Conf-9410290--2 EGG-M-94358

MODELING RECRYSTALLIZATION KINETICS DURING STRIP ROLLING

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ABSTRACT

In order to simulate the microstructural evolution during hot strip rolling, double-hit compression tests have been carried out on plain carbon steels. Using the softening data obtained by these tests, mathematical models were developed to predict the overall kinetics of static recrystallization under roughing and finishing mill conditions. These models include the effects of deformation temperature, applied strain, strain rate and initial austenite grain size. Predictions based on these models are in reasonable agreement with the present experimental results.

LIST OF SYMBOLS

d_0	(μm)	initial austenite grain diameter before deformation
F_S		fraction of softening
F_X		fraction of recrystallization
k		empirical constant
p		empirical constant
q		empirical constant
Q_{rex}	($Jmol^{-1}$)	apparent activation energy for recrystallization
r		empirical constant
R	($Jmol^{-1}$°K^{-1})	gas constant
t	(s)	time
$t_{0.5}$	(s)	time for 50% recrystallization
T	(°K)	temperature
ε		applied strain

$\dot{\varepsilon}$	(s^{-1})	strain rate
σ_m	(MPa)	flow stress at the end of the first stage deformation during a double-hit test
σ_1	(MPa)	yield stress for the first stage deformation
σ_2	(MPa)	yield stress for the second stage deformation

1. INTRODUCTION

Restoration processes can take place in steels during the period of interruption between each stand in the mill [1-3], (the interstand time). If the deformed microstructure can not be restored completely during the interpass time at the later stage of continuous strip rolling, the strain acquired in the previous rolling pass accumulates progressively, which significantly influences the flow strength and the resulting microstructure. Thus, knowledge of the recrystallization kinetics is essential in the steel industry for predicting rolling loads and the mechanical properties of the final hot-rolled steel sheets. Although numbers of investigations have been performed in this area [1-8], more detailed research is still required before the recrystallization kinetics during strip rolling can be fully predicted in computer models. The objectives of the present study were thus twofold:

1. To measure the progress of recrystallization during the hot deformation of steels.
2. To develop predictive models which can be employed in hot strip rolling operations for quantifying the kinetics of recrystallization.

2. EXPERIMENTAL MATERIALS AND SCHEDULES

A plain carbon A36 steel provided in the form of transfer bar by USS-Gary Works was employed for this investigation. Its chemical composition in weight percent is shown in Table 1. Compression specimens 15 mm in length and 10 mm in diameter were machined, with their cylinder axes parallel to the through-thickness direction of the as-received material.

Table 1. Chemical compositions of the A36 steel tested (wt.%)

C	Mn	P	S	Si	Cu	Ni	Cr	Al	N
0.17	0.74	0.009	0.008	0.012	0.016	0.010	0.019	0.04	0.0047

The softening taking place between each stand in a hot strip rolling operation was simulated by double-hit hot deformation experiments using a Gleeble-1500 testing machine. One set of the stress-strain curves obtained during these tests is presented in Figure 1. In this case, the specimen was reheated at 1150 °C for 300 seconds, cooled to 1000 °C, then held for 180 seconds and deformed at a strain rate of 1 s^{-1} up to a strain of 0.2. The inter-hit time employed was 1 second. Since the yield strength at high temperature is a sensitive measure of the microstructural state of the steel, the fractional softening, F_S, can be evaluated by the following expression [6-9]:

$$F_s = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \quad (1)$$

where σ_m is the flow stress at the end of the first stage deformation, and σ_1 and σ_2 are the yield stresses determined at an offset strain of 0.002 for the first and second stage deformation respectively, as shown in Figure 1.

The first set of laboratory double hit testing experiments were designed to investigate the effect of deformation temperature and strain rate on the kinetics of recrystallization, simulating the industrial rolling conditions, where possible. The following primary parameters were employed in these Gleeble axisymmetric compression tests:

Heating rate (°Cs^{-1}):	5
Reheating temperature (°C) :	1150
Soaking time (s):	300
Cooling rate to deformation temperature (°Cs^{-1}):	1
Holding time before deformation (s):	180
Applied strain for each hit:	0.2
Strain rate (s^{-1}):	0.01, 0.1, 1, 10
Deformation temperature (°C):	900, 950, 1000, 1100

Since the initial microstructure obtained before rough rolling is different from that generated prior to finish rolling, the influence of initial grain size on the progress of recrystallization under both operation conditions must be distinguished. For this purpose, different reheating schedules were used for the second set of experiments:

Reheating temperature (°C)	Soaking time (s)
1200	600
1150	300
1150	60
1100	60
1050	60
1000	60
950	60

The size distribution of austenite grains under each reheating condition was measured. Their mean volumetrical diameters range from 18 μm to 284 μm; a procedure recommended by Takayama et al. was used, as authored on an accompanying paper [10].

In addition, a third set of experiments was also performed for analyzing the effect of strain on the rate of recrystallization. During these tests, the strain applied for each hit ranged from 0.08 to 0.35, which in no case exceeded the peak strain for dynamic recrystallization.

3. SOFTENING RESULTS

3.1. Influence of strain rate

In order to reveal the effect of strain rate on softening kinetics, a typical set of softening curves determined by the double-hit technique is presented in Figure 2 where the fractional softening is plotted against the logarithm of the inter-hit time. For these testing conditions, the specimens were reheated to 1150 °C, held for 300 seconds, and then cooled to 1000 °C at 1 $°Cs^{-1}$ and given a hit strain of 0.2 at the latter temperature. The results confirm that the rate of recrystallization is increased as the strain rate is increased. This is due to the higher dislocation density produced by deformation at the higher strain rate, which in turn increases the driving force for recrystallization.

