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## DYNAMIC RESPONSE OF METALS TO SINGLE AND MULTISTAGE, CONSTANT STRAIN RATE COMPRESSION

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Résumé - Des tests simples et multiples d'action de compression uni-axiale sont pratiqués sur des métaux Al-Mg-Si et des alliages d'acier 0.02% Nb HSLA. Le degré de sensibilité à la vitesse, l'énergie d'activation et l'effet d'interruption de la déformation plastique des métaux sont déterminés.

Abstract - Single and multistage, uniaxial compression tests are conducted on Al-Mg-Si and 0.02% Nb HSLA steel alloys. Rate sensitivity, activation energy and the effect of interruption on the flow strength of the metals are determined.

I - INTRODUCTION

Mathematical models of hot or cold strip rolling must describe the conditions of equilibrium within the deforming strip, the deformation of the work rolls, the frictional conditions at the roll-strip interface and must characterize the metal's resistance to deformation - see References [1] - [9].

Numerous publications may be found in the literature, presenting data on the behaviour of materials as a function of strain, rate of strain and temperature - see for example, References [10] - [15]. As well, empirical relations giving functional forms of the above data are available, some of which are described in References [16]-[19]. Close examination of those relations reveal, however, that their predictions differ broadly and that not all of them are of direct use when modelling of the rolling process is required - see Reference [20].

The project described in this paper is concerned with the last component of the model - the flow strength. The behaviour of two different alloys, subjected to single and multistage, constant strain rate compression is examined. History dependence of the flow strength is determined by observing the metals' response to various strains, rate of strain, and unloading times per cycles of compression. The applicability of the Arrhenius equation to account for the flow strength as a function of strain, rate of strain and temperature is discussed.

II - EXPERIMENTAL MATERIAL, EQUIPMENT & METHOD

Two materials were chosen for the present set of experiments. For the room temperature tests an Al-Mg-Si alloy, prepared by the Aluminum Company of Canada Ltd. was used; for the high temperature tests, 0.02% Nb bearing HSLA steel, donated by the Republic Steel Corporation of the USA was selected. The chemical composition of the metals, by weight %, is given in Table 1.

|            | Cu   | C   | Fe   | Mg   | Mn    | Ni    | Si  | Ti    | Zn    | P     | Al   | Nb  |
|------------|------|-----|------|------|-------|-------|-----|-------|-------|-------|------|-----|
| HSLA Steel | -    | .09 | rest | -    | .90   | -     | .02 | -     | -     | <.008 | .04  | .02 |
| Al-Mg-Si   | .002 | -   | .002 | 1.00 | <.001 | <.001 | .64 | <.001 | <.001 | -     | rest | -   |

TABLE 1 Chemical Composition of the Materials

The experiments were carried out on a microprocessor controlled servohydraulic testing system, the schematic diagram of which is shown in Figure 1. By providing an exponentially decaying voltage to the servovalve, the actuator travels to cause constant strain rate throughout its stroke. Strain rates of up to 50 s<sup>-1</sup> are reached, using specimens not higher than 20 mm. The dynamic response of the system is adequate; even at high speeds, when the time taken to overcome the inertia of the servovalve is significant, command and feedback signals differ by no more than 10%. Data acquisition is achieved by the A/D converter of the computer and the resulting true stress - true strain curves are obtained directly on the attached printer/plotter. Further, to simulate the conditions in the finishing train of a hot strip mill, interrupted compression testing, up to 10 stages, can be conducted. Strains, rates of strain and unloading times may be selected per cycle, in an interactive manner, at the keyboard of the computer.

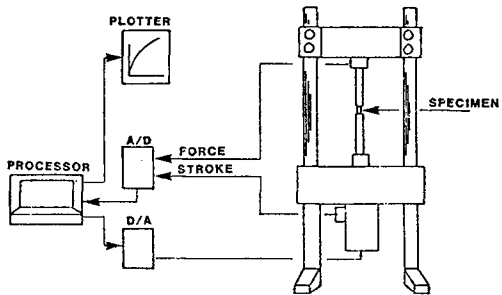


FIGURE 1

The tests on the aluminum alloy were carried out at room temperatures. The objectives were twofold. First, the rate sensitivity of the metal was to be determined after which the dependence of the flow strength on loading history was to be examined. During compression, friction at the sample-platen interface was minimized by two layers of teflon tapes. The samples measured 7 mm in diameter and 12 mm in height.

For high temperature testing the steel samples - approximately 5 mm in diameter and 8 mm high - were austenitized at 1150°C for 30 minutes, air cooled to test temperature, compressed and quenched in water. Solution treatment, testing and quenching were done in insulated Inconel containers which ensured that no chilling at the platen/sample interfaces occurred during the experiment. However, quenching was not as fast as it would have been without the container and in many cases the austenitic structure was not preserved. The ends of the specimens were lubricated with molten glass.

