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Mechanical characterization and modeling of the heavy tungsten alloy IT180

Martina Scapin

Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Corso Duca degli Abruzzi, 24-10129 Torino, Italy

A R T I C L E I N F O

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A B S T R A C T

Pure tungsten or its alloys (WHA) find applications in several fields, especially due to the fact that these materials show a good combination of mechanical and thermal properties and they are commonly used in aerospace, automotive, metal working processes, military and nuclear technologies. Looking at the scientific literature, a lack in the mechanical characterization over wide ranges in temperature and strain-rates was found, especially for W–Ni–Cu alloys.

In this work, the mechanical characterization and the consequent material modeling of the tungsten alloy INERMET® IT180 were performed. The material is actually used in the collimation system of the Large Hadron Collider at CERN and several studies are currently under development in order to be able to numerically predict the material damage in case of energy beam impact, but to do this, a confident strength model has to be obtained. This is the basis of this work, in which a test campaign in compression and tension at different strain-rates and temperatures was carried out. The dynamic tests were performed using Hopkinson Bar setups, and the heating of the specimen was reached using an induction coil system. The experimental data were, finally, used to extract the coefficient of three different material models via an analytical approach.

1. Introduction

Pure tungsten or its alloys (WHA) find applications in several fields, especially due to the fact that these materials show a good combination of mechanical and thermal properties: high density, high mechanical strength also at high temperatures, high Young's modulus, moderate ductility, low thermal expansion, high thermal conductivity, good machinability and excellent resistance to corrosion. As a matter of fact, they are commonly used in aerospace, automotive, metal working processes, military and nuclear technologies. In more detail, these materials are often used for balancing, absorbing vibrations or source mass components [1]. They are also suitable for shielding, collimation [2,3] or target [4,5] components in medical, nuclear or industrial technologies: tungsten can provide the same effect as other materials, such as lead, but reducing the physical dimensions of the components. Tungsten alloys are finally appropriate in severe tooling applications, such as die casting, extrusion or in general, high temperature conditions. In military applications the WHAs are specialized as a kinetic energy penetrator since, for example, they represent a valid alternative to conventional depleted uranium penetrators, which are extremely environmentally unsafe materials [6–10].

The high melting point of pure tungsten makes it impossible to apply the manufacturing techniques commonly used for other metals, such as melting and casting in a mold. In this case, a powder metallurgy technique is often used for the material production, in which the tungsten powders are mixed with the other low melting elements, such as copper, nickel, iron, cobalt, and chromium. The liquid phase sintering process implies that the mixed powders are compacted and then subjected to heat treatment below the W melting temperature. In this way, the lower melting elements melt forming the matrix that bonds the unmolten W particles together. In general, the result of the sintering process is a spheroidized microstructure, in which the rounded phase is pure tungsten surrounded by a metallic binder phase also containing dissolved tungsten (solid solution). The tungsten spheres show the typical BCC structure with a very high Young's modulus, while the binder phase has commonly a FCC structure and is responsible of the ductility of the resultant material. Therefore, the mechanical properties of the final alloy are mainly related to the complex interaction between the two phases as well as their own properties, depending also by the loading condition.

Generally, the tungsten heavy alloys are split into two wide categories: those with Ni–Fe and those with Ni–Cu as the binder phase. From a commercial point of view, one of the big suppliers, the Plansee company, names the W–Ni–Fe alloys (WNF) as DENSIMET®, while the W–Ni–Cu alloys (WNC) as INERMET®.

In this work the main goal was the mechanical characterization and the consequent material modeling of the tungsten alloy INERMET® IT180. The test campaign involved both compression and tension tests at different strain-rates and tension tests at different temperatures

E-mail address: martina.scapin@polito.it.

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both in quasi-static and dynamic regimes. The obtained results were finally used to identify a suitable strength model for the mechanical behavior description. The motivation at the basis of this research was that INERMET® IT180 is currently used and under study as material in the collimation system of the Large Hadron Collider at CERN (Geneva, Switzerland). The collimators are devices which can directly interact with the high energy beam: the energy deposition on the bulk material could be potentially destructive for these components, generating the outgoing of shock-waves and deforming the material in very high strain-rate and temperature conditions [11]. The experimental phase in these extreme conditions is very expensive in terms of cost and resources [12]. From this, the importance to be able to numerically simulate these events with a high level of confidence. To do this, it is necessary to define a proper strength model for the hit material, able to correctly reproduce the mechanical behavior over a wide range in strain-rate and temperature.

2. Bibliografic review

Looking at the scientific literature, the mechanical behavior of W–Ni–Fe alloys have been studied under several loading conditions for a long time, while fewer studies can be found for W–Ni–Cu alloys.

For WHA alloys, several works dealt with the mechanical characterization in compression [7–10,13–16], tension [4,5,17–22] or fatigue [4,5] at different temperatures [17,18,22], strain-rates [7,9,15,18,20] or both of them [8,10,13,14,16,19].

