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On the Recrystallisation Characteristics and Kinetics of a 9SMn28 Free Cutting Steel

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Abstract. The static and metadynamic recrystallisation characteristics of a 9SMn28 (EN 1.0715) free cutting steel have been evaluated by employing the stress relaxation technique. In the steel, the sulphur was bound in the form of numerous MnS inclusions. Fractional softening laws stating the kinetics of static and metadynamic softening behaviour were experimentally determined and compared with the existing literature data for C/C-Mn steels. The analysis of the static recrystallisation data suggested the powers of the strain and strain rate to be -2.7 and -0.13, respectively, and the apparent activation energy was estimated as 177 kJ/mol. The power of grain size was taken from a regression model developed previously that is able to predict the static recrystallisation kinetics of vast number of carbon and microalloyed steel grades. Even though a fraction of Mn was out of the solid solution in the form of sulphides, the predictions by the regression model as accounting the balance Mn in the solid solution were quite close to the experimental data, confirming the applicability of the model. As expected, the metadynamic recrystallisation behaviour showed a strong dependence on the strain rate, the power being -0.78 and the apparent activation energy 57 kJ/mol.

Introduction

Free cutting steels owe their excellent machinability properties to the presence of high sulphur (typically, 0.2-0.35%) and often have a low carbon content (typically, 0.07%) in order to maintain a low strength and keep the cutting forces and cutting temperatures low [1]. The presence of large volume fractions of MnS inclusions in these steels improves the cuttability by acting as internal crack initiation sites and reducing both the force required to create a chip and the friction between the tool and the chip.

These free cutting steels are industrially processed through hot rolling into bars or rods and undergo severe plastic deformation during processing. The hot workability characteristics of low carbon free cutting steels have been extensively studied by Ochoa et al. [2]. It was reported that due to the pinning effect exerted by sulphur-rich particles, grain growth is delayed up to reheating temperatures as high as 1250°C, thus resulting in a fine austenite grain size prior to subsequent deformation. It was demonstrated that during hot working, the damage due to debonding of matrix-inclusion interfaces can be retarded or its effect delayed during the initiation of dynamic recrystallisation (DRX), which in turn depends on the dynamically recrystallised grain size and its interaction with the particle distribution in the matrix [2]. On the other hand, some regions in the bar rolling near the surface may only experience static recrystallisation (SRX) due to lower temperatures and therefore, higher critical strains for DRX. It is, therefore, important to evaluate the constitutive flow stress behaviour and static and dynamic softening behaviour of free cutting steels for hot working in a safe processing regime to facilitate a damage-free microstructure. In this study, the static (SRX) and metadynamic (MDRX) recrystallisation characteristics have been studied by employing the stress relaxation technique, the details of which are described elsewhere [3,4].

Experimental

A bloom of free cutting steel (9SMn28 grade; 0.08C-0.02Si-1.1Mn-0.424S-0.18Cr-0.22Ni-0.2Cu-0.06P-0.09Mo-0.11V-0.0074N; dia 8 mm) was hot rolled at CSM pilot mill and specimens of the dimensions ϕ8 mm x 10 mm were machined from segregation-free areas for axisymmetric compression and stress relaxation testing. The tests were carried out in a Gleeble 1500 thermomechanical simulator. A graphite foil was used as lubricant between the specimen and the tungsten carbide anvils and a tantalum foil to prevent sticking. The specimens were heated at a rate of 10°C/s to the reheating temperature 1150°C, held for 2 minutes, followed by cooling at 5°C/s to the deformation temperature and then compressed up to a prescribed strain after stabilising the temperature for 15 s at the deformation temperature. Using the stroke mode, the strain was held constant after the deformation and the compressive force relaxed as a function of time. The stress relaxation data were then fitted to the Avrami equation at around 50% recrystallised fractions to enable estimation of recrystallisation rate as a function of holding time. In this way, a single experiment can give a complete curve showing recrystallised fraction vs. time for a given set of conditions [3,4]. Stress relaxation tests were carried out in the temperature range 850-1100°C and both the strain (0.15-0.6) and strain rate (0.01-5 s^{-1}) were suitably varied to achieve a broad range of deformation parameters for evaluating both SRX and MDRX characteristics. Austenite grain size was measured by the linear intercept method on specimens directly quenched in water spray from the reheating temperature and etched in saturated picral/teepol solution.

