Hot Deformation of 304 Type Austenitic Stainless Steel at High Strain Rates

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1. Introduction

Hot rolling produces plates and strips in several gauges and lengths. Plates are usually manufactured in reversible mills equipped with front and end run out tables with relatively long rest periods between reductions. The slabs are deformed in successive passes of equivalent strains averaging approximately 0.3. The strain rates employed in this process are in the range of 1 to 10 s$^{-1}$ from the first to the last pass. Plate rolling is hence a manufacturing process by which reductions of relatively low strains and moderate strain rates are used to shape the material.$^{1,2}$ The process of hot strip rolling is, on the other hand, performed in two stages: roughing and finishing. The former has a schedule with many similarities to the plate rolling features, that is, it is carried out with long interpass times and mild strain rates applied per pass. Finishing, however, is usually performed in tandem mills and the time intervals between the first passes are of the order of a few seconds, decreasing sharply to interrupt periods as short as a few tenths of a second in between the last stands. All passes are applied without reversals at strain rates in the range of 10 to 100 s$^{-1}$ from the beginning to the end of the process.$^{3,5}$

Several types of mechanical testing techniques are employed to emulate some aspects of the process of hot rolling. Among those, the use of axial and plane strain compression as well as torsion testing has been frequently reported in the literature. The advantages and disadvantages of each experimental technique when compared to one another in respect to their performances as a tool for hot rolling simulation are well known and well documented.$^{6-11}$ Torsion, particularly, is often employed not only to simulate hot rolling but also to produce stress–strain curves for the derivation of constitutive equations suitable to be used in flow curve modeling.$^{12}$ Mechanical testing, however, presents some limitations, the most serious of them, perhaps, regards the maximum strain rate attainable during deformation. The usual strain rates reported by researchers do not surpass a value of around 10 s$^{-1}$ and, only very rarely tests are conducted at strain rates of the order of 50 s$^{-1}$, as reported elsewhere.$^{8,13,14}$ Therefore, hot rolling loads at strain rates such as those found in the finishing stands of a hot strip and rod mills can be estimated only by the extrapolation of data obtained at considerable lower ranges of strain rates. This may be or may be not realistic since it seems that, up to these days, there is a lack of unequivocal experimental evidence for the hypothesis of calculating loads from extrapolated data.$^{15-18}$

This work presents a simple experimental technique through which strain rates up to 100 s$^{-1}$ can be attained during hot torsion testing. Stress–strain curves were obtained for a range of strain rates from 0.1 to 100 s$^{-1}$. The data so collected were fitted using a $Z$ versus log(sinh($\sigma$/$\epsilon$)) diagram allowing an assessment of the behavior of the stresses measured at strain rates closer to those related to the industrial hot rolling schedules. It is clearly shown that data collected from low strain rate testing can be fairly reasonably extrapolated to higher orders of magnitude of strain rate, as thoroughly assumed in the literature.

2. Experimental Technique

An austenitic stainless steel type 304 with chemical composition 0.073C, 1.26Mn, 0.52Si, 0.037P, 0.006S, 18.14Cr, 9.90Ni and 0.054Mo, all numbers in weight %, was used in the present research. Torsion testing at constant temperature and strain rate was carried out using a servo-hydraulic, computer controlled machine equipped with a radiant furnace. Temperatures were measured employing cromel-alumel thermocouples mineral insulated and protected by a tube of 316 type stainless steel. Data on torque and angular displacement were digitally collected during testing and stored in magnetic media for further processing.

The samples used in the experiments had different length to diameter ratios. The samples employed to obtain stress–strain curves at strain rates equal or smaller than 10 s$^{-1}$ (long samples) had 14.4 mm of length and 6.37 mm of diameter. The samples used in the experiments to obtain stress–strain curves at higher strain rates, 50 and 100 s$^{-1}$, short samples, had 1.8 mm of length and the same diameter as the long torsion samples. That is, for a given angular displacement, a deformation higher by a factor of 8 was imparted to the short samples when compared to the long specimens. The hydraulic actuator moved at a maximum rotation speed of 1 000 rpm delivering a maximum strain rate of 13 and 107 s$^{-1}$ respectively for long and short length samples. Therefore, for the sample geometry employed in this work, strain rates of up to 100 s$^{-1}$ were attained without major experimental troubles.