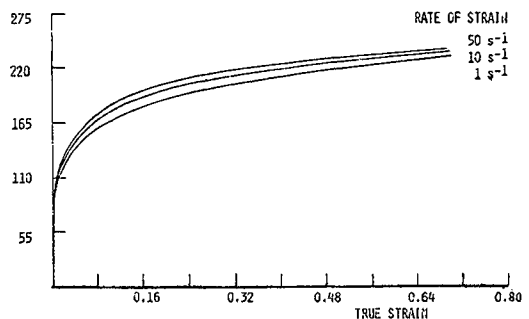


FIGURE 2

### III - RESULTS

True stress-true strain curves of the Al-Mg-Si alloy at various constant strain rates are shown in Figure 2. The tests were conducted at 20°C. As observed, the material is rate-sensitive at room temperatures, however, as straining proceeds, rate sensitivity is diminishing. Assuming that equations of the form  $\sigma = C\dot{\epsilon}^m$  are valid, rate sensitivity at a strain of 0.16 is found to be 0.020 while at a strain level of 0.64 rate sensitivity is reduced to 0.012.

The results of three stage compression tests on the same alloy are given in Figures 3 and 4. In Figure 3 the strain rate for each cycle is  $5 \text{ s}^{-1}$  and the unloading time between cycles is 50 ms. In Figure 4 strain rates of  $5 \text{ s}^{-1}$ ,  $50 \text{ s}^{-1}$  and  $5 \text{ s}^{-1}$  are chosen for each consecutive cycle. Unloading times are as in Figure 3. It is observed that interrupting the test has no effect on the behaviour of the alloy. Further when the rate of straining is changed in addition to interrupted testing the material attempts to follow the behaviour shown in Figure 2. This is also observed in Figure 5 which shows the response of the alloy to six stage compression. In that test the rates of strain were increased for each cycle and 100 ms unloading times in between each cycle were used.

The beginning of dynamic recrystallization has been associated with a peak in the stress-strain curve of a material. In the present experiments no peak strengths are observed - at least for strains up to 0.80 in Figures 2-5. This appears to confirm the results of Zaidi [21] and Tutcher [22] on Al-2Mg and Al-3Mg alloys, respectively.

Constant strain rate compression tests at  $\dot{\epsilon}=0.2, 1, 10$  and  $50 \text{ s}^{-1}$  were conducted on the Nb bearing HSLA steel. The flow curves have been presented elsewhere - see Reference [26] - the general results of the single stage tests are repeated here for completeness.

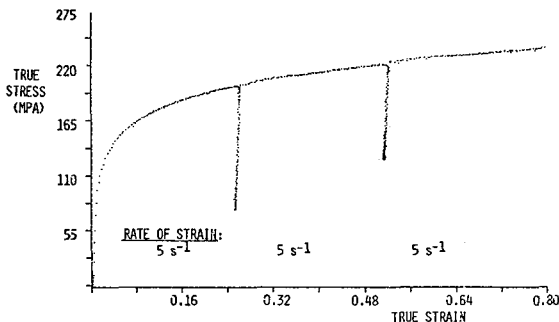


FIGURE 3

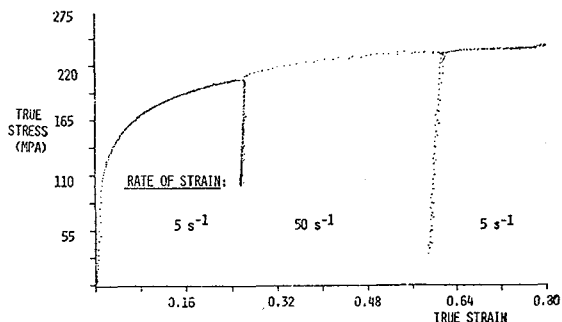


FIGURE 4

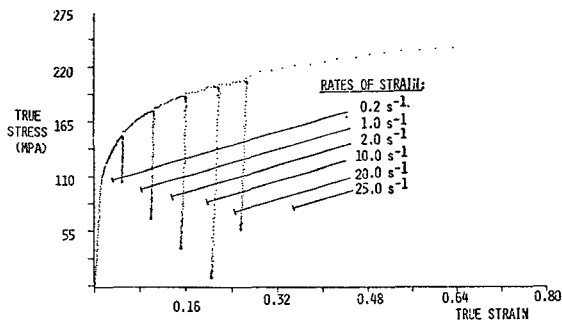


FIGURE 5

The temperature dependence of the peak flow strength of the Nb bearing HSLA steel alloy is given in Figure 6. The rate sensitivity of the material is calculated as 0.142 at 950°C, 0.124 at 850°C and 0.088 at 750°C. The values above 800°C compare well to those of Reference [23]. There the authors obtained a strain rate exponent of 0.116 for 0.05% Nb HSLA steel. Their test was done in torsion.

