CONSTITUTIVE EQUATIONS FOR AUSTENITIC STAINLESS STEELS HOT DEFORMED AT HIGH STRAIN RATES

J. A DeAlmeida
Process Development Corporation do Brasil
Av. Juscelino Kubitschek, 140- SL 802- Centro
32510-070 - Betim, Minas Gerais, Brasil
jalmeidajj@uol.com.br

R. Barbosa
Universidade Federal de Minas Gerais. Departamento de Engenharia Metalúrgica e de Materiais.
R. Espírito Santo 35, sala 206- Centro,
30160-030- Belo Horizonte, Minas Gerais, Brasil
rbarbosa@demet.ufmg.br

Abstract. *Hot torsion testing is commonly used in the simulation of hot rolling although the technique presents some import limitations, among them the low strain rates at which tests are usually conducted. This work presents a simple laboratory testing technique able to produce data for stress-strain curves to strain rates as high as* $100s^{-1}$*, hence compatible with those found in the industry.*

The rate of straining during torsion testing depends on the rate of twisting of the actuator and on the ratio r/L of the sample. The higher this ratio, that is, the larger the sample radius or the smaller its length, the larger will be the rate at which the sample will be deformed for a given RPM at the actuator. The present paper reports experiments with r/L ratios 15 times higher than the usually employed in hot torsion. This, together with the ability of rotating the sample at 1000RPM produced the strain rates needed to obtain stress-strain curves at rates similar to those present at hot rolling of several industry products.

Keywords*: Constitutive equations, austenitic stainless steels, hot torsion testing*

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 $10s^{-1}$ 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 (Boratto et al., 1988; Bai et al., 1993). 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 $100s^{-1}$ from the beginning to the end of the process (Jonas, 2000; Siciliano, Jr., 1996, 2000).

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 (Sellars, 1985; Braga et al., 1993; Davenport et al., 2000; McQueen and Ryan, 2002; Rao et al., 1993). 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. 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 $10s^{-1}$ and, only very rarely tests are conducted at strain rates of the order of $50s^{-1}$, as reported elsewhere (Davenport et al., 2000; McQueen and Ryan, 2002). 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 (Millitzer et al., 2000; Huang et al., 2001).

This work presents a simple experimental technique through which strain rates up to $100s^{-1}$ can be attained during hot torsion testing. Stress-strain curves were obtained for a range of strain rates from 0.1 to $100s^{-1}$. The data so collected were fitted using a Z versus log (sinh(ασ)) 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 Procedure

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 $10s^{-1}$ (long samples) had 14.4mm of length and 6.37mm of diameter. The samples used in the experiments to obtain stress-strain curves at higher strain rates, 50 and $100s^{-1}$, short samples, had 1.8mm 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 1000 RPM delivering a maximum strain rate of 13 and $107s^{-1}$ respectively for long and short length samples. Therefore, for the sample geometry employed in this work, strain rates of up to $100s^{-1}$ were attained without major experimental troubles.

Testing procedure consisted of heating the sample up to a temperature of 1473K (1200°C) for 900s (15min) followed by a controlled cooling of the specimen down to test temperature at a rate of 1K/s (1°C/s). The sample was then held at this temperature for a period of 600s (10min) aiming at promoting temperature equalization throughout the specimen prior to deformation. In the case of the tests conducted at 1473K (1200°C), the homogenization procedure was not necessary and deformation started right after the pre-heating time of 600s (10min). The samples were twisted at temperatures of 1473, 1373, 1273 e 1173K (1200, 1100, 1000 e 900°C) and at rates of 0,1, 1, 10, 50 e $100s^{-1}$. Torque and angular displacement were converted to equivalent stress-strain curves using Fields and Backofen (1957)