Results and discussion

Flow stress and relaxation behaviour. Examples of typical true stress-true strain curves obtained on the 9SMn28 steel compressed at 0.1 s^{-1} in the temperature range 850-1100°C are shown in Fig. 1, which display work hardening in the beginning up to a peak stress, followed by considerable softening until the steady-state condition is reached (except at 850°C). These characteristics are typical of DRX. Except for its higher peak strains, the flow stress behaviour of the free cutting steel at different temperatures and strain rates is found to be similar to those of low C/C-Mn steels studied earlier, c.f., [4,5].

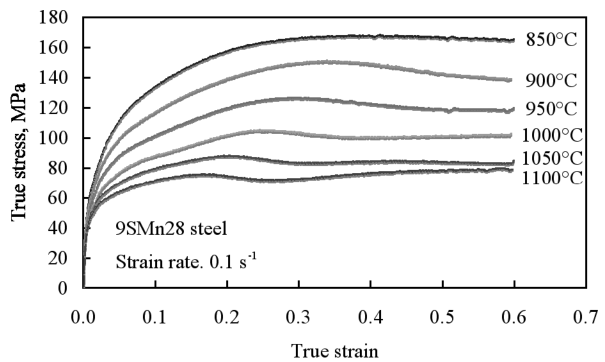

Fig. 1. True stress – true strain curves revealing the occurrence of DRX.

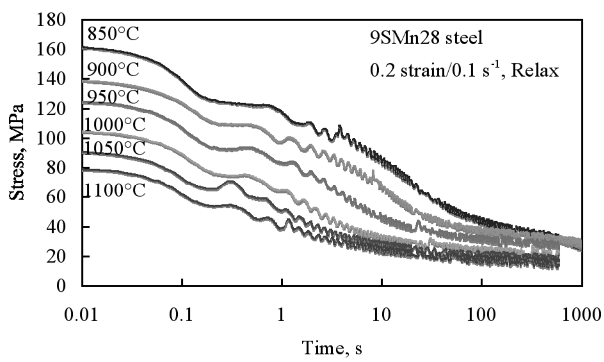

Fig. 2. Typical stress relaxation curves obtained on specimens deformed to 0.2 strain at 0.1 s^{-1}.

Examples of typical stress relaxation curves are shown in Fig. 2, which display essentially three stages on the logarithmic time scale. It has been presented earlier that the initial and final linear stages on the curves correspond to the occurrence of static recovery (SRV) and the intermediate fast drop in the stress level is typical of SRX and MDRX process [4,5]. Stress relaxation curves were extensively analysed to determine the kinetics of SRX or MDRX processes as a function of deformation parameters. The degree of softening at a given time can be determined from recrystallised fraction vs. time curves computed from the stress relaxation curves, such as times for 5%, 50% and 95% softening (t_5, t_{50} and t_{95}, respectively). Complete softening was obtained in most cases, even though the final flow stress remained higher at lower temperatures (~900°C). Examples of recrystallised fraction vs. time curves fitted with the Avrami-type curves are shown in Fig. 3, where the accelerating effect of strain rate on the kinetics of MDRX is demonstrated on specimens deformed at 1000°C to a true strain of 0.6. The t_{50} times are plotted as a function of true strain in Fig. 4 and the relationship is quite similar to that noticed in other C-Mn steels [4,5]. At small strains, the t_{50} value is strongly dependent on applied strain up to a certain level, beyond which it becomes nearly independent of it and these two regions are characteristically typical of SRX and MDRX, respectively. As will be discussed later, the effect of temperature is markedly significant at small strains, but quite insignificant at higher strains.

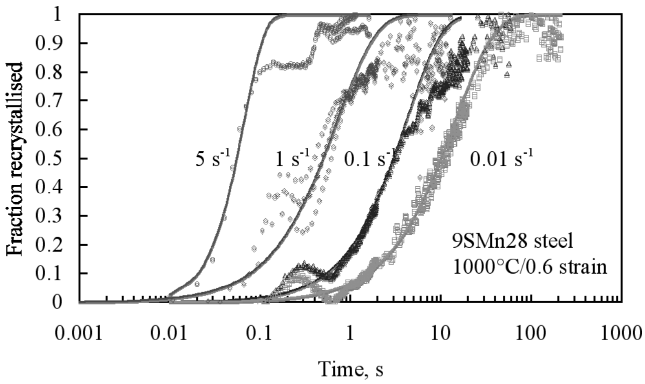

Fig. 3. Recrystallised fraction vs. time curves computed from stress relaxation curves showing accelerating effect of strain rate on MDRX kinetics.