It is generally agreed that the Arrhenius equation

$$\dot{\epsilon} = A\sigma^n \exp(-\Delta H/RT) ,$$

where  $\dot{\epsilon}$  is the strain rate,  $\sigma$  is the peak or steady state strength,  $\Delta H$  is the activation energy,  $R$  is the universal gas constant and  $T$  is the temperature, represents high temperature behaviour of metals well. It has also been shown - see Sankar et al. [23] - that the peak resistance to deformation of Niobium bearing HSLA steels may be predicted, with reasonable accuracy, using that equation. Alternatively, knowing  $\sigma$  the activation energy may be computed.

Following Anand [24], the activation energy for the 0.02% Nb alloy was calculated as 433 kJ/mole, a value which compares well to that of [23]. For their steel the authors have determined  $\Delta H$  to be 434 kJ/mole. It appears that  $n$  and  $\Delta H$  are not strongly dependent on Niobium content.

Material behaviour in a technological forming process depends on many parameters, more than those contained in the Arrhenius equation. In order to describe strain softening and steady state conditions, an equation of the form

$$\sigma = \sigma(\epsilon, \dot{\epsilon}, T, \%Nb, \%C, \%Mn, \epsilon_{peak}, \dot{\sigma}_{peak})$$

would be required.

The equations proposed by Shida [19] and Halal and Kaflanglu [25] are capable of modelling softening only. The present author is unaware of the existence of any empirical relation that gives the flow

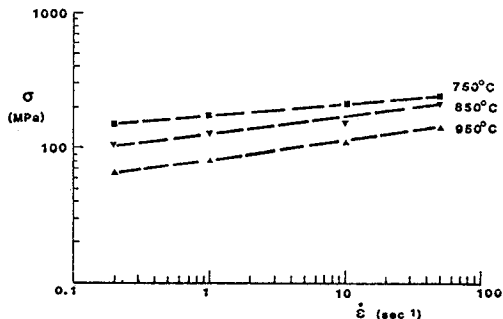


FIGURE 6

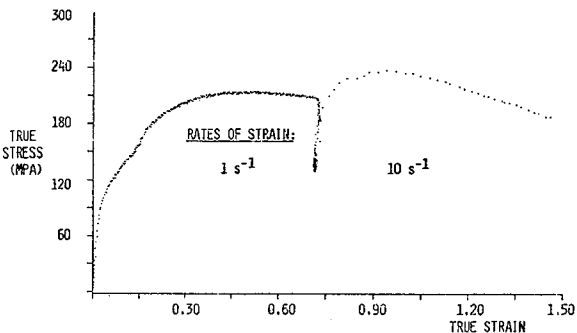


FIGURE 7

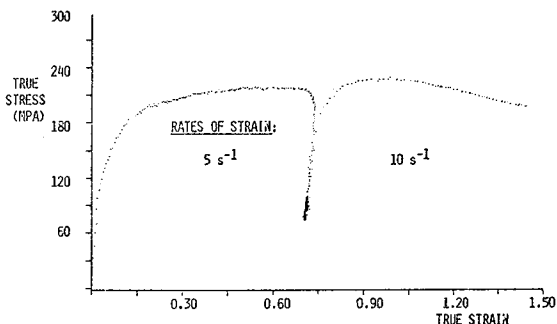


FIGURE 8

strength in the steady state region as well. The functional form suggested above is proposed for further discussion.

Figures 7 and 8 show true stress-true strain curves of the steel, subjected to two stage testing at 750°C. In Figure 7 the rate of strain was increased from  $1 \text{ s}^{-1}$  to  $10 \text{ s}^{-1}$  at  $\epsilon = 0.6$ ; in Figure 8,  $5 \text{ s}^{-1}$  and  $10 \text{ s}^{-1}$  were used. No history dependence is noticed, however, fractional softening appears to be more pronounced in Figure 8, even though unloading times for both experiments were the same.

The beginning of dynamic recrystallization is observed in both cycles of deformation in Figure 7. In Figure 8 not enough time is available to overcome the retardation effect of the Niobium in the first cycle. In the second cycle, however, significant softening is observed.

#### IV.- CONCLUSIONS

The behaviour of two metals, subjected to single and multistage, constant strain rate compression was investigated. Rate sensitivity, dependence of the flow strength on loading history and softening were examined. Parameters in the Arrhenius equation were calculated. A possible functional form of a constitutive relation for high temperature behaviour of steels was described.

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