$$\sigma = \frac{3.3\sqrt{3}}{2\pi}\frac{\Gamma}{R^3} \tag{1}$$

and

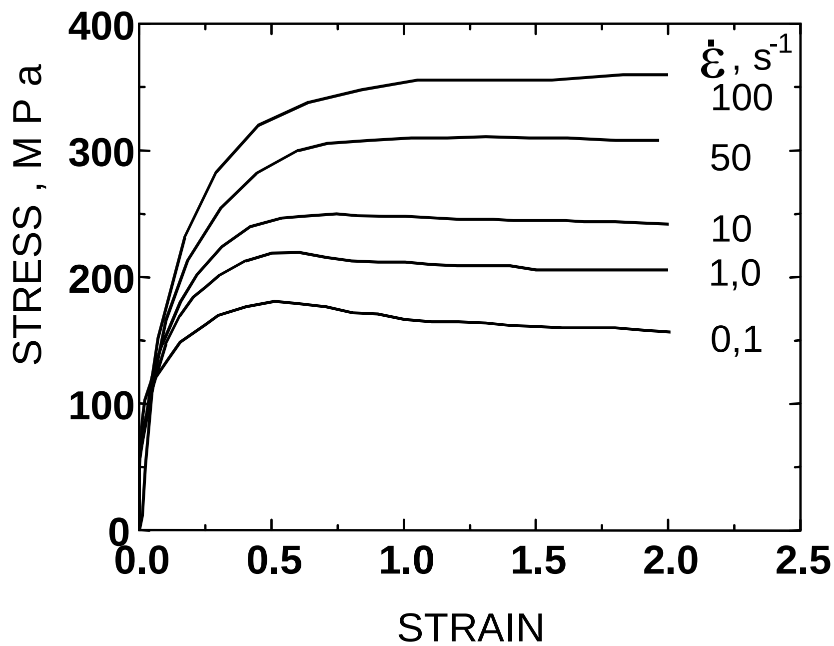
$$\varepsilon = \frac{1}{\sqrt{3}}\frac{R}{L}\theta \tag{2}$$

Here, R and L are the sample radius and length, respectively and Γ and θ are the measured torque and angular displacement.

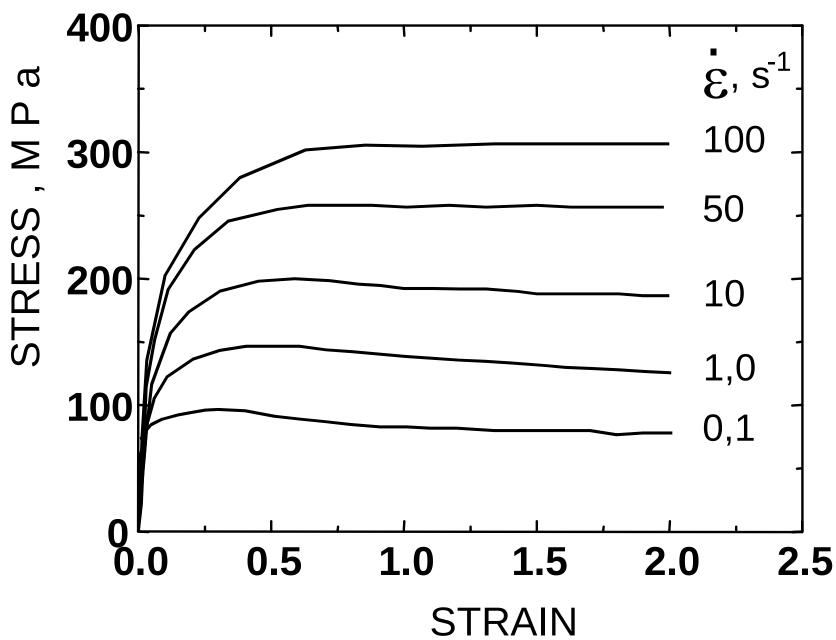
3. Results and discussion

Figs. 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 1173K (900°C) as a reference. It can be noticed that a peak stress is reached at strain rates of 0.1, 1 e de $10s^{-1}$, 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 [20,21)]. Here, the value of this stress is of the order of 180MPa at a strain of approximately 0.5 for the sample tested at a strain rate of $0.1s^{-1}$. The peak stress in this case is well established since the steady state stress is approximately 160MPa. At a strain rate of $1s^{-1}$, the peak stress, the peak strain and the steady state stress, are, respectively, 210MPa, 0.5 and 200MPa. 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 $10s^{-1}$, the peak stress, the peak strain and the steady state stress are 240MPa, 0.7 and 230MPa 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