Some of the common results obtained from compression tests on WNF can be summarized as follows. The material is strain-rate and temperature sensitive [13,14], as expected for a BCC material [8,9,15], and there is a mutual influence between theses effects (i.e., the thermal softening is not the same at different strain-rates or vice versa [9,13]). Up to medium-high strain-rates, the relation between stress and strain-rate seems to be logarithmic [13,14]: this highlights a deformation process based on thermal activation without a steep increase at very high strain-rates (change in the microstructural deformation mechanism). At very high strain-rates, different results were found: in some cases, as in [14] the behavior was logarithmic, in other cases, as in [9] a change in the deformation mechanism was found. The material is subjected to thermal softening at very high strain-rate, due to the heat conversion of plastic work [14]. The percentage of void and the roughness of the specimen surface play important roles in the determination of the material properties and this justifies the need to control and optimize both sintering and machining operations [5].

In the most part of the above mentioned works, also the fracture analysis was performed, analyzing the microstructure evolution and the crack propagation. As well explained in [14], in a sintered material, as those here analyzed, there are four possible fracture paths: the separation between tungsten grains at their interface, the separation at the interface between tungsten and binder phases, the cleavage inside a tungsten grain and, finally, the matrix failure. Depending on which of these failure modes becomes predominant, the strength and the ductility of the material are more or less pronounced. Different authors found that larger grain deformation occurs at high temperature or strain-rate [7,14]. Different failure modes were found from fractographic observation depending on the testing condition, but also on the quality of the materials coming from the sintering process. In some cases at low temperature and strain-rate the failure path was along the matrix and the tungsten–tungsten interfaces [9] without any cleavage in tungsten grains until high temperatures were reached [16]. At high strain-rates a more significant influence of microcracks formation and coalescence was found [13,15] and the brittle transgranular cleavage of tungsten grains becomes significant even if the matrix failure is still ductile [14,16]. In some cases, also an increase of voids coalesce was found at high temperature and low strain-rate [13]. In some studies, the experimental data were used to get the parameters identification for different strength material models [9,10,14,16,18]. The most used strength models were: the Johnson–Cook (J–C) model [23], the Zerilli–Armstrong (Z–A) model [24] or other models in which strain-rate and temperature are mutually related. The need of an ad-hoc model calibration comes from the fact that even if the amount of tungsten is high with respect the other elements, the model parameters obtained for pure tungsten do not fit the experimental data of the alloy. The strategies used for the coefficient determination could be the analytical data interpolation [9,14] or a numerical inverse approach.

A more limited number of works can be found for the mechanical characterization in tension. The data available show that no necking or limited necking occur at room temperature in quasi-static conditions [18] and that the most frequently fracture mode is the intergranular failure at tungsten–tungsten interfaces [5]. At high strain-rates the material softens increasing the strain and again the weakest point are the interfaces between tungsten grains where the failure starts in the direction perpendicular to the loading direction [20]. The results for WNC alloys show that this material is sensitive both in temperature and strain-rate and the deformation decreases increasing the strain-rate and reducing the temperature [19]. In [20] a crystal plasticity model within a failure model was applied to reproduce the experimental data. In [19] both Z–A and J–C model parameters were obtained by fitting the experimental data and the comparison demonstrated that the Z–A model was more suitable.

As it is easy to understand, the alloy chemistry influences the mechanical properties of tungsten alloys. From this it is possible to conclude that results obtained from WNF alloys could not be considered as valid for WNC ones. The problem is that in the authors' knowledge only few works are available for WNC alloys [4,21,22]. In these works it was found that, the WNC alloys have much inferior tensile properties and hardness at room temperature: in more detail, both the material strength and the elongation at failure are lower. The cause is mainly related to the amount and the dimension of tungsten particles, which influences the fracture mode of the material. In [4] the microstructure and fractographic analyses of both the types of alloy demonstrated that the tungsten alloy with nickel and iron has smaller tungsten grains and a smaller amount of tungsten–tungsten interfaces. The dimension of the tungsten grains depends on the sintering temperature: the WNC alloys require higher temperature and this result is bigger grains [21]. This implies a lower amount of binder phase and an increase in the tungsten–tungsten interfacial area, which reduces the ductility, since it is the weak link in the microstructure.

3. Material under investigation & experimental setup

As previously mentioned in the Introduction, the final objective of this work is the numerical simulation of high energy beam impact against INERMET® IT180 components. Due to material thermo-mechanical properties within high Z number (70.83), it is actually used in the LHC as particles absorber to stop the last shower of particles before sensitive equipment. The material was supplied by Plansee and has the nominal composition of 95 wt.% W, 3.5 wt.% Ni and 1.5 wt.% Cu. As it is possible to see from the microstructure of Fig. 1, the W grains are quite big, with an average dimension of about 100 μm, which are surrounded by the binder phase, providing the necessary thermal and electrically continuity to the material.

Since there is a big lack in the mechanical characterization of this alloy varying temperature and strain-rate over wide ranges, the author reports in this work the experimental results obtained from the test campaign, from which several strength material models were obtained.

The strain-rate and temperature are variables of fundamental importance for the definition of the mechanical behavior of materials. In some elastic–plastic models, the effects, coming from these two quantities, are considered to act independently. This approach allows greatly simplifying the experimental phase correlated to the parameter identification of the material model: the parameters for the strain-rate sensitivity could be extracted from tests at different strain-rates at a