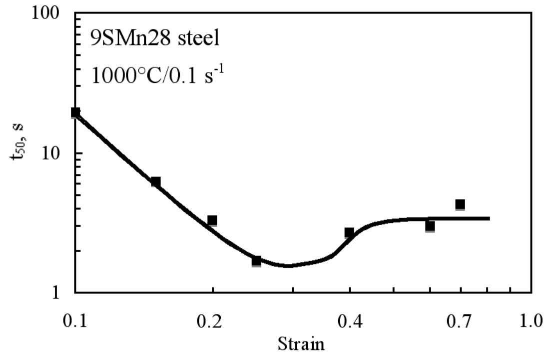

Fig. 4. Dependence of t_{50} on strain revealing two different regimes corresponding to SRX and MDRX.

On the other hand, the effect of strain rate seems to be insignificant at small strains in SRX regime, as revealed in Fig. 5, which shows a plot of t_{50} times against the strain rate. As discussed later, at higher strains beyond the critical strain ε_c, the dependence of recrystallisation times on the strain rate becomes quite pronounced owing to the onset of MDRX process [4,5].

SRX characteristics and kinetics. Deformation below a critical strain (ε_c) for the onset of DRX was employed to determine the static recrystallisation characteristics. The critical strain was considered to be about 0.8 times the peak strain, ε_p [6,7] that can be readily estimated from the shape of the true stress-true strain curves. For example, critical strain values for the specimens compressed at 0.1 s^{-1} (the grain size: 23 μm) are about 0.32, 0.27, 0.23, 0.2 and 0.16 at 850, 900, 950, 1000 and 1050°C, respectively (Fig. 1).

The strain exponent (p) was estimated to be about -2.7 from the data in Fig. 4 at a short strain range of 0.1-0.2. Values of the strain exponent reported in the literature vary widely, c.f. [4-7]. However, the present value seems quite reasonable, if compared to the data on C/C-Mn steels and a medium-carbon spring steel (-2.5) and Nb/Nb-Ti steels (-2.8) based on systematic tests by the stress relaxation technique, which have been used for developing the regression model for the SRX kinetics [8-10]. Hodgson and Gibbs [11] also fitted their data for C-Mn as well as Ti- and V-steels with the strain exponent of -2.5.

As expected, the effect of strain rate was relatively insignificant at small strains, the strain rate exponent (q) being of the order of -0.13, as estimated from Fig. 5. This value is comparable to those obtained earlier for Armco iron (-0.1), C/C-Mn steels (-0.11), medium carbon spring steel (-0.125) and also Ti-steels (-0.12) by the stress relaxation technique [8-10]. Accordingly, its effect has sometimes been ignored in some equations, c.f. [6], but values as high as -0.53 have been reported elsewhere based on torsion tests [12].

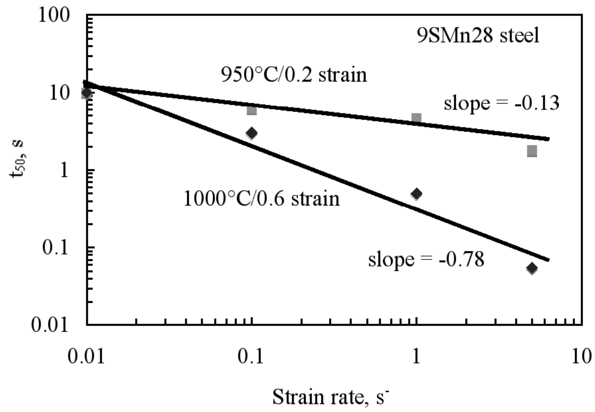

Fig. 5. Estimation of exponents for the strain rate in the SRX and MDRX regimes.