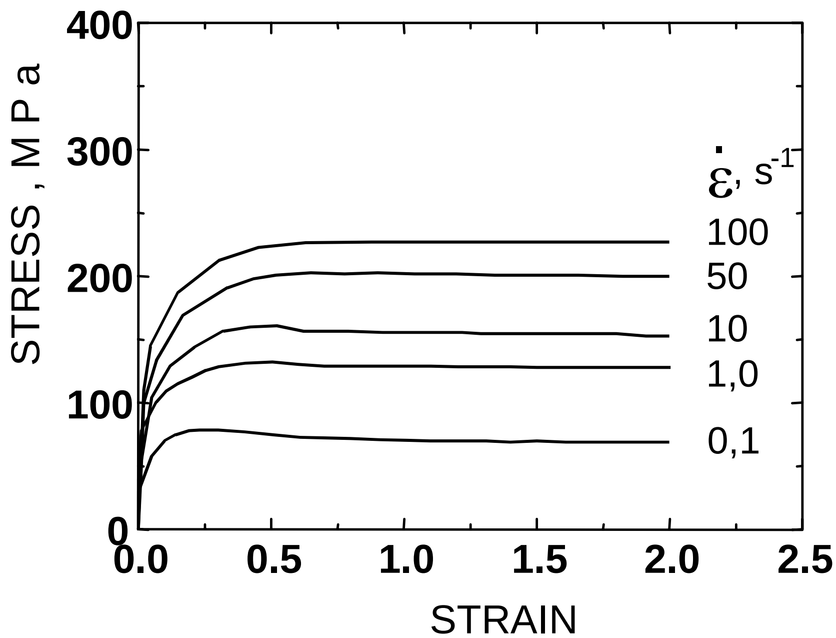
$50s^{-1}$, the peak stress virtually disappears and for a rate of $100s^{-1}$ the curve reaches a steady state stress without showing no peak stress. Dynamic recrystallization, therefore, seems to occur at rates of 0.1, 1 e $10s^{-1}$ but it is apparently suppressed at higher strain rates, particularly 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.



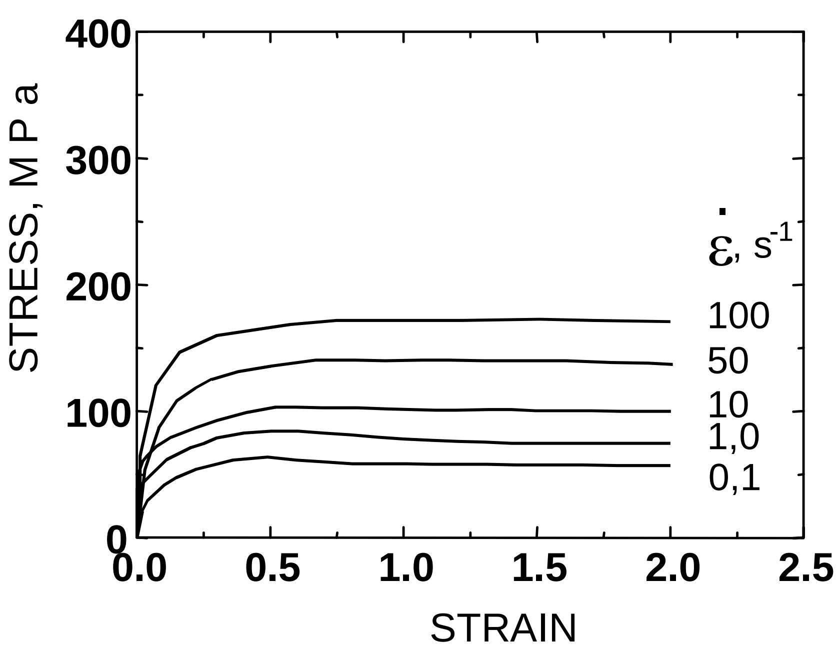
(a)



(b)



(c)



(d)

Figure 1. Stress-strain curves for samples at temperatures of (a) 1173K (900^{o}C), (b) 1273K (1000^{o}C), (c) 1373K (1100^{o}C) and (d) 1473K (1200^{o}C) and several strain rates. The prevailing dynamic softening mechanism changes from dynamic recrystallization for strain rates equal or lower than $10s^{-1}$ to incipient dynamic recrystallization at $50s^{-1}$ and then to dynamic recovery at $100s^{-1}$.