Testing procedure consisted of heating the sample up to a temperature of 1 473 K (1 200°C) for 900 s (15 min) followed by a controlled cooling of the specimen down to test temperature at a rate of 1 K/s (1°C/s). The sample was then held at this temperature for a period of 600 s (10 min) aiming at promoting temperature equalization throughout the specimen prior to deformation. In the case of the tests conducted at 1 473 K (1 200°C), the homogenization procedure was not necessary and deformation started right after the pre-heating time of 600 s (10 min). The samples were twisted at temperatures of 1 473, 1 373, 1 273, 1 173 K (1 200, 1 100, 1 000, 900°C) and at rates of 0.1, 1, 10, 50, 100 s$^{-1}$. Torque and angular displacement were converted to equivalent stress-strain curves using:

$$\sigma = \frac{3\sqrt{3}}{2\pi} \frac{\Gamma}{R}$$ .......................... (1)

and

$$\epsilon = \frac{1}{\sqrt{3}} \frac{R}{L}$$ .......................... (2)
Here, $R$ and $L$ are the sample radius and length, respectively and $\Gamma$ and $\theta$ are the measured torque and angular displacement.

Adiabatic heating is an important factor to be considered in the experiments carried out at high strain rates. Whenever the temperature of the sample surface increased due to deformation heating, the power input to the radiant furnace was decreased so to compensate either totally or at least partially any effects of temperature increase on the measurement of the stresses. This technique showed to be correct since no substantial increase in temperature was recorded at the end of the high strain rate tests, confirming observations reported elsewhere.\textsuperscript{6}

3. Results and Discussion

Figure 1 shows the stress–strain curves obtained for stainless steel type 304 tested at the temperatures employed in this work. All curves present similar shapes regardless of testing temperature. A brief analysis of the shape of all stress strain curves is carried out here taking the results obtained for the temperature of 1 173 K (900°C) as a reference. It can be noticed that a peak stress is reached at strain rates of 0.1, 1 and of 10 s\textsuperscript{−1}, the latter being almost unperceivable, leading to a steady state stress slightly smaller than the peak stress. The value of peak stress is a marked characteristic of the occurrence of dynamic recrystallization.\textsuperscript{20,21} Here, the value of this stress is of the order of 180 MPa at a strain of approximately 0.5 for the sample tested at a strain rate of 0.1 s\textsuperscript{−1}. The peak stress in this case is well established since the steady state stress is approximately 160 MPa. At a strain rate of 1 s\textsuperscript{−1}, the peak stress, the peak strain and the steady state stress, are, respectively, 210 MPa, 0.7 and 230 MPa for a strain rate of 1 s\textsuperscript{−1}. The peak stress in this case is well established since the steady state stress is approximately 160 MPa. At a strain rate of 1 s\textsuperscript{−1}, the peak stress, the peak strain and the steady state stress, are, respectively, 210 MPa, 0.7 and 230 MPa. It can then be clearly noticed that the difference between the steady state and the peak stress decreases with increases in the strain rate. In the case of strain rates of 10 s\textsuperscript{−1}, the peak stress, the peak strain and the steady state stress are 240 MPa, 0.7 and 230 MPa for a strain of 2.0. In this case, the differences between the steady state and the peak stress are almost negligible. However, when the strain rates become higher than 50 s\textsuperscript{−1}, the peak stress virtually disappears and for a rate of 100 s\textsuperscript{−1} the curve reaches a steady state stress without showing no peak stress. Dynamic recrystallization, therefore, seems to occur at rates of 0.1, 1 and 10 s\textsuperscript{−1} but it is apparently suppressed at higher strain rates, particularly at lower temperatures such as 900°C, for the strains applied to the samples in this work. The same picture could be drawn for samples tested at the remaining temperatures.

Rolling load is a function of process and geometry variables as well as of the friction coefficient and of the stress needed to deform a metal. There are several equations that can be used to estimate the value of the load during rolling all of them, however, depend on the estimation of the mean stress needed to carry out the operation. The mean flow stress, on its turn, depends on temperature, strain and the strain rate applied during deformation. Hence, a “constitutive equation” relating the stress to testing temperature and strain rate and an “evolution equation” to describe the dependence of the stresses on strain are required.\textsuperscript{6,5} An equation of the form shown below is usually employed to describe the dependence of stress on the temperature and strain rate,

\begin{equation}
Z = \bar{\epsilon} \exp \left( \frac{Q_{\text{def}}}{RT} \right) = A (\sinh(\alpha \tau))^{\beta} \quad \text{.........(5)}
\end{equation}

Here, $Z$ is the Zener–Hollomon parameter, $Q_{\text{def}}$ is an activation energy, $R$ is the gas constant, 8.31 J/(mol K), $A$, $n$ and $\alpha$ are constants. The activation energy of hot working is not usually related to a single activation mechanism since the microstructure is always changing during the process of deformation. Therefore, $Q_{\text{def}}$ is actually an apparent activation energy relating the stress to an equilibrium substructure such as the one observed at a steady state stress. However, as widely published in the literature, it is more practical to use a peak stress rather than a steady state stress when the case is of estimating rolling loads.\textsuperscript{6} This is because, if the
peak or the maximum stresses can be estimated, then the maximum rolling loads can be also assessed. In the present work, the peak stresses were considered for samples deformed at strain rates up to 10 s⁻¹. For strain rates higher than 10 s⁻¹, the steady state stress and the strain at which this steady state stress were achieved was taken into consideration. This approach has been used before and it has been documented in the literature.⁵ The reason for taking this procedure is that in this way the maximum rolling loads could still be estimated in a relatively simple way. Moreover, the apparent activation energy, an important experimental fitting parameter, would still being calculated at a point in the stress strain curve where the strain would be the minimum for the achievement of a null work hardening rate. This procedure yielded a very successful fitting between the maximum stress and Z as it is clearly shown in Fig. 2, noticing that the correlation coefficient, R², is equal to 0.974. The experimental data were fitted by Eq. (5) using an activation energy for deformation of 410 kcal/mol, an average value found for type 304 steel, as reported in the literature.⁶ The slope of the curve is n, the stress exponent in Eq. (5) and its value is 4.01, close to the average value of 4.3 reported for the steel used in this work.⁶

The value of maximum stress obtained from the samples tested at 100 s⁻¹ is distributed in a range of 3 orders of magnitude of Z values. If the measurements of the maximum stresses obtained at tests conducted at 50 s⁻¹ were also taken into account, the orders of magnitude of Z values covered would be wider still. More importantly, results obtained from low strain rates tests are also scattered over a wide range of Z values, overlapping, very substantially, on those results obtained from high strain rate.

Although the results reported here comes from very simple experiments, its consequences to rolling load predictions are evident. Firstly, in spite of a change in the major dynamic softening mechanism as the strain rate increases significantly from 0.1 to 100 s⁻¹, 4 orders of magnitude, the behavior of the maximum stress as a function of Z can still be described by a very simple and convenient relationship. Secondly, it becomes quite evident that further extrapolation to even higher strain rates is possible thus achieving those rates found in the finishing stands of rod mill rolling, for instance.¹⁷ This is of practical importance since strain rates of the order of 500 s⁻¹, as expected to be found in rod rolling finishing, appears to be unachievable by any ordinary mechanical testing technique known, at least as far as the absence of reports on this matter in the literature may suggest.

4. Conclusions

The present results lead to the following conclusions:

(1) Stress–strain curves at strain rates higher than 50 s⁻¹ can be obtained from simple experiments employing mechanical testing such as torsion by adopting a suitable sample radius to length ratio. In the case of type 304 stainless steels, for the maximum strains of 2.0 employed in this work, the prevailing dynamic softening mechanism changed from dynamic recrystallization at strain rates lower than 10 s⁻¹ to incipient dynamic recrystallization at 50 s⁻¹ to dynamic recovery at 100 s⁻¹, for most test temperatures. Nonetheless, a plot of the maximum stress versus Z was fitted by a hyperbolic sine function over the entire range of strain rates used in this work.

(2) In spite of change in the prevailing dynamic softening mechanism during the experiments reported in this paper, a suitable correlation was obtained for the maximum stress versus Z for the entire range of strain rates tested. This suggests that an extrapolation of maximum stress values to higher strain rates is feasible, even if the original data were obtained from relatively low strain rate experiments. The implication of this finding is that the present results can be used to obtain values of maximum stresses at rates even higher than 100 s⁻¹ as, for instance, those occurring during wire rod finishing rolling.

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