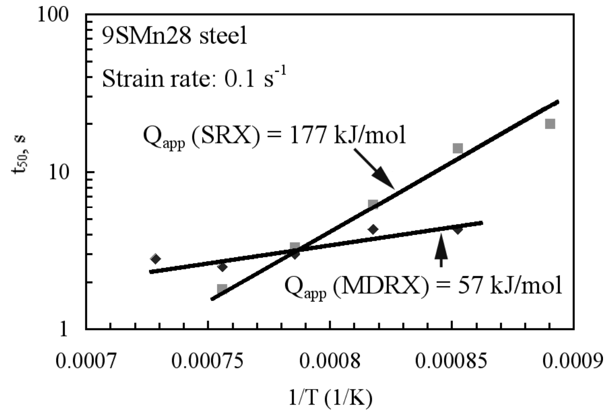

Fig. 6. Estimation of Q_{app} for both the SRX and MDRX processes.

The effect of temperature on the kinetics of SRX is quite significant. The apparent activation energy (Q_{app}) of SRX was determined from t_{50} values in the temperature range 900-1050°C as 177 kJ/mol (Fig. 6). The activation energy of deformation (Q_{def}) has been estimated from the peak strain data of the tests shown in Fig. 1 employing the method suggested elsewhere [13] and it was computed to be 324 kJ/mol. This value is quite reasonable if compared to the values 300-312 kJ/mol commonly reported in literature for C-Mn steels [4-6,13,14]. Somani et al. [8-10] have also used a value of 340 kJ/mol in the course of development of regression models for the predictions of activation energy and kinetics of SRX process in hot deformed austenite.

As shown in Fig. 3, the relaxation data have been fitted with the Avrami type equation around 50% of the recrystallised fraction, and the Avrami exponent of 1-1.2 was proposed for SRX to get reasonable fitting with experimental data, even though it seems that a lower slope would fit better at the final stage, similarly as reported by Karjalainen and Perttula [4,5]. At any strain rate, it appeared that a similar exponent (1-1.1) was valid even at higher strains (MDRX range) also, as discussed in subsequent section. These values are, however, somewhat lower than those reported earlier (1.4-1.7) [4,5,8].

The austenite grain size was measured on specimens directly quenched from the reheating temperature at 1150°C and it was estimated to be about 23 μm, closely similar to that obtained by Ochoa et al. [2]. No specific study was undertaken to vary the grain size and to estimate the grain size exponent (s) for two reasons: first, it is quite difficult to get large variations in grain size owing to the presence of sulphide inclusions, which retard the grain growth process up to at least 1250°C [2] and secondly, the grain size exponent has also been found to be strongly grain size dependent [8-10]. Hence, the equation developed for the grain size exponent (s) in the previous regression model [8-10] has been employed here in predicting the SRX kinetics.

In summary, the following fractional softening equation was developed, which fits the experimental data fairly accurately:

$$t_{50} = A\, \varepsilon^{p}\, \varepsilon'^{q}\, d^{s}\, \exp(Q_{app}/RT) = 1.3 \times 10^{-11}\, \varepsilon^{-2.7}\, \varepsilon'^{-0.13}\, d^{s}\, \exp(177000/RT) \qquad (1)$$

where A is a constant, ε the strain, ε' strain rate, d the grain size, R the universal gas constant and T the absolute temperature.

The unique regression model [8-10], developed at the University of Oulu that is able to predict the SRX kinetics of common carbon steel grades including microalloyed steels, was used to predict the SRX kinetics of the present steel as well. A linear regression equation was established in the model to predict the activation energy of SRX (Q_{rex}) for hot deformed austenite as sum effects of potent solute elements [9,10]. The model predicts Q_{rex} ~232 kJ/mol, a value which is higher than the experimental value of 219 kJ/mol, as computed from the experimental data: $Q_{rex} = Q_{app} - q^{*}Q_{def}$. However, a fraction of Mn combines with S to form MnS inclusions: in the range 950-1150°C, this steel has 0.01-0.04% S_{ss}, 0.86-0.88% Mn_{ss}, 0.4% S_{pp} and 0.22% Mn_{pp},, where subscripts 'ss' and 'pp' represent 'solid solution' and 'precipitates', respectively. For this Mn_{ss} range, the predicted Q_{rex} is about 218 kJ/mol, which is in excellent agreement with the experimental result. The predicted values of t_{50} times from the model were found to be about 0.65-1.3 times the experimental values, which can be considered to be very reasonable [8,9]. The present predictions from the regression model further confirm its robustness and any scatter or variations in results should in no way be attributed to the presence of the sulphide inclusions. Finally, as expected the SRX behaviour of the 9SMn25 free cutting steel was found closely similar to that of C/C-Mn steels.

MDRX characteristics and kinetics. In the high strain region following the onset of DRX beyond the peak strain, ε_p, the post-dynamic, i.e. MDRX behaviour displays significantly different characteristics compared to those of SRX, viz. there is a weak dependence on strain (slightly increasing with strain, Fig. 4, similarly as in Ref. [5]), but there is, however, a strong dependence on strain rate. The strain rate exponent (q) determined over the strain rate range of 0.01-5 s^{-1} showed a value of the order of -0.78 computed from the stress relaxation tests carried out following deformation to 0.6 strain (Fig. 5), where practically all the measurements are in the steady-state regime. In agreement, Hodgson et al. [11] and Karjalainen and Perttula [5] reported a value of the order of -0.8 for C-Mn steels. Similarly, systematic relaxation tests carried out on a number of C/C-Mn steels yielded strain rate exponent values in the range -0.75 to -0.8.

The sharp increase in the strain rate exponent from a low value near the peak strain to a high value of the order of -0.8 suggests the possibility of the existence of an intermediate transient region, the details of which are reviewed elsewhere [5]. Contrary to strong dependence of SRX process on the austenite grain size, the MDRX process is independent of it and essentially concerns the recrystallisation by the growth of pre-existing nuclei. However, the high strain rate dependence of MDRX may have practical consequences in high strain rate processes, such as strip or bar rolling. The MDRX process becomes extremely fast so that it finally controls the rolling load requirements and the resultant austenite grain size just before the phase transformation in cooling. Bianchi and Karjalainen [15] have recently modelled the DRX and MDRX behaviour of a medium-carbon steel under changing strain rate conditions in rod rolling. Likewise, the MDRX process is of immense practical importance in bar rolling of free cutting steels as well.

Unlike the SRX process, the temperature has a very small influence on the apparent activation energy of MDRX, estimated as ~57 kJ/mol at strains of about 0.6 (Fig. 6). This value is consistent if compared with those observed earlier [11,5]. The Q_{rex} for MDRX has been computed to be about 311 kJ/mol, which is quite high compared to that obtained for the SRX process (~200 kJ/mol). Q_{rex} measurements on a medium-carbon steel also gave much lower value for the SRX process. In contrast, Karjalainen and Perttula [5] reported practically similar Q_{rex} values (290-300 kJ/mol) for SRX and MDRX processes in a low-carbon steel.

As mentioned earlier, the exponents used in the Avrami equations for fitting the relaxation curves at about 50% of the recrystallised fractions were practically identical to those used for the SRX process, i.e. in the range of 1-1.1.

The following fractional softening equation describing the t_{50} times for the MDRX process at different strain rates and temperatures fit well with the experimental data:

$$t_{50} = 2.43 \times 10^{-3}\, \varepsilon'^{-0.785} \exp(57000/RT) \qquad (2)$$

Higher stress levels were noticed at the end of relaxation in some tests, however, these have nothing to do with extent of softening and should be considered as a consequence of experimental inaccuracy owing to the elasticity of the test machine, which is described in further details elsewhere [4,5].

Summary and conclusions

The flow stress behaviour and recrystallisation characteristics of a 9SMn28 free cutting steel are closely similar to those reported for C/C-Mn steels in the literature.

The SRX kinetics showed a strong dependence on strain and a weak dependence on strain rate, the exponent being -2.7 and -0.13, respectively. On the contrary, the MDRX kinetics showed an exactly opposite behaviour with a strong dependence on strain rate (the exponent -0.78) and no dependence on strain.

As expected, Q_{app} revealed a strong dependence of SRX on temperature (177 kJ/mol) in comparison to the MDRX process, which showed a very low influence (57 kJ/mol). Q_{def} has been computed as 324 kJ/mol and the corresponding Q_{rex} values for the two processes are 219 and 311 kJ/mol, respectively.

The Q_{rex} and t_{50} predictions by the SRX regression model [8-10] were quite reasonable, and improved marginally after considering the real amount of Mn in the solid solution (218 kJ/mol; ~0.65-1.3 times the experimental values), suggesting a wide applicability of the model.

Acknowledgements

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