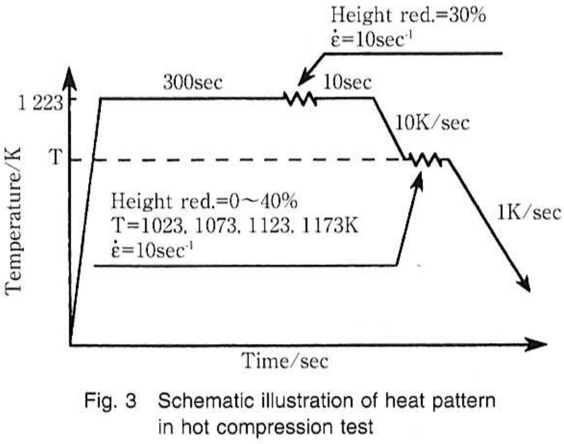


Fig. 3 Schematic illustration of heat pattern in hot compression test

At the second stage, the test piece was cooled down to the aimed temperature between 1 023K and 1 173K and the scheduled height reduction between 0% and 40% was given to the test piece. The test piece was then cooled down to the room temperature in the cooling rate of 1K/sec, which is the same value as the production line's. In order to observe the microstructure, the test pieces were cut into two halves in the axisymmetric plane including the axe. The cut surface was subjected to mechanical polishing. The polished surface was etched chemically in a nital, which is the mixture of 3% NHO_3 and 97% ethyl alcohol, and observation of the pearlite grain size wad carried out by an optical microscope. The method adopted to judge the grain size was the comparison method.

2.2 Numerical Analyses of the Compression Test

In order to analyze the distribution of the plastic strain in the test piece after the compression test by hot deformation simulator, axisymmetric rigid-plastic finite element analyses were carried out using a code "ELFEN" developed by Rockfield Software Limited, University College of Swansea,Wales. The stress-strain relationship adopted was Misaka's equation[8] which is expressed by equation (1).

$$\sigma/\mathrm{kgf} = \exp[0.126-1.75C+0.594C^2+(2851+2968C-1170C^2)/T]\cdot\varepsilon^{0.21}\cdot\dot{\varepsilon}^{0.13} \quad (1)$$

T : Absolute temperature (K) ,

ε : Logarithmic strain

$\dot{\varepsilon}$: Mean strain rate (1/sec), C : Carbon content (%)

The conditions for the numerical analyses are shown in **Table 4**. The distribution pattern of plastic strain is compared with that of the grain size observed after the investigation in section 2.1. An example is shown in **Fig. 4** It is obvious that there is a good qualitative correlation between the distribution patterns of grain size and plastic strain.

Table 4 Conditions of FEM analyses in hot compression test

Material	AISI 1045
Working temperature	1 023K to 1 173K
Flow stress	Misaka's equation (1)
Friction coefficient	0.3 (Coulomb's law)
Working speed	10mm/sec

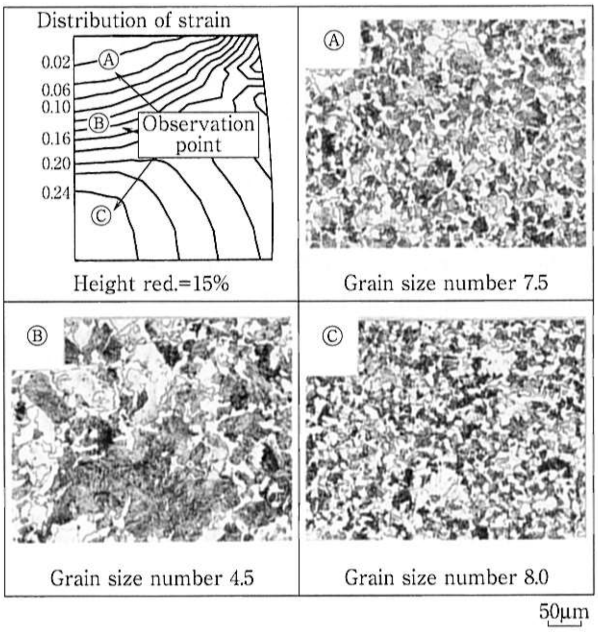


Fig. 4 Comparison of distribution of equivalent plastic strain and microstructure at 1 123K

