A new constitutive model for nitrogen austenitic stainless steel

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ABSTRACT

Quasi-static, quasi-dynamic and dynamic compression tests have been performed on a nitrogen alloyed austenitic stainless steel. This alloy achieves a high hardening modulus and a good ductility at all strain rates. In addition, this steel is very sensitive to strain rate. The temperature sensitivity has been determined for temperatures varying between 20°C and 400°C. Microstructural analysis has been performed on samples subjected to different loads in order to relate the microstructure to the material behaviour. Johnson-Cook and Zerilli-Armstrong models have been selected to fit the experimental data into constitutive equations. These models are unable to reproduce the behaviour of this type of steel over the complete range of tests. A new constitutive model that better fits all the experimental data at different strain, strain rate and temperature has been determined. This empirical model supposes that the influence of the main parameters is independent. Single Taylor impact tests have been realized to validate the models. Live observations of the specimen during impact have been achieved using a special CCD camera set-up. The overall profiles at different times were compared to numerical predictions performed with LS-DYNA.

INTRODUCTION

Nitrogen-alloyed austenitic steels are novel materials. The solid solution nitrogen leads to an improvement in the mechanical properties (high strength, good ductility and a high hardening modulus) as well as in the corrosion-resistance properties. The alloy elements such as chromium, manganese, molybdenum and vanadium increase the nitrogen solubility. Higher nitrogen contents decrease the stacking fault energy and stabilize the austenitic structure so that no strain-induced transformation to α-martensite and ε-martensite occurs [1].
The aim of this work is to study the compression behaviour and the microstructural evolution of a nitrogen austenitic stainless steel and to propose a constitutive relation that correctly reproduces the behaviour of this kind of steel in a certain range of strain, strain rate and temperature.
To achieve this goal, quasi-static (10^{-3} s^{-1}) and quasi-dynamic (5.2 s^{-1}) compression tests have been performed on a universal testing machine. Dynamic compression tests ($2.5.10^3$ s^{-1}) have been carried out using classical split-Hopkinson bar apparatus. A new plasticity model has been defined and implemented in LS-DYNA as a *MAT_USER_MATERIAL_MODEL. Taylor impact tests have been used to validate the plasticity models.

1 MECHANICAL BEHAVIOUR

The studied nitrogen austenitic stainless steel, referred to as Uranus B66®, is produced by *Creusot-Loire Industrie* and contains a high amount of nickel and chromium.

1.1 Compression tests at room temperature

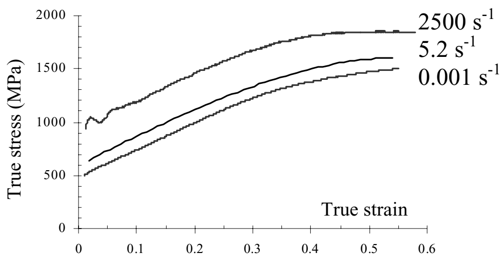


Figure 1: Stress-strain curves of Uranus B66 at room temperature for different strain rates

Stress-strain curves for Uranus B66 deformed at various strain rates at room temperature are shown in Figure 1. The increase of temperature that appears with strain in the adiabatic conditions (quasi-dynamic and dynamic loading) induces thermal softening. This thermal softening has been estimated and corrected for in all the following adiabatic stress-strain curves. Moreover, Uranus B66 has a high strain rate sensitivity ; the average flow stress being raised by 500 MPa as the strain rate is increased from 10^{-3} s^{-1} to 2.5 10^3 s^{-1}(Figure 1). The dynamic curve at high strain rate (2500/s) shows a distinct strain-rate effect on stress when compared with low-rate curves. On the other hand, Uranus B66 presents a high strain hardening rate, independent on the strain rate, with a saturation of the stress at strains over 35%.

1.2 Compression tests at high temperature

Figure 2 shows the stress-strain curves obtained for Uranus B66 deformed in quasi-static and dynamic loading for temperatures from 20°C to 400°C. The precipitation of chromium nitrides at temperature over 500°C limits the maximal testing temperature. As expected at low strain rate (Figure 2), the strain hardening decreases slightly with increasing temperature.

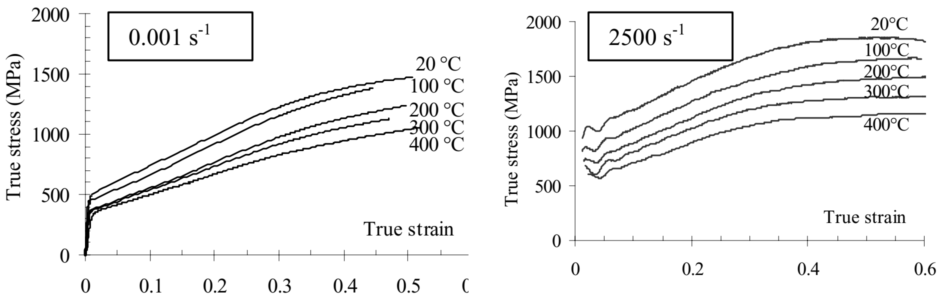


Figure 2 : Stress-strain curves of Uranus B66 at different temperatures for strain rates of 10^{-3} s^{-1} and 2.5 10^{3} s^{-1}

At high strain-rate, flow curves are quasi-parallel, indicating that the temperature has no significant effect on the strain hardening. In all cases, stress saturation appears clearly for plastic deformation above 35%.

Otherwise, the stress-strain response sensitivity to temperature is much more important at high strain rates than in quasi-static conditions. At 10^{-3} s^{-1}, the difference in stress recorded between 20°C and 400°C for $\varepsilon = 0.5$ is $\Delta\sigma$ = 430 MPa. At 10^{+3} s^{-1}, the difference reaches $\Delta\sigma$ = 707 MPa.

1.3 Plasticity models

Several constitutive relations have been developed to describe the mechanical behaviour of materials under dynamic loading. Two of these models, implemented in most dynamic codes, have been selected to model this material : Johnson-Cook (J-C) model [3] and Zerilli-Armstrong (Z-A) model [4]. Their respective constitutive relations are quite simple. The J-C model is an empirically equation including the effects of strain rate and temperature. It expresses the equivalent flow stress σ as follows :

$$\sigma = [\sigma_0 + B\varepsilon^n]\,[1 + C.\ln(\dot{\varepsilon}^*)]\,[1 - T^{*m}]$$

where σ is the stress, ε is the plastic strain, $\dot{\varepsilon}^*$ is the normalised plastic strain rate and $T^* = (T - T_0)/(T_m - T_0)$ with T_0 being the room temperature and T_m the melt temperature, σ_0, B, C, n and m are constants.

The Z-A model is a physics based model. For FCC materials, it can be expressed as follows :

$$\sigma = \sigma_0 + C_1\varepsilon^{1/2}[\exp(-C_2T + C_3T.\ln(\dot{\varepsilon}^*)]$$

where T is the test temperature, σ_0, C_1, C_2 and C_3 are constants.

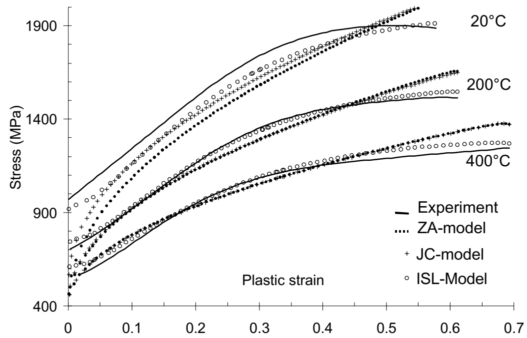
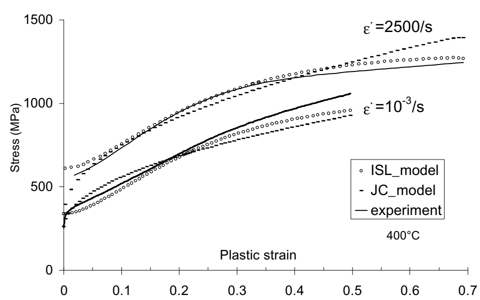


Figure 3 : Experimental and simulated stress-strain curves at high strain rate and different temperatures

Figure 3 presents the results of these models compared to some experimental data at high strain rate. The coefficients have been fitted to all quasi-static, quasi-dynamic and dynamic compression tests results at room temperature and above.
The J-C model seems to give the best correlation between experimental data and simulation results, particularly at low strain levels. In fact, Z-A also proposed a modified model taking into account the effect of a possible saturation of stress with strain ; but the results are only slightly better than for the original model and not as good as those from the J-C model. In this model, the temperature dependence of the shear modulus is weak and does not reproduce the strong dependence of the yield strength to temperature and strain rate. Also the occurrence of a stress saturation on the experimental curves is not reproduced satisfactorily.



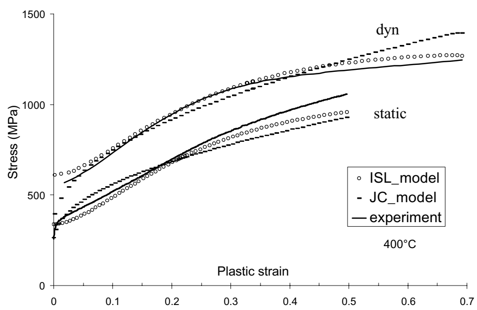


Figure 4 & Figure 5 : Experimental and simulated stress-strain curves at 20°C and 400°C by static and dynamic loading.

As these models do not reproduce properly the behaviour of this steel, a new constitutive model has been suggested. The resulting equation is :

$$\sigma=[\sigma_0+C_1(1-exp(-\varepsilon/C_2))^n+C_3Ln(\dot{e}\,^*)](1-T^{*m})$$

where σ_0, C_1, C_2, C_3, n, and m are constants.
Through the term 1-exp(-ε/C_2), the stress is constant when the strain takes an infinite value. This term is to be related to the occurrence of a stress saturation, which characterizes the experimental curves. The viscous term C_3.ln($\dot{e}\,^*$) is taken into account additively due to the fact that the strain rate has no visible effect on the strain hardening. The term for the temperature sensitivity is the same as in the J-C model.
A good agreement between the experimental data and the results of the new introduced model can be seen in Figure 3, from low to high strains achievable by compression. Figure 4 shows that the fitting of this model covers all the experiments by static, quasi-dynamic and dynamic loading at room temperature and also at high

temperature. Further investigations have been done at -196°C ; the agreement is not so good because, at very low temperature, the mechanisms of deformation are different.

2 User material model in LS-DYNA

The new plasticity model has been defined as a user material in LS-DYNA. This material model is based on the formula :

$$\sigma=[C1+C2(1-\exp(-\varepsilon/C_3))^{C4}+C5.Ln(\dot{\varepsilon}^*)](1-T^{*C6})$$

C1,..C6 are user input parameters. This material law is used with a Gruneisen equation of state that is defined in the material subroutine. The input deck for this material is defined as follows :

```
*MAT_USER_DEFINED_MATERIAL_MODELS
$   mid          ro       mt      lmc     nhv   iortho  ibulk       ig
      1 8.1999998       43       48      10              25        1
$ ivect    ifail    itermal
      1       0
$          g         cf1         cf2          c3          c4         cf5          c6
 0.7700000 708.000-5 1063.00-5 0.1756800 1.8415900 27.7900-5 0.7633700
$     eps0        cp      p cut off      ispall          it          melt tmp   room tmp
 1.00000-6 5.10000-6-2.0000000 0.0000000 0.0000000         1723.0000 298.00000
$        d1          d2          d3          d4          d5          d6 (failure parameters)

$  bulk visc
 1.7351200
$

$  coefficient of eos  (mie gruneisen)
$          c          s1          s2          s3    gamma0           A          E0          v0
 0.4600000 1.3299999 0.0000000 0.0000000 1.6700000 0.4300000 0.0000000 0.0000000
```

3 Taylor impact tests

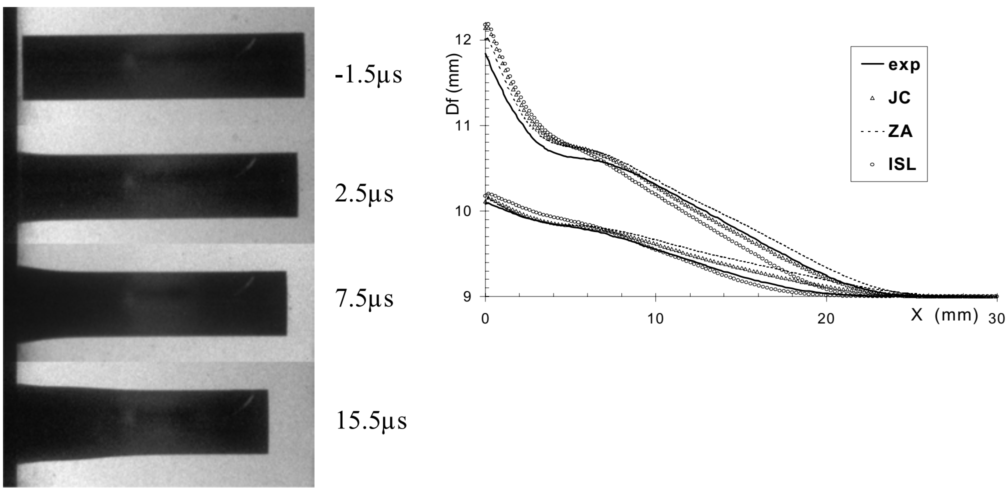


Figure 6 : Impact at 222 m/s and comparison between experimental and computed profiles of post-tested cylinders

Cylinder impact tests provide an independent tool to evaluate the models in a large range of strain, strain rate and temperature. The validation of the models was performed by comparing the measured profile of the deformed cylinder to the numerical predictions, during and after impact.
The use of a special device developed at *Institute Saint-Louis* on the basis of CCD cameras allows to obtain up to 8 pictures at different time sequences during the impact of the cylinder on a rigid target (Figure 6). Several cylinder impact tests were conducted at velocities ranging from 150 to 280m/s.
Numerical simulations were carried out with LS-DYNA using the J-C, Z-A and the new material.
Experimental results on the variation of the diameter vs. the distance to the impacted face of the projectiles post-mortem are given in Figure 6 for two different velocities in comparison with the computed results ; the final length is not represented here. The good strength and the great strain hardening rate of Uranus B66 allow to reach high level of impact velocities and large deformation of the cylinder.
There appear to be little performance differences between the three models. Experimental results from the head of the cylinder at low velocity is well reproduced with the J-C or Z-A model, whereas the second part of the deformed cylinder, after bulging, is better reproduced by the new model at low velocity and by the J-C model at high velocity.

4 CONCLUSION

Dynamical behaviour of nitrogen alloyed steel "Uranus B66" has been investigated in compression. It exhibits a high strain rate sensitivity and a high strain hardening; the temperature sensitivity depends on the dynamic loading rate.
The results have been fitted into constitutive equations using J-C and Z-A models. These models do not reproduce correctly the typical behaviour of this steel in the complete range. A new model, mainly based on empirical considerations, has been integrated in LS-DYNA as user defined model. The validation of the models was performed using the cylinder impact test. The new material law fits better the behaviour in case of impact the experimental data than the J-C and Z-A models.

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