3.2. Influence of applied strain

The experimental softening data illustrating the influence of applied strain on the recrystallization kinetics are shown in Figure 3. These data are collected from the tests employing a reheating temperature of 1150 °C, a holding time of 300 seconds, a cooling rate of 1

°Cs^{-1}, a deformation temperature of 1000 °C and a strain rate of 1 s^{-1}. As demonstrated in Figure 3, the applied strain has the same effect as that of strain rate, i.e., the higher the hit strain, the greater the softening fraction. This can also be attributed to the higher dislocation density generated by the increased deformation.

3.3. Influence of reheating temperature

As described above, different reheating schedules were employed to reveal the effects of initial grain size. Some softening curves measured for this purpose are presented in Figure 4. As can be seen from this figure, when constant deformation temperature, hit strain and strain rate were employed, softening and thus recrystallization kinetics are slightly delayed as the reheating temperature is increased. This can be attributed to the larger initial austenite grain size acquired at the higher reheating temperature, which results in a decrease in the density of nucleation sites for recrystallization.

3.4. Influence of deformation temperature

Some experimental softening data showing the influence of deformation temperature are presented in Figure 5. For these experiments, the specimens were reheated to 1150 °C and held for 300 seconds, cooled to different testing temperatures at 1 °Cs^{-1} and then deformed up to a strain of 0.2 at a strain rate of s^{-1}. It is evident from this figure that the softening and thus recrystallization kinetics are speeded up as the deformation temperature is increased. At a holding time (interhit time) of 1 second, for example, the fractional softening occurring in this steel increases from about 22% at 900 °C to 48% at 1000 °C, and further to 80% at 1100 °C.

4. MODELING

In most cases, the kinetics of static recrystallization are defined in terms of the time for 50% recrystallization, $t_{0.5}$, by an Avrami equation of the following form [11-16]:

$$F_X = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^k\right] \qquad (2)$$

where F_X is the fraction of recrystallization taking place during isothermal holding. Since static recrystallization in austenite can be assumed to begin at F_S=0.2 [17, 18], the fraction recrystallized, F_X, can be determined from the measured softening data by:

$$F_X = \frac{F_S - 0.2}{1 - 0.2} = \frac{F_S - 0.2}{0.8} \tag{3}$$

Obviously, the complete description of the recrystallization kinetics requires knowledge of the dependence of $t_{0.5}$ and k on the deformation parameters, as will be considered in the subsections that follow.

4.1. Dependence of $t_{0.5}$ on strain rate

The influence of strain rate on softening, and therefore on recrystallization, was shown in Figure 2. It was demonstrated in this figure that the recrystallization kinetics are accelerated with increasing strain rate. In order to evaluate such an effect, the dependence of the time for 50% recrystallization, $t_{0.5}$, on strain rate, $\dot{\varepsilon}$, is plotted on a *log-log* scale in Figure 6 for the specimens either reheated at 1150 °C and deformed at 1000 °C or reheated at 1000 °C and deformed at 900 °C. The same hit strain of 0.2 was applied in each case. It can be seen that the relevant data can be fitted by nearly parallel lines on this scale, which suggests an empirical power law relationship between $t_{0.5}$ and strain rate, i.e. $t_{0.5} \propto \dot{\varepsilon}^{-p}$. Under the present experimental conditions, the values of p are approximately constant and lie between 0.28 and 0.38. These values are in good agreement with the value of 0.28 reported by Perdrix [19] and Choquet et al. [20] and with the value of 0.41 by Laasraoui and Jonas [21] for other C-Mn steels.

4.2. Dependence of $t_{0.5}$ on applied strain

Based on the softening data presented in Figure 3, an example of strain dependence of the time for 50% recrystallization, $t_{0.5}$, is given in Figure 7. This diagram indicates that the strain dependence can also be fitted by a straight line on the *log-log* scale, which supports the validity of a power function of the form $t_{0.5} \propto \varepsilon^{-q}$. Within the present interval of applied strain, the value of q shows no special trend and is a constant close to 3/2. This is slightly smaller than the value of q=2 reported by Senuma and Yada [13] for other steels. It should be noted that the above power function is only valid as the applied strain is lower than the critical strain for dynamic recrystallization.

4.3. Dependence of $t_{0.5}$ on initial austenite grain size

It has been found in the previous investigations [11, 14-16, 22] that $t_{0.5}$ also has a power dependence on initial austenite grain size d_0: $t_{0.5} \propto d_0^r$. The value of r has been reported to be 1 by Hodgson and Gibbs [11], and to be 2 by Saiki [14], Sellars [15] and Roberts et al. [22]. In the present work, the curves for the tests employing lower reheating temperatures fit $r = 1$. Since the initial austenite grain sizes are smaller under such conditions, this value can thus be used for predicting $t_{0.5}$ for finishing mill operations. As the reheating temperatures are increased high enough to generate initial grain sizes larger than 150 μm, the best fit to the data is then given by $r = 2$. This value of r was therefore adopted for predicting $t_{0.5}$ under roughing mill conditions.

4.4. Dependence of $t_{0.5}$ on deformation temperature

Considering that recrystallization is basically a thermally activated process, the relevant activation energy can be estimated by plotting the characteristic recrystallization time, $t_{0.5}$, *vs* the inverse absolute temperature, i.e., by employing the well-known expression $t_{0.5} \propto \exp(Q_{rex}/RT)$. For the present C-Mn steels, average values of Q_{rex} of about 220 kJmol^{-1} and 295 kJmol^{-1} were determined in this way for the experimental curves corresponding to the roughing and finishing mill conditions, respectively. The difference between these two values indicates that static recrystallization becomes more sluggish during finishing than during roughing, even though the applied strain and strain rate could be higher during finish rolling.

It is of interest to compare the current Q_{rex} results with the literature data of 230kJmol^{-1} reported by Hodgson and Gibbs [11], 300kJmol^{-1} by Saike [14] and Sellars [15], and 301kJmol^{-1} by Perdrix [19]. Although these reported values are close to those obtained in the present study, the authors did not clarify their application range. It is also worthy of note that the above reported and measured values for Q_{rex} are apparent and not true activation energies. Thus, these values characterize the overall process of recrystallization under specific conditions.

4.5. Empirical models for static recrystallization during strip rolling

It has been shown that empirical models are useful as inputs into computer programs for hot rolling process modeling [23-25]. Based on the above data analyses, the effects of applied strain, strain rate, initial austenite grain size and deformation temperature were summarized in two mathematical expressions for predicting the time for 50% recrystallization, $t_{0.5}$, as follows:

$$t_{0.5} = 1.83 \times 10^{-15} \times d_0^2 \varepsilon^{-\frac{3}{2}} \dot{\varepsilon}^{-\frac{1}{3}} \exp\left(\frac{220{,}000}{RT}\right) \tag{4}$$

for roughing mill conditions, and

$$t_{0.5} = 6.68 \times 10^{-16} \times d_0 \varepsilon^{-\frac{3}{2}} \dot{\varepsilon}^{-\frac{1}{3}} \exp\left(\frac{295{,}000}{RT}\right) \tag{5}$$

for finishing mill conditions.

The calculated values of $t_{0.5}$ are compared with the experimental results in Figure 8, where a fairly good correlation between the model predictions and experimental measurements can be observed. Further putting the $t_{0.5}$ data in Equation (2), the exponential k has been fitted to be about 3/2 for roughing operation and 2 for finishing operation, respectively. These values are similar to those reported in previous investigations for other C-Mn steels [11-17].

5. CONCLUSIONS

1. The kinetics of softening and recrystallization are accelerated as either applied strain or strain rate is increased. Such effects can be explained by the increased driving force obtained during deformation to higher strains and increased strain rates, and can be modeled using a power function for the dependence of $t_{0.5}$. These results also have fundamental implications with respect to industrial strip rolling. Considering that the strain and strain rates used in the finishing passes are much higher than those employed in the laboratory simulations, care must be taken to avoid underestimating the degree of softening occurring between finishing stands.

2. Increasing the reheating temperature and soak time results in a decrease in the softening rate due to the resulting larger initial austenite grain size. When the size of the initial grains is smaller than 150 µm, $t_{0.5}$ is almost linear with d_0. As d_0 increases above 150 µm, however, $t_{0.5}$ increases with the square of d_0. The former observation has been considered when fitting the recrystallization model for rough rolling, while the latter has been involved in developing a mathematical expression for finishing rolling.

3. An increase in the deformation temperature leads to an acceleration of softening and thus enhanced recrystallization kinetics. This can be attributed to the higher mobility of recrystallizing grain boundaries at higher deformation temperatures. Such an effect can be readily described by an Arrhenius relationship. The apparent activation energy under roughing mill conditions has been determined to be smaller than under finishing mill conditions, which indicates a larger barrier for static recrystallization during finishing than roughing.

ACKNOWLEDGMENTS

The authors are grateful to AISI (the American Iron and Steel Institute) and DOE (the Department of Energy) for permission to publish this paper. They would also like to thank U.S. Steel for providing the tested materials. The able assistance of B. Chau performing the Gleeble tests and Z. Ru performing some data analyses is gratefully acknowledged.

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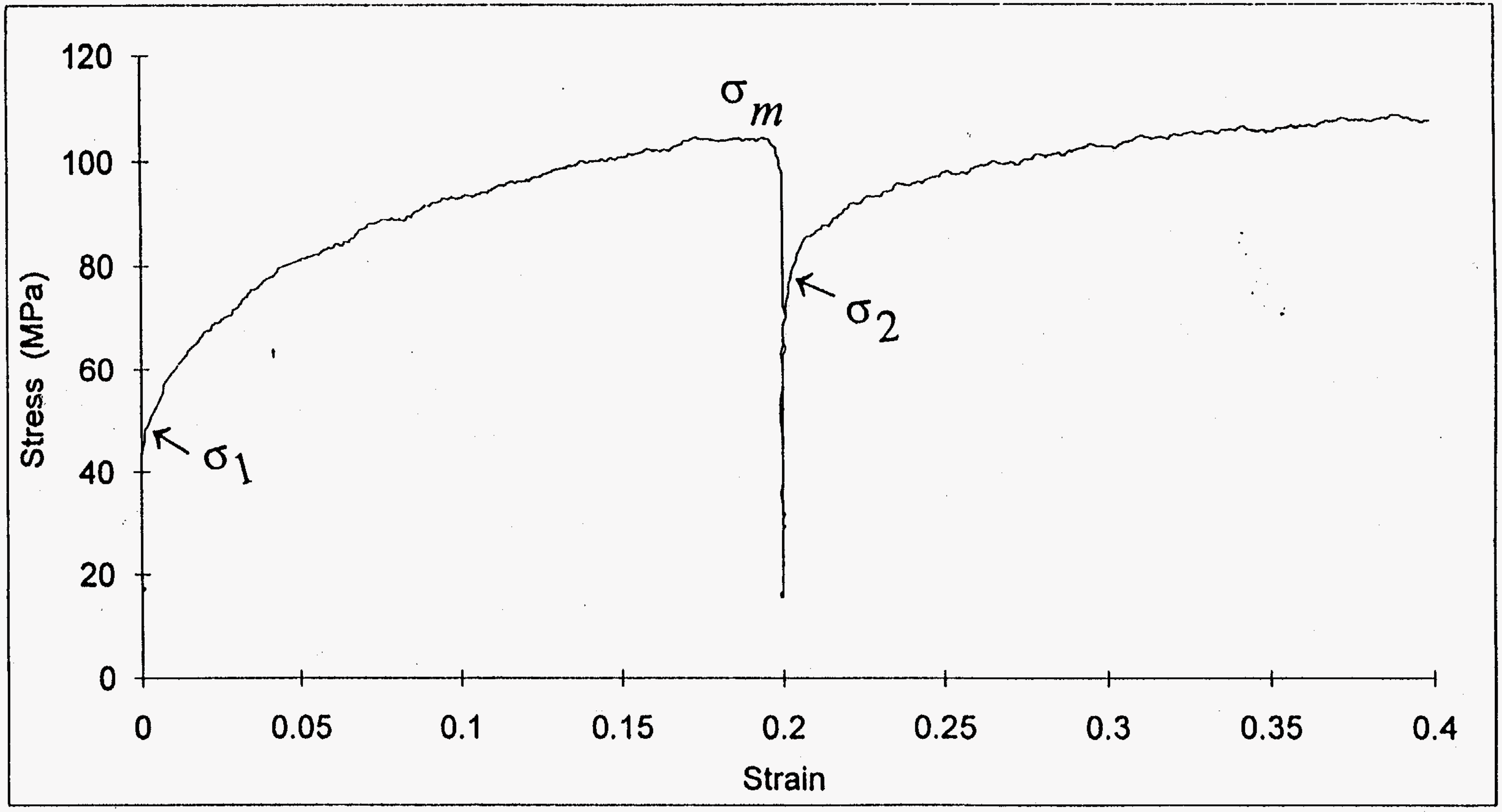


Fig. 1. Typical flow curves obtained during a double-hit test using a reheating temperature of 1150 °C, soaking time of 300 seconds, a deformation temperature of 1000 °C, hit strains of 0.2, a strain rate of 1 s^{-1} and an inter-hit time of 1 second.

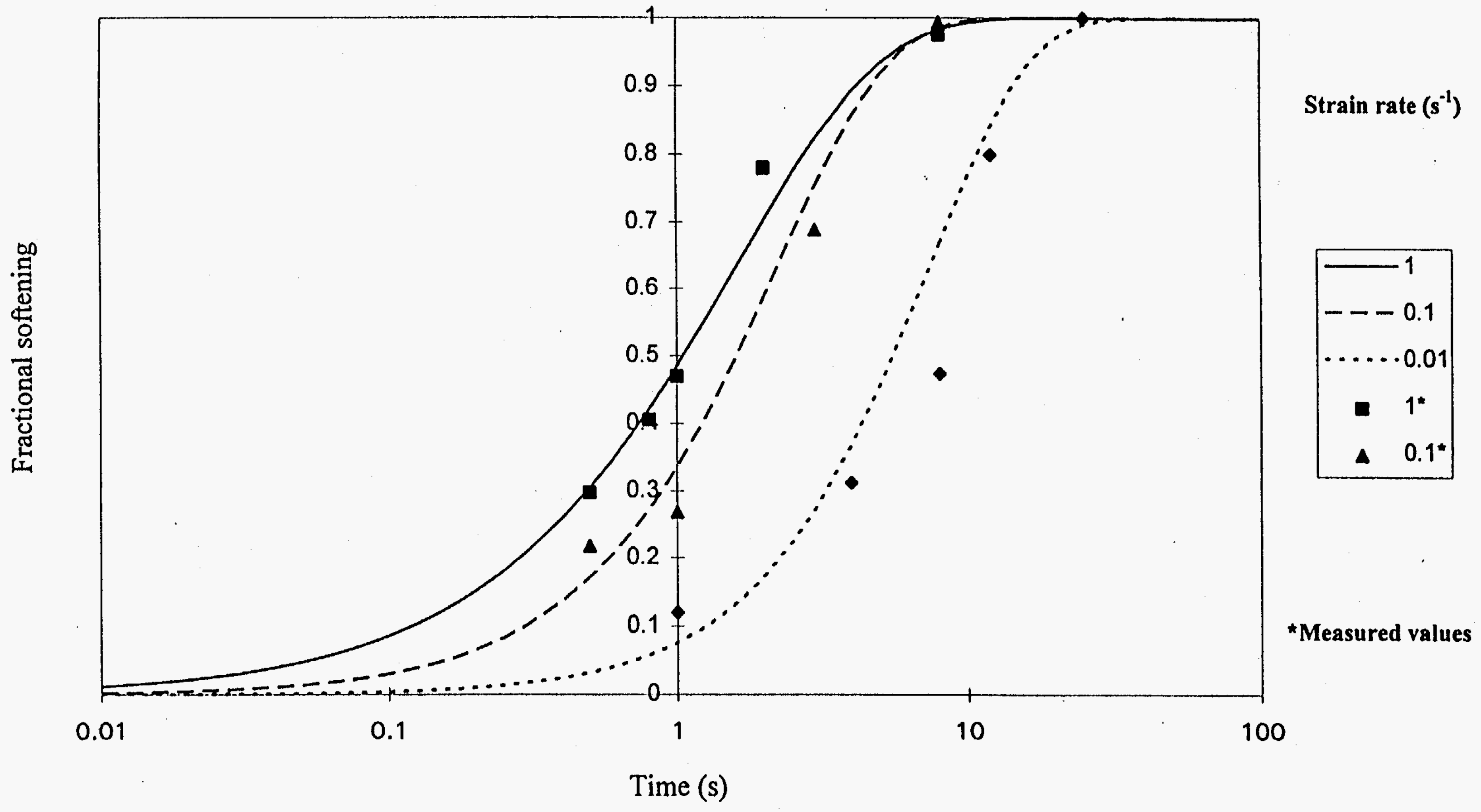


Fig. 2. Fractional softening curves obtained after reheating to 1150 °C, holding for 300 seconds, cooling at 1 °Cs^{-1} to 1000 °C and applying a hit strain of 0.2 at 1000 °C using different strain rates.