2.3 Results of Fundamental Analyses

Comparison was made of the distributed grain size and the distributed plastic strain in the specimen and it was found that there was a good quantitative correlation between the two regardless of the reduction in the specimen's height. The influence of temperature and equivalent plastic strain on the final grain size is shown in **Fig. 5**. The result regarding the distribution of grain size is summarized as follows :

(1) the same value of equivalent plastic strain gives the same grain size regardless of the position in the specimen,

(2) For example working temperature at 1 123K, when the equivalent plastic strain is less than 0.08, change in grain size is not observed after the compression test,

(3) grain coarsening phenomenon appears when the value of equivalent plastic strain falls within 0.08 and 0.15,

(4) and the grain becomes finer than the mother specimen's when the value of plastic strain is over 0.15.

The width of the narrow band in **Fig. 5**, in which grain coarsening phenomenon appears, diminishes as the temperature decreases, and the both boundary lines of the band declines as the temperature increases.

Conventional rolling has been carried out within

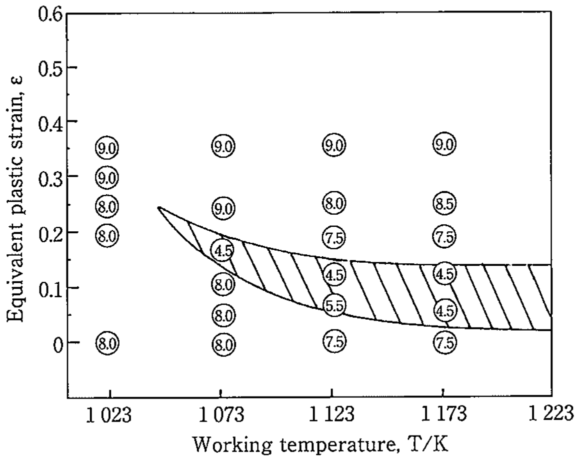


Fig. 5 Effect of working temperature and equivalent plastic strain on grain size after plastic working

the domain above the upper boundary of the narrow band, and there is no need of worrying about the occurrence of grain coarsening phenomenon. However, in the case of sizing, the rolling condition, especially reduction in area per stand, is totally different and the following assumption can be possible. If a set of temperature and the equivalent plastic strain at any point or in any area in the cross section of the rolled bar falls within this narrow band, the grain size at the point or in the area becomes large after sizing. The validity of this hypothesis will be verified in the next section.

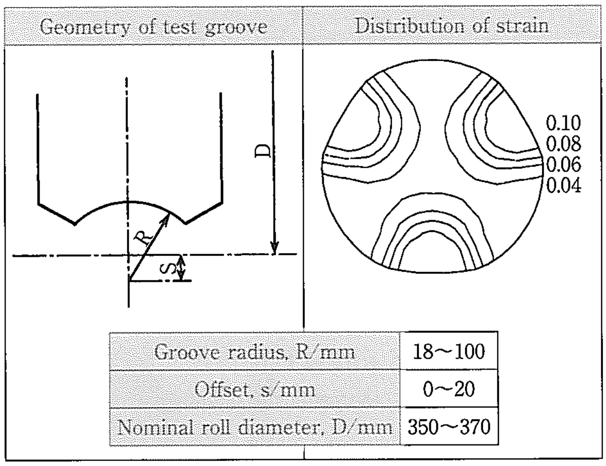
3. Experimental Verification by A Single Stand Rolling

A new groove for 3-roll-type stand was designed to observe the behaviour of the grain after slight reduction by sizing. This groove was made specifically for the experiment and the roundness of bar after rolling was neglected to get a wide range of plastic strain distribution in the cross section. Namely, the minimum value of equivalent plastic strain in the cross section is located well below the narrow band in **Fig. 5**, and the maximum value well above the band. The groove design was carried out by using a 3D FEM code "CORMILL" developed by Professor Yanagimoto of the University of Tokyo[9,10]. Boundary conditions for the analyses are shown in **Table 5**. The mother bar was assumed strain free, because the present groove was set in the production line well downstream after the intermediate tandem stands to be completed. The test groove geometry and the aimed distribution pattern of the equivalent plastic strain in the cross section are shown in **Fig. 6**. There are patchy areas where the equivalent plastic strain falls within the band in **Fig. 5**, and the validity of the present hypothesis is easily judged by comparing these patchy areas with the distributed zone of large grain in the rolled bar.

A 3-roll-stand having this groove is installed in the production line after the 2-roll-type intermediate tandem stands and experiment was carried out. The rolling conditions is given in **Table 6**. Two values of area reduction, light reduction and heavy reduction, were tested by changing the size of the mother bar to obtain the full range of plastic strain.

Table 5 Conditions of FEM analyses on sizing

Material	AISI 1045
Rolling temperature	1 123K
Initial bar diameter	30mm
Flow stress σ	$\sigma/\mathrm{MPa}=192.2\varepsilon^{0.21}\dot{\varepsilon}^{0.13}$ Misaka's equation (1)
Friction coefficient	0.3 (Coulomb's law)
Mesh division	8 (width) × 5 (thickness) × 14 (rolling direction)
Front & back tensions	0



Groove radius, R/mm	18~100
Offset, s/mm	0~20
Nominal roll diameter, D/mm	350~370

Fig. 6 Geometry of test groove and distribution of equivalent plastic strain after single stand rolling

Samples were taken both before and after the test stand. They were kicked off the line and cooled down

Table 6 Conditions of test rolling

Material	AISI 1045
Rolling temperature at sizing	1 123K
Entry bar diameter at sizing	30mm
Passing time from intermediate mill to finishing mill	10 sec

to the room temperature naturally in the air. They were then subjected to polishing and etching in the same manner as those in the fundamental experiments by a hot deformation simulator and the grain size was observed by an optical microscope using a comparison method.

The results is shown in **Photo 2** and **Fig. 7**. The pearlite grain size in the mother bar was uniform in the cross section, and the average grain size number was 7.5 at any portion, which indicates that recrystallization was completed. It was therefore correct that the mother bar in the analyses was assumed to be strain free. Obviously there is a good quantitative agreement between the two patchy areas, the area where appearance of coarse grain is predicted by FEM and **Fig. 5** and the area in the rolled bar where coarse grain appeared. It is observed that coarse grains are located only in the patchy areas of which equivalent plastic strain falls within the value of 0.06 and 0.15. The grain size number of those areas where the equivalent plastic strain is lower than 0.06 is between 7.0 and 7.5 and is almost unchanged from that of the mother bar's. These critical values of the equivalent plastic strain well coincide with the boundary values of the narrow band in **Fig. 5**. These results suggest that the present hypothesis regarding the crucial condition of grain coarsening phenomenon may be correct.

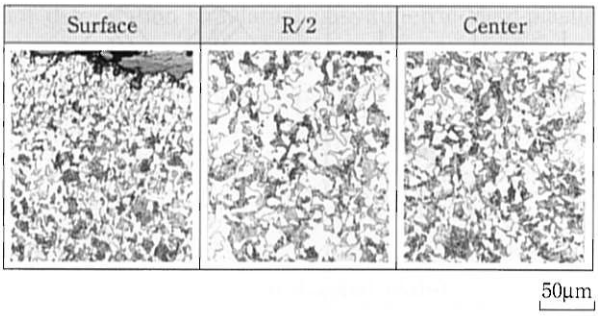


Photo 2 Microstructure of entry bar

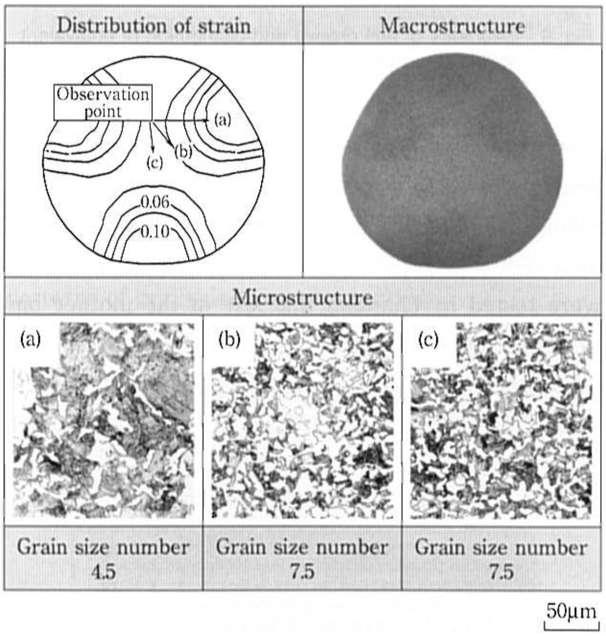


Fig. 7 Comparison of predicted strain distribution and macrostructure and microstructure after single stand rolling