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 [6, 8)]. An equation of the form shown below is usually employed to describe the dependence of stress on the temperature and strain rate,

$$Z = \dot{\varepsilon}\ \exp\left(\frac{Qdef}{RT}\right) = A(\mathrm{senh}(\alpha\,\sigma))^n \tag{5}$$

Here, Z is the Zener-Hollomon parameter, Qdef is an activation energy, R is the gas constant, 8.31J/(mol K), A, n and α 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, Qdef 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 (McQueen and Ryan, 2002). 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 $10s^{-1}$. For strain rates higher than $10s^{-1}$, the steady state stress and the strain at which this steady state stress was achieved was taken into consideration. This approach has been used before and it has been documented in the literature (McQueen and Ryan, 2002). 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 working 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, R^2, is equal to 0.984.

Fig. 2 show that the value of maximum stress obtained from the samples tested at $100s^{-1}$ 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 $50s^{-1}$ 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 $100s^{-1}$, 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 (Sellars, 1985). This is of practical importance since strain rates of the order of $500s^{-1}$, 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:

Stress-strain curves at strain rates higher than $50s^{-1}$ 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 2.5 employed in this work, the prevailing dynamic softening mechanism changed from dynamic recrystallization at strain rates lower than $10s^{-1}$ to incipient dynamic recrystallization at $50s^{-1}$ to dynamic recovery at $100s^{-1}$, for most test temperatures. Nonetheless, a plot of the maximum stress versus Z was fitted by a hyperbolic sine function over an entire range of strain rates used in this work.

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 $100s^{-1}$ as, for instance, those occurring during wire rod finishing rolling.

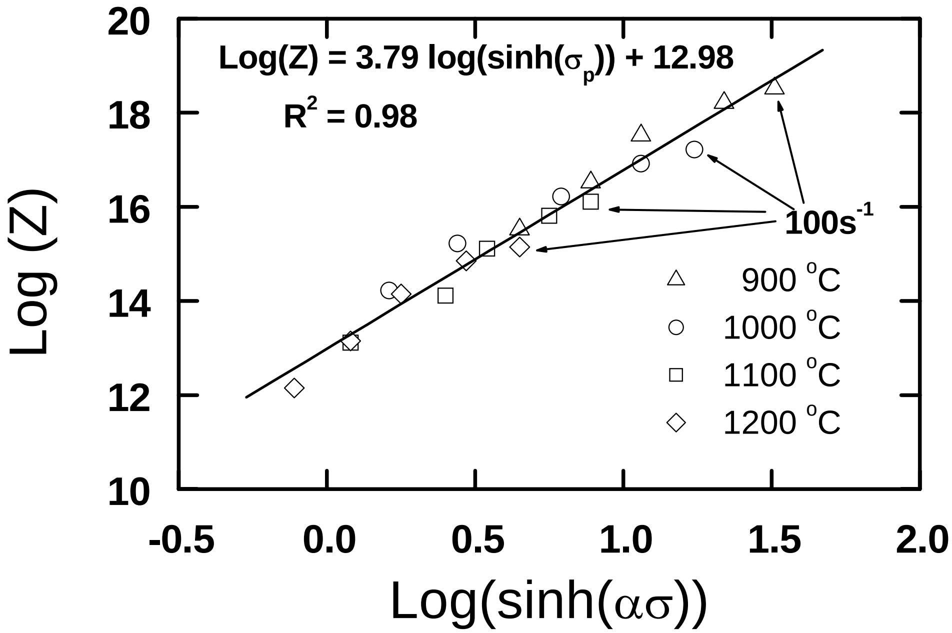


Figure 2. The dependence of the maximum stress on the value of Z for tests conducted at several temperatures. Data obtained from tests performed at $100s^{-1}$ overlap on those measured from tests conducted at lower strain rates showing that an extrapolation from the lower strain rate data sub-set to higher orders of strain rate stresses is feasible.