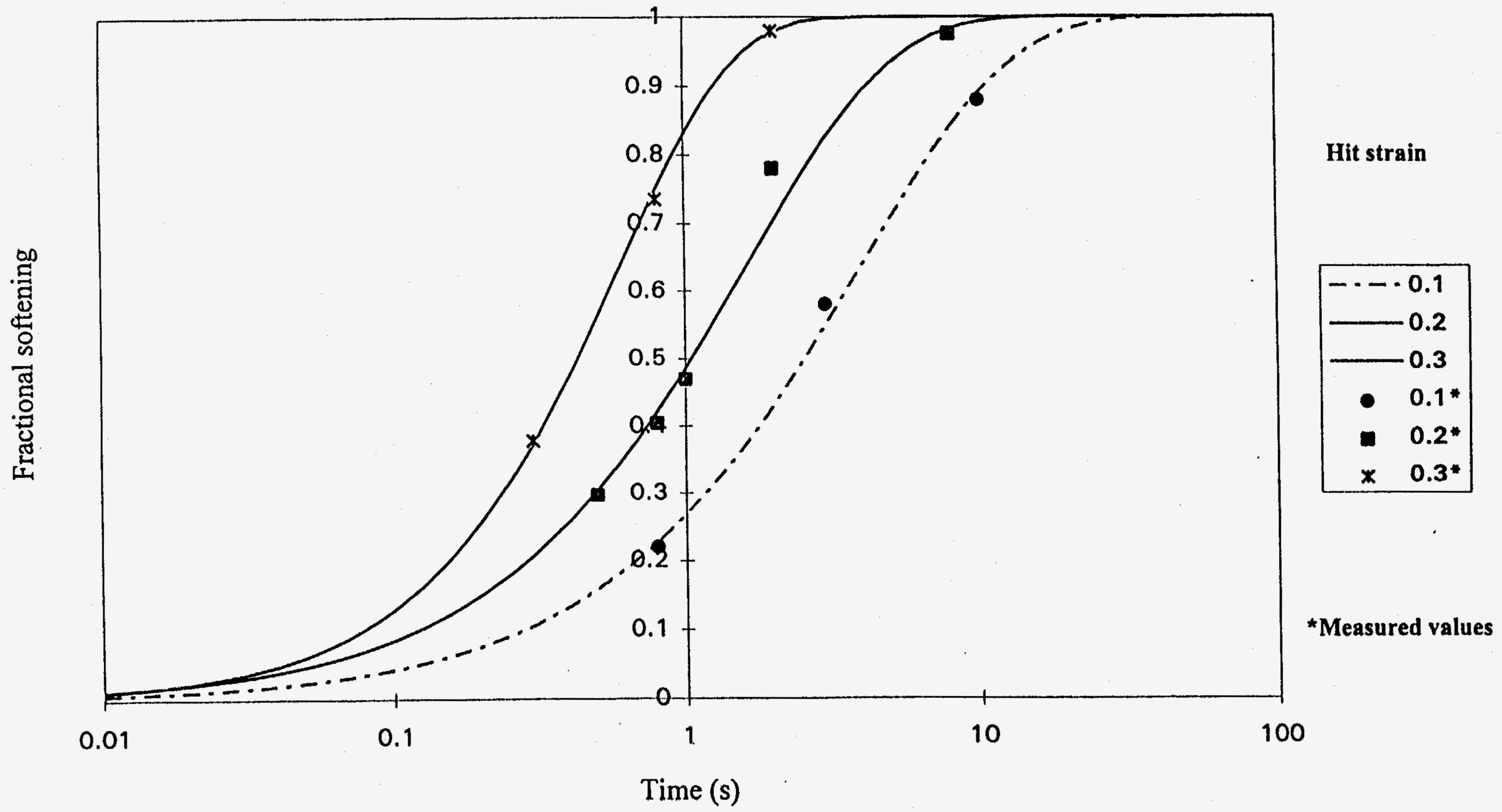


Fig. 3. Fractional softening curves obtained after reheating to 1150 °C, holding for 300 seconds, cooling at 1 $°Cs^{-1}$ to 1000 °C and applying different hit strains at a strain rate of 1 s^{-1} at 1000 °C.