4. Proposal of A New Rolling Conditions for Tandem Sizing

In the actual production line, sizing rolling is completed by using a set of tandem stands in order to ensure the required roundness of a product. Therefore, it is necessary to investigate the effect of tandem sizing on the grain coarsening phenomenon, especially regarding the accumulation effect of the plastic strain in sizing. In other words, it must be investigated whether the effect of accumulated plastic strain throughout the tandem sizing have the same effect on the grain coarsening phenomenon as that in the single stand sizing regardless of the affect of recrystallization between the adjacent stands in sizing. Finite element analyses were first carried out on the sizing using 2 sizing stands. The boundary conditions were the same as those in **Table 5**. Four cases of consecutive heavy reduction and also light reduction at sizing were investigated, which is shown in **Table 7**. The equivalent plastic strain was accumulated to observe the similar patchy area of strain as that in **Fig. 7**.

Experiments were then carried out on the production line. The rolling conditions were the same as that in **Table 6**. The time necessary for a bar to go through the interstand space in sizing was between 0.05 and 0.08 sec. Observation was again given of the grain size in the cross section. Comparison of the results is given in **Fig. 8**. It is obvious that same condi-

Table 7 Draft schedule in 2 stands sizing test

	1st. stand reduction	2nd. stand reduction	Total reduction
Case-1	12.5%	13%	23.9%
Case-2	10%	5%	14.5%
Case-3	6.5%	11%	16.8%
Case-4	5%	5%	9.8%

tion in the case of a single stand rolling is applicable to the tandem sizing. When the accumulated equivalent plastic strain falls within the narrow band in **Fig. 5** grain coarsening phenomenon occurs. This results suggests that accumulated equivalent plastic strain is preserved until the sizing is completed, as the time interval is very short for a bar to go through the interstand space in tandem sizing.

It is concluded that a set of sizing grooves must be designed by which accumulated equivalent plastic strain becomes outside the narrow band in **Fig. 5**. Practicable choice may be the upper zone of the band, as it is highly difficult physically to obtain the desired roundness by a consecutive extremely light reduction in sizing.

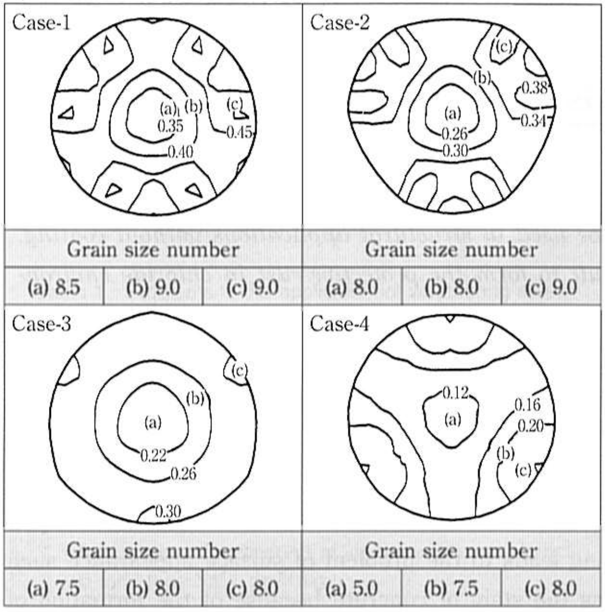


Fig. 8 Comparison of distribution of equivalent plastic strain and grain size number after 2 stands sizing

5. Conclusions

(1) The condition under which grain coarsening phenomenon occurs in hot metal working was experimentally made clear for a typical medium carbon steel for cold forging AISI 1045 by using a hot deformation simulator.

(2) It was found that there is a narrow band in the temperature-equivalent plastic strain domain within which grain coarsening phenomenon occurs.

(3) By using both this result and finite element analyses, prediction was successfully made on distribution of grain size in the cross section of a bar rolled by single stand sizing designed specifically for the verification of the validity.

(4) It was experimentally investigated in the production line that the accumulation effect stands of equivalent plastic strain throughout tandem sizing of normal speed as far as the grain coarsening condition is concerned.

(5) A proposal was made on the design of draft schedule for sizing to get rid of the occurrence of coarse grain in product.

(6) Present method is also applicable to other steels than AISI 1045.

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