Rare Metal Materials and Engineering
Volume 46, Issue 10, October 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(10): 2753-2762.

ARTICLE

Dynamic Behavior and Constitutive Model for Two Tantalum-Tungsten Alloys under Elevated Strain Rates

Gao Fei[1], Zhang Xianfeng[1], Serjouei Ahmad[2], Wang Mingyang[1], Li Lei[1], Xiong Wei[1], Zhang Jiang[3]

[1] Nanjing University of Science & Technology, Nanjing 210094, China; [2] Nanyang Technological University, Singapore 639798; [3]Ningbo Branch of China Academy of Ordnance Science, Ningbo 315103, China

Abstract: The quasi-static and dynamic deformation behavior of two Ta-W alloys (Ta-2.5W and Ta-10W, mass fraction) was investigated by the quasi-static and dynamic compression test and Split Hopkinson pressure bar (SHPB) and Taylor impact tests. The results show that the yield stress of Ta-W alloys exhibits sensitivity to strain rate and W content. Based on the quasi-static and high strain-rate experimental data, the material constants in Johnson-Cook (JC) model were obtained for the two Ta-W alloys. In addition, validation of the derived constitutive model was carried out through comparison of Taylor impact inhomogeneous deformations under high strain rate (10^3~10^4 s^{-1}), obtained from simulations with their experimental counterparts. It is shown that the simulation results agree well with post-test geometries in terms of side profiles and impact-interface footprints for Taylor impact tests. To bridge the different spatial scale involved in the process of tantalum-tungsten alloy deformation, a meso-scale research was proposed via optical microscope (OM) image analysis. The results presented in this paper, provide new insights into the mechanisms suitable for the constitutive relations determination process.

Key words: tantalum-tungsten alloys; SHPB; dynamic behavior; Taylor impact; constitutive model

Tantalum (Ta) and tantalum-based alloys continue to attract scientific and engineering interests due to their high density, melting point, excellent formability, good heat conductivity, good fracture toughness (even at low temperatures), corrosion resistance, and weldability [1]. Based on these characteristics, Ta and its alloys are widely used in the fields of electron, chemical, aerospace, weapons, etc. [2].

The structure and mechanical properties of Ta and its alloy are markedly influenced by the internal factors such as the content of trace impurity and crystal structure. They have attracted, due to their high sensitivity to the change of temperature and strain rate, the attention of many researchers[3-6]. The yield stresses of unalloyed Ta and tantalum-tungsten (Ta-W) alloys, exhibit very high sensitivity to strain rate, while their hardening exponent has been found to be insensitive to strain rate and temperature at low temperatures or at high strain rates [7]. Further experimental and theoretical studies were carried out by Gray[8] on the influence of strain rate on the substructure evolution in metals and alloys. Zhang et al [9] studied the mechanical properties of several tantalum alloys with higher W content. They found that the strength and hardness of Ta-W alloys increase linearly with the increase of W content, and the decline of ductility is not significant with the increase of W content, implying that the Ta-W alloys have high strength and good plasticity properties. To date, a number of popular strength models have been used to predict the constitutive behavior of tantalum-tungsten alloys over a range of strain rates. The models proposed by Johnson and Cook [10] (JC model), Zerilli and Armstrong [11] (ZA model), and Steinberg et al [12], are among the most widely known and

Received date: October 11, 2016
Foundation item: the Zijin Intelligent Program, Nanjing University of Science and Technology (2013_ZJ_0101); Qing Lan Project of Jiangsu Province; State Key Laboratory of Explosion Science and Technology (Beijing Institute of Technology) (KFJJ15-07M)
Corresponding author: Zhang Xianfeng, Ph. D., Professor, School of Mechanical Engineering, Nanjing University of Science & Technology, Nanjing 210094, P. R. China, E-mail: lynx@mail.njust.edu.cn

frequently used. A comparative study of the JC and modified JC constitutive relations for Ta was performed by Peng et al [13] and Bai et al [14]. Material parameters of the mechanical threshold stress (MTS), JC, and ZA constitutive relations for Ta and Ta-W alloys were derived by Chen and Gray[7]. The results of this study substantiate the applicability of these models for describing the high strain-rate deformation of Ta and Ta-W alloys.

Split Hopkinson pressure bar (SHPB) and Taylor impact techniques have been widely used to measure and validate mechanical properties of metallic materials at high strain-rate. The FE code, ABAQUS/Explicit, used in the current study, allows efficient reproduction of the dynamic loading processes at high speed events [15-17].

Currently, the Taylor test is primarily used in conjunction with numerical simulations as a valuable tool for validating constitutive models of various ductile materials due to the large deformation, large gradients of deformation and stress, unique deformation profiles and high strain rate (10^3 s^{-1}), which can be achieved in this test. By numerical simulations, Teng et al [18] found three distinct fracture modes for 2024-T351 aluminum alloy and Weldox 406 E steel: the confined fracture inside the cylinder, the shear cracking on the lateral surface and the petalling. Xiao et al [19, 20] investigated the effect of projectile hardness on the deformation and fracture behavior of 38CrSi steel and aluminum alloy 7A04-T6 in the Taylor impact test and simulations. Rakvåg et al [21, 22] revealed five distinct deformation and fracture modes in the projectile during Taylor bar impact tests for steel of different hardness values.

Recently, Lopatnikov et al [17] conducted a research to model and simulate dynamic deformation of foam materials during the Taylor cylinder-Hopkinson bar impact experiment, based on the unique non-linear deformation behavior mechanism. However, a systematic study of the complete process from the deformation of quasi-static to their dynamic behavior from elevated strain-rates (SHPB combined with Taylor impact) associated with the simulation of deformation analysis is not yet available in the open literature.

Presented here are quasi-static, SHPB and Taylor impact experimental results for two tantalum-tungsten (Ta-W) alloys, namely Ta-2.5W and Ta-10W alloys. The experimental results are used to develop and validate an empirically-based constitutive relation for the flow stress. In addition, the determined corresponding constitutive parameters of Ta-2.5W and Ta-10W are compared. Furthermore, validation of the JC constitutive model is performed through comparison of results obtained from numerical simulations, using ABAQUS, for their experimental SHPB and Taylor impact counterparts. According to the test and simulation results, a good agreement was observed for the post-test geometries in terms of side profiles and impact-interface footprints for Taylor impact test. With the method of macro-meso incorporation, OM analyses are used to qualitatively characterize the composition and distribution of constituents as well as the characteristics of deformation surfaces along the longitudinal direction.

1 Experimental

1.1 Quasi-static compression test

The quasi-static compression tests were conducted using a CSS-44100 Universal Materials Testing Machine with a 300 kN loading capacity. The tests were carried out under displacement control, with a constant cross-head speed of 0.5 mm/min. This corresponded to a nominal strain rate of 8.3×10^{-4} s^{-1}. The lengths and diameters of the initial and final specimens from each experiment are listed in Table 1. Fig.1 shows the quasi-static compression test results of four cylindrical specimens, where the compression stress is presented as positive numbers. As depicted in Fig.1, the yield stress varies from 238 MPa (Ta-2.5W) to 550 MPa (Ta-10W) when the W content varies from 2.5% to 10%. The stress-strain curves of individual Ta-W alloy specimens are similar in shape; