Mechanical characterization of alloys in extreme conditions of high strain rates and high temperature

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Abstract. The aim of this paper is the description of the mechanical characterization of alloys under extreme conditions of temperature and loading. In fact, in the frame of the Cost Action CA15102 “Solutions for Critical Raw Materials Under Extreme Conditions (CRM-EXTREME)” this aspect is crucial and many industrial applications have to consider the dynamic response of materials. Indeed, for a reduction and substitution of CRMs in alloys is necessary to design the materials and understand if the new materials behave better or if the substitution or reduction badly affect their performance. For this reason, a deep knowledge of the mechanical behaviour at high strain-rates of considered materials is required. In general, machinery manufacturing industry or transport industry as well as energy industry have important dynamic phenomena that are simultaneously affected by extended strain, high strain-rate, damage and pressure, as well as conspicuous temperature gradients. The experimental results in extreme conditions of high strain rate and high temperature of an austenitic stainless steel as well as a high-chromium tempered martensitic reduced activation steel Eurofer97 are presented.

1. Introduction
The knowledge of mechanical dynamic behaviour of materials under extreme conditions of high strain rates and high temperature allows the development of reliable material models and their use in several industrial sectors such as energy, automotive, transportation and machine manufacturing. The mechanical characterization requires the use of adequate techniques able to describe the behaviour of these materials in such severe conditions of loads and temperature. In fact, the accuracy of the mechanical assessment and the design of products made of high value alloys and metal-matrix composites subjected to rapid loading and high temperature strongly depends on the precision of the material’s constitutive law in reproducing the real behaviour of such materials. As a consequence, the mechanical characterization is one of the fruitful ways in order to find viable alternatives to CRMs and promote the industrial exploitation of substituted materials. The optimisation of such alternative materials should then pass through high strain rate testing phase that are obtained by imposing an acting pulse by means of special dynamic testing devices. These apparatuses generate a stress wave pulse well controlled in amplitude and duration which is propagated without dispersion and uncontrolled reflections to load and deform until fracture a specimen and to allow the record analysis by using the well proofed uniaxial elastic waves propagation theory. The methodology proposed for this characterization is the Split Hopkinson-Kolsky Bar technique, that is the scientifically most recognized methodology for the precision measurements of pulses parameters, allow the
characterization of the material dynamic properties. This contribution aims to present a precision measurement methodology of the material stress-strain curves carried out by means of a modified Hopkinson bar used in the DynaMat Laboratory. The results at high strain rate with high temperature of austenitic stainless steels as well as high-chromium tempered martensitic reduced activation steel Eurofer97 will be presented.

2. Experimental techniques for high strain rate regimes
An innovative version of the split Hopkinson bar, which can be used for performing tension, compression and shear tests, in the strain-rate range $10^2$ to $10^3$ s$^{-1}$ ($10^4$ s$^{-1}$ in shear), was developed and patented at the Joint Research Centre of the European Commission in the seventies in the frame of nuclear reactor safety studies of severe accidents [1-2]. In the last decades, this technology has been extensively adopted in many other fields [3-11].

The development of the JRC-Modified split Hopkinson bar was particularly needed in order to dispose of a unique versatile equipment capable of working in tension, compression and shear, generating the long duration pulses. Using the classic SHPB dynamic testing equipment it would have been necessary to launch long projectile in order to obtain such pulse duration of few milliseconds, what is a very difficult task, in particular for the realisation of a plane impact of the projectile on the input bar, an absolute necessary condition for the generation of the elastic stress plane wave pulse needed for a correct analysis of the SHPB by means of the one-dimensional elastic plane stress wave propagation theory.

The main modification to the classical split Hopkinson pressure bar consists in the substitution of the projectile, normally used to generate the impact loading pulse, with a statically elastic pre-tensioned bar which is the physical continuation of the input bar as shown in figure 1, where different configurations, for testing materials in tension, compression and shear, are shown.

![Figure 1. Functioning schemes of the JRC-Modified Hopkinson Bar device.](image)

These devices were used for decades in the analysis of the nuclear materials under harsh conditions as high temperature, high strain rate, irradiation etc. [12].

The way of functioning the JRC-modified Hopkinson bar, consists of the different phases: firstly, elastic energy is stored in the pre-tensioned loading bar by statically tensioning (or twisting) the length of this bar; secondly, by suddenly rupturing a brittle intermediate piece placed in the blocking device a rectangular stress wave pulse is generated and propagates through the input bar, the specimen and the output bar, provoking a state of stress in the specimen till fracture; finally, signals of the input $\epsilon_I(t)$,
reflected $\varepsilon_R(t)$ and transmitted $\varepsilon_T(t)$ pulses are recorded by the strain-gauge stations glued on the input and output bars which remain in the elastic regime. Having realised the condition of the specimen deformation in a homogeneous stress state (that means having kept the specimen gauge length sufficiently short in a way that the wave reflections inside the gauge length provide the stress homogenization), and by the application of the elastic one-dimensional stress wave propagation theory, average stress $\sigma$, strain $\epsilon$, and strain-rate $\dot{\epsilon}$ in the specimen can be determined with the following relationships:

$$\sigma(t) = E \frac{A}{A_0} \varepsilon_T(t)$$  \hspace{1cm} (1)$$

$$\varepsilon(t) = -\frac{2C_0}{L} \int_0^t \varepsilon_R(t) \, dt$$ \hspace{1cm} (2)$$

$$\dot{\epsilon}(t) = -\frac{2C_0}{L} \varepsilon_R(t)$$ \hspace{1cm} (3)$$

where: $L =$ gauge length of the specimen, $A_0 =$ cross-sectional area of the specimen, $t =$ test time, $E =$ elastic modulus of the bar, $A =$ cross-sectional area of the bar and $C_0 =$ the elastic wave speed in the bars.

3. Extreme conditions of high temperature and high strain rate
The mechanical characterization of materials under harsh condition of strain rate and temperature can be obtained adding to the MHB a heating system [13-14]. The functioning scheme is shown in figure 2.

![Figure 2. Functioning schemes of the JRC-Modified Hopkinson Bar device with heating systems [13.]](image)

3.1. Austenitic stainless steels
The austenitic stainless steels AISI304 (EN 1.4301) was characterized in a wide interval of strain rates [15]. The effects of the high temperatures on its dynamic behaviour was the object of another study [16]. High temperatures were obtained by using an Ambrell compact EASYHEAT induction water-cooled heating systems with maximum power of 2.4kW (see figure 3) [13]. Round samples having 3 mm in diameter and 5 mm of gauge length were used [13-16]. The composition of the austenitic steel AISI304 here examined is shown in Table 1. It has fully austenitic microstructure and contains a large amount of alloying elements as Cr and Ni in order to improve pitting and corrosion resistance.

| Table 1. Chemical composition (wt.%) of AISI304 (EN 1.4301) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| C               | S   | P   | Si  | Mn  | Cr  | Ni  | Mo  | Cu  | Sn  | Al  | Co  | Nb  | N2  | Fe  |
| 0.025           | 0.003|0.032|0.370|1.200|18.26|8.10 |0.34 |0.880|0.010|0.004|0.100|0.020|0.053|Bal.|


In figure 3, the setup for the high strain rate tests at elevated temperature is shown. It is possible to observe, the input ① and the output bars ② of the SHTB, the heating system ③, the water-cooled induction coil ④, the sample to be tested ⑥ connected by means of a thermocouple to a thermal controller ⑤ and the cooling system ⑦ for the input and output bars, respectively.

![Experimental setup for high strain rate combined with high temperature.](image1)

**Figure 3.** Experimental set-up for high strain rate combined with high temperature.

![Functioning schemes of the JRC-Modified Hopkinson Bar device.](image2)

**Figure 4.** Functioning schemes of the JRC-Modified Hopkinson Bar device.

![Reduction factor of the ultimate tensile strength at high strain rate in function of the temperature.](image3)

**Figure 5.** Reduction factor of the ultimate tensile strength at high strain rate in function of the temperature.
In figure 4 the influence on the reflected pulses is depicted highlighting their variation in function of the different temperatures. The influence of the temperature can be observed in figure 5 where the decrement of the ultimate tensile strength in function of the temperature is shown.

Finally, the stress versus strain diagrams are depicted in figure 6 both in terms of engineering and true values.

![Figure 6](image_url)

*Figure 6. Engineering versus strain (left) and true stress versus true strain (right) diagrams at different temperatures.*

### 3.2. Material constitutive relationships

The material constitutive relationship is a formulation that describe the flow stress as a function of strain, strain-rate and temperature. There are two families of functions. The first is directly obtained by best fitting of experimental values and often expressed as a product of different member each describing only one effect $\sigma(\varepsilon, \dot{\varepsilon}, T) = f(\varepsilon) \cdot g(\dot{\varepsilon}) \cdot h(T)$. The most famous model was proposed by Johnson and Cook [18]. The second one the flow stress is obtained as addition of different members representing respectively strain hardening, strain-rate and thermal softening. The most popular expression was proposed by Zerilli and Armstrong [19] in the form $\sigma(\varepsilon, \dot{\varepsilon}, T) = f(\varepsilon) + g(\dot{\varepsilon}) + h(T)$ and is physical based and are consistent with micromechanics of material behaviour (dislocation density etc). These equations need a certain number of experiments at different strain-rate, different temperature, in order to calibrate the model on the material. Higher is the precision of the results higher is the accurateness of the numerical provision obtained.

As example for this austenitic stainless steel the parameter of the Johnson and Cook relationship were obtained from the experimental results. This is a widely used model, based on three phenomena, the isotropic hardening, the strain-rate hardening and the thermal softening.

$$\sigma_{JC} = (A + B \cdot \varepsilon_p^n) \cdot \left(1 + C \cdot \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \cdot (1 - T^m)$$  \hspace{1cm} (4)

The parameters to be determined from the experimental results are $A$, $B$, and $n$ in order to take into account the strain-hardening, as well as $C$ and $m$ that represent the strain-rate sensitivity and the thermal softening respectively. The previously mentioned material parameters are reported in Table 2.

**Table 2. Johnson-Cook parameters for AISI304 (EN 1.4301) steel**

| A [MPa] | B [MPa] | N [-] | C [-] | m [-] |
|---------|---------|-------|-------|-------|
| 559     | 1924    | 1.040 | 0.00710 | 0.87 |
3.3. High-chromium tempered martensitic reduced activation steel Eurofer97

Eurofer97 has been selected by EU as reference structural material and will be used to fabricate the Test Blanket Modules of the International Thermonuclear Fusion Reactor (ITER). It is a reduced activation steel and it is a tempered martensitic stainless steel of the 7–9 wt% Cr class produced by Böhler company. The concentration of the main alloying elements is (in wt.%) 0.1% C, 8.9% Cr, 1% W, 0.2% V and 0.15% Ta (see Table 3).

**Table 3. Chemical composition (wt.%) of Eurofer97**

| Element | C  | S  | P  | Ta | Mn | Cr | V  | W  | Cu | Ti | Al | Co | N  | Si | Fe   |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|------|
|          | 0.11| 0.001| 0.0001| 0.12| 0.55| 8.95| 0.2 | 1.06| 0.005| 0.001| 0.009| 0.004| 0.022| 0.03| Bal. |

In order to obtain the reduced-activation behaviour, several alloying elements commonly added to commercial martensitic stainless steels like Ni, Nb and Mo have been either removed (Ni), or replaced (Nb and Mo) by elements with shorter half-lives (W, V, Ta) [20]. This steel is very clean and its inclusions level is extremely low. The mechanical properties are the following: E=217 GPa, ν=0.3, ρ=7750 kg/m³; σ_y=546 MPa; σ_u=668 MPa.

The strain rate effect on the stress versus strain diagram as well as the effect of high and low temperature can be observed in figure 7 and 8.

![Engineering stress vs strain curves at room temperature and different strain rates](image1)

**Figure 7.** Engineering stress vs strain curves at room temperature and different strain rates (left) and engineering stress vs strain curves at room, high and low temperature at different strain rates (right).

The influence of the temperature on the dynamic behaviour of Eurofer97 can be described by the Zerilli-Armstrong relationship for the body centered cubic (bcc) metal. The relationship proposed for bcc metals is:

\[ \sigma_{ZA} = c_0 + c_1 \cdot \exp(-c_3 \cdot T + c_4 \cdot \ln(\dot{\varepsilon})) + c_5 \varepsilon^n \]  

(5)

where, c_1, c_3, c_4, c_5 and n are the five material constants for the bcc model, while c_0 take into account the influence of the dislocation density on the yield stress [21].

**Table 4. Zerilli-Armstrong parameters for Eurofer97 steel**

| c_0  | c_1     | c_3     | c_4     | c_5     | n    |
|------|---------|---------|---------|---------|------|
| [MPa] | [°K⁻¹] | [°K⁻¹] | [MPa]   | [-]     |
| 1075 | 2.063 · 10⁻¹ | 6.762 · 10⁻¹ | 673.1 | 0.5320 |
4. Concluding remarks
In order to analyse the mechanical behaviour of steel alloys at high strain rate and high temperature has been presented the experimental set-up needed for the study of their dynamic behaviour. The experimental results of two steel alloys such as austenitic stainless steel and high-chromium tempered martensitic reduced activation steel Eurofer97 obtained in extreme conditions of high strain rate and high temperature have been presented and discussed. These results are in the direction of better understanding of these materials under harsh conditions and have allowed to obtain the description of the materials in terms of numerical model [17] and material relationships [15, 16, 20, 21]. This analysis is required whenever a Critical Raw Material has to be replaced by an alloy, especially if it is subjected to extreme temperature and deformation rates. Future projects will be addressed to the study of the effects of the reduction or substitution of Critical Raw Materials in the manufacturing, transport and energy industries in such extreme condition of loading and temperature.

5. References

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