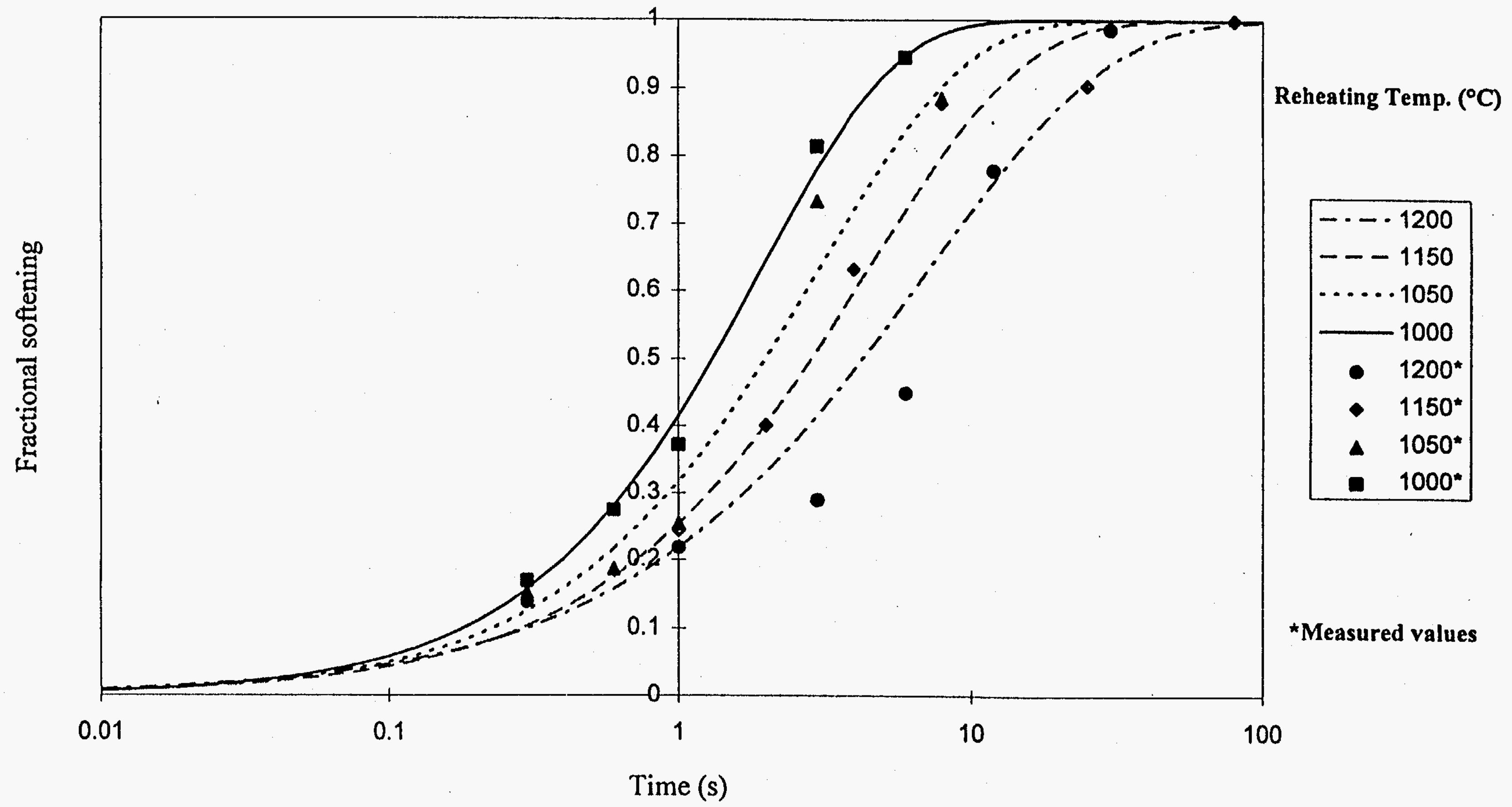


Fig. 4. Fractional softening curves obtained after reheating at different temperatures and applying a hit strain of 0.2 at a strain rate of 1 s^{-1} at 900 °C.

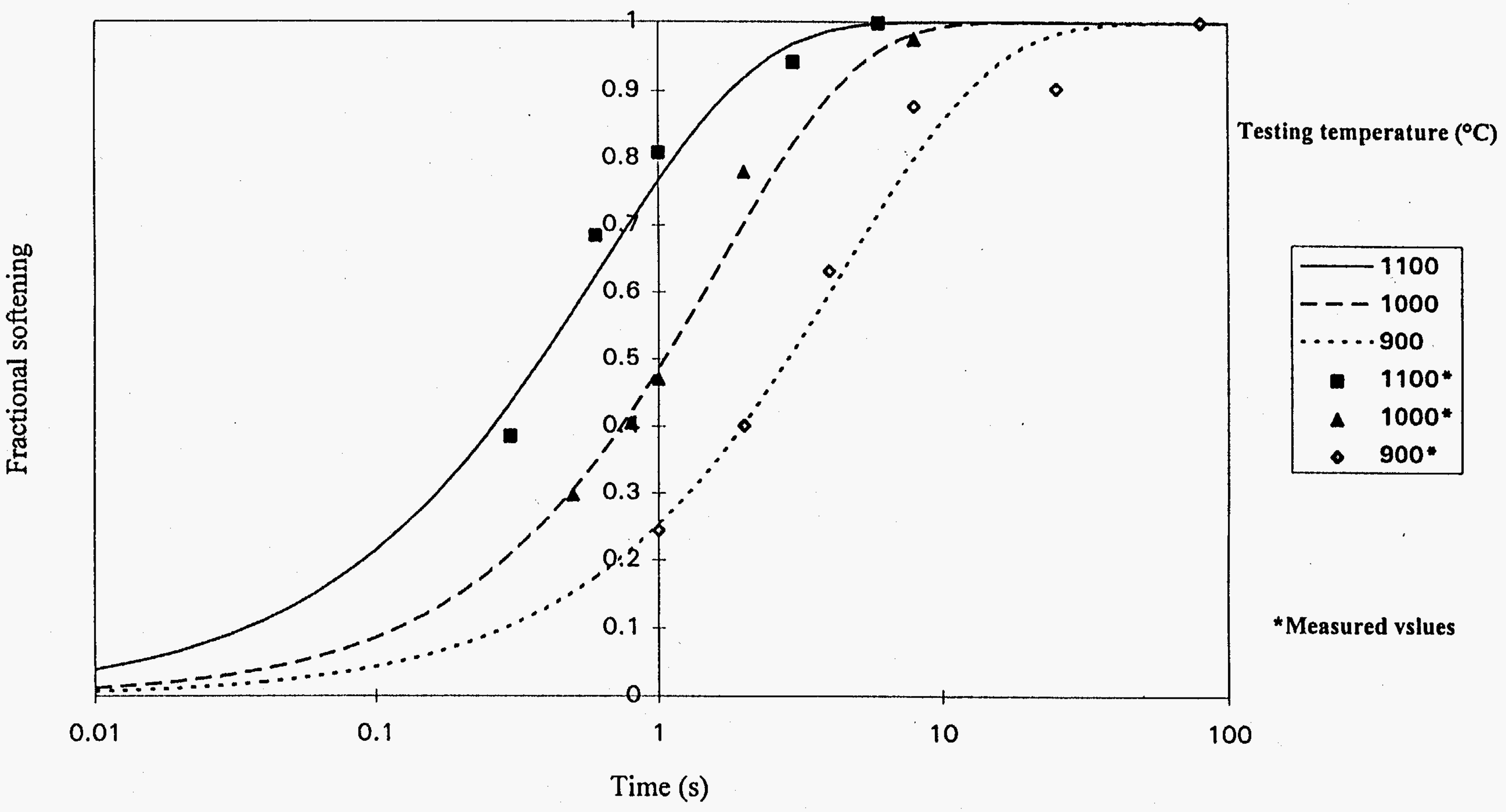


Fig. 5. Fractional softening curves obtained after reheating to 1150 °C, holding for 300 seconds, cooling to the desired testing temperature at 1 °Cs^{-1} and then applying a hit strain of 0.2 at a strain rate of 1 s^{-1}.

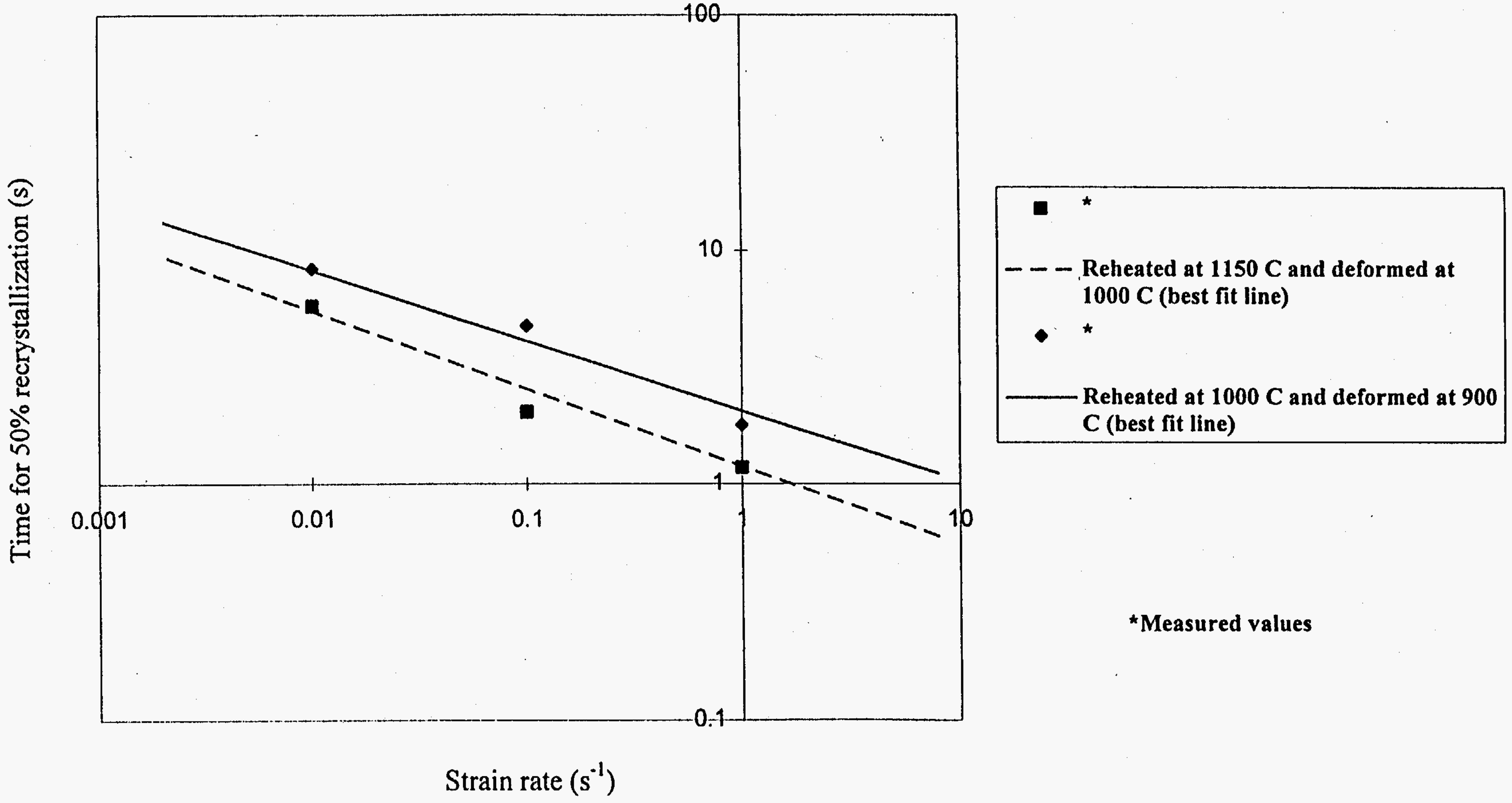


Fig. 6. Dependence of the time for 50% recrystallization, $t_{0.5}$, on strain rate, $\dot{\varepsilon}$, employing a hit strain of 0.2.

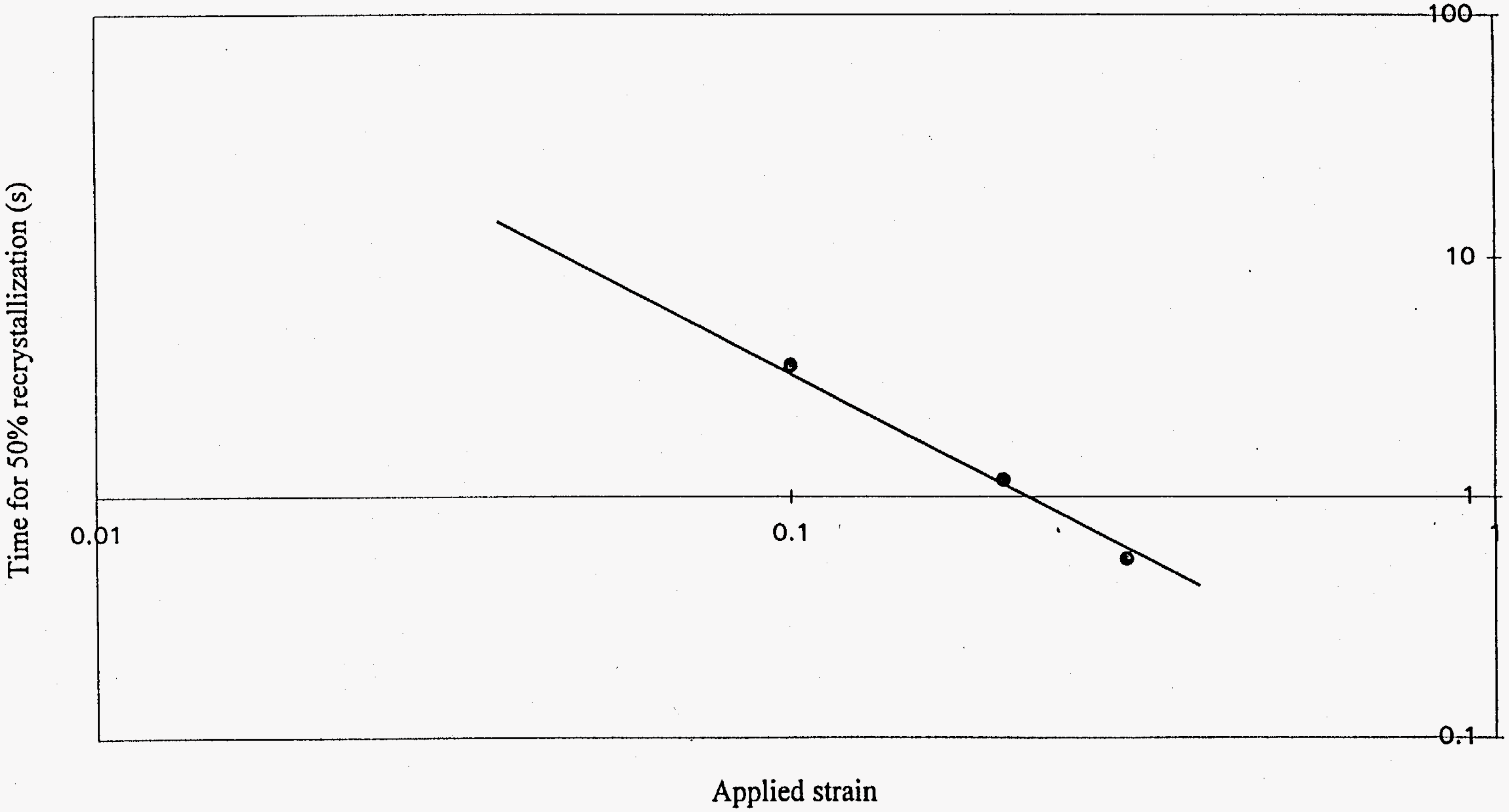
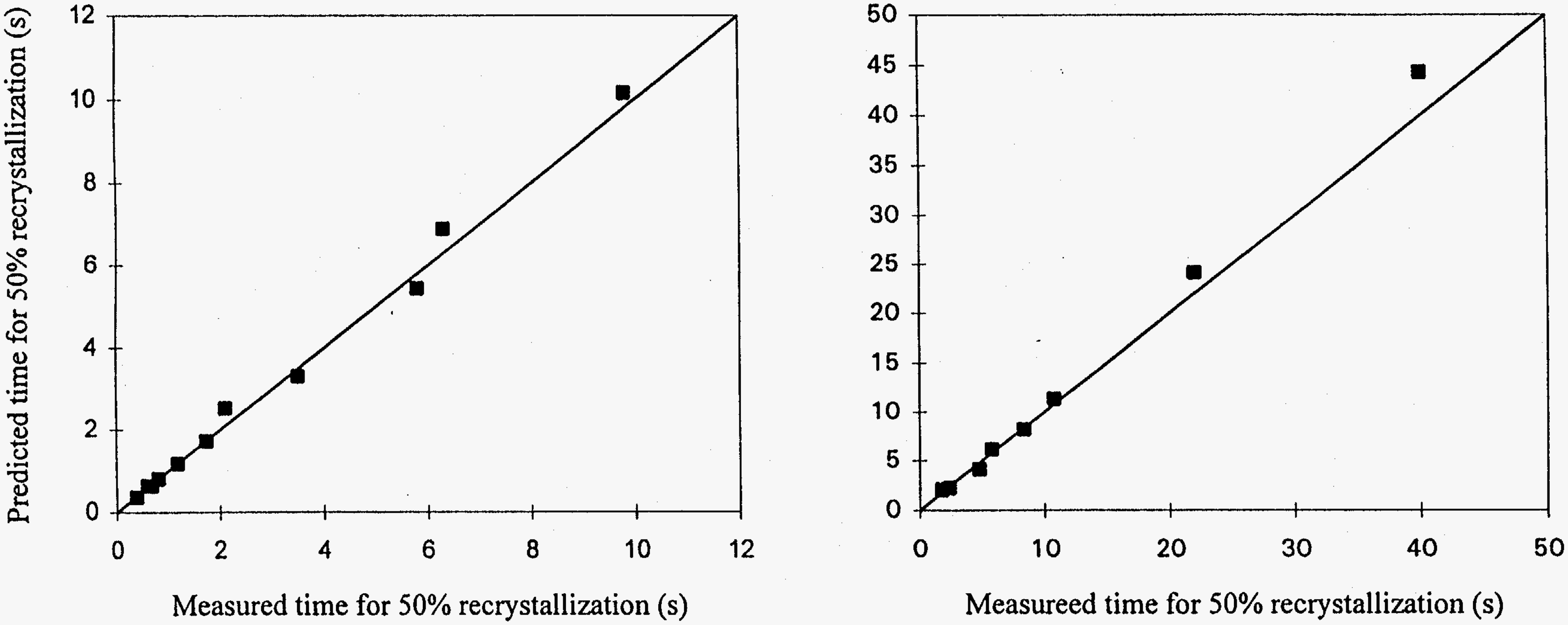


Fig. 7. Dependence of the time for 50% recrystallization, $t_{0.5}$, on applied strain, ε, employing a strain rate of 1 s^{-1}.



(*a*)

(*b*)

Fig. 8. Comparison between the measured and predicted time for 50% recrystallization, $t_{0.5}$, under (*a*) rough and (*b*) finish rolling conditions.