5. Acknowledgements

The authors acknowledge CNPq and PRPq-UFMG for the financial support given to this research.

6. References

Boratto, F., Barbosa, R., Yue, S. and Jonas, J. J., 1988, "Effect of Chemical Composition on the Critical Temperature of Microalloyed Steels", Proceedings on the Int. Conf. Physical Metallurgy of Thermomechanical Processing of Steels and Other Metals (THERMEC '88), Vol. 1, Tokyo, Japan, pp. 383-390.

Bai, D. Q. Yue, S., Sun, W. P. and Jonas, J. J., 1993, "Effect of Deformation Parameters on the No-Recrystallization Temperature in Nb-Bearing Steels" Metallurgical Transactions A, Vol. 24, pp. 2151-2159.

Siciliano Jr., F., Minami, K., Maccagno, T.M. and Jonas, J.J., 1996, "Mathematical Modeling of the Mean Flow Stress. Fractional Softening and Grain Size during Hot Strip Rolling of C-Mn Steels", ISIJ International, Vol. 36, pp. 1500-1506.

Jonas, J.J., 2000, "The hot strip mill as an experimental tool", ISIJ International, Vol.40, pp. 731-738.

Siciliano Jr., F. and Jonas, J.J., 2000, "Mathematical Modeling of the Hot Strip Rolling of Microalloyed Nb. Multiply-alloyed Cr-Mo and Plain C-Mn Steels", Metallurgical and Materials Transactions A, Vol. 31. pp. 511-530.

McQueen, H. and. Ryan, N.D., 2002, "Constitutive analysis in hot working", Materials Science and Engineering A, Vol. A322, pp. 43-63.

Sellars, C. M., 1985, "The kinetics of softening processes during hot working of austenite", Czechoslovak Journal of Physics, Vol. B35.,pp. 239-248.

Davenport, S.B., Silk, N.J., Sparks, C.N. and Sellars, C.M., 2000, "Development of constitutive equations for modelling of hot rolling", Materials Science and Technology, Vol. 16, pp. 539-547.

Rao, K.P., Hawbolt, E.B., McQueen, H.J. and Baragar, D., 1993, "Constitutive Relationships for Hot Deformation of a Carbon Steel: a Comparison Study of Compression Tests and Torsion Tests", Canadian Metallurgical Quartely, Vol. 32. n.2, pp. 165-175.

Braga, H.C., Barbosa, R. and Breme, J., 1993, "Hot strength of Ti and Ti6Al4V deformed in axial compression", Scripta Metallurgica e Materialia, Vol.28, pp. 979-983.

Medina, S.F. and Hernandez, C.A., 1996, “The influence of chemical composition on peak strain of deformed austenite in low alloy and microalloyed steels”, Acta Materialia, Vol. 44, pp. 137-154.

McQueen, H., 2002b, “Elevated temperature deformation at forming rates of 10^{-2} to $10^{2}s^{-1}$”, Metallurgical and Materials Transactions A, Vol. 33, pp. 345-363.

Millitzer, M., Hawbolt, E.B. and Meadowcroft, T.R., 2000, “Microstructural model for hot strip rolling of high-strength low-alloy steels”, Metallurgical and Materials Transactions A, Vol. 31, pp. 1247-1259.

Huang, C., Hawbolt, E.B., Chen, X., Meadowcroft, T.R. and Matlock, D.K., 2001, “Flow stress modelling and warm rolling simulation behaviour of two Ti-Nb intersticial-free steels in the ferrite region”, Acta Materialia, Vol. 49, pp. 1445-1452.

Fields, D.S. and Backofen, W. A., 1957, “Determination of strain-hardening characteristics by torsion testing”, American Society for Testing and Materials, Vol. 57, pp. 1259-1272.

7. Responsibility notice

The authors are the only responsible for the printed material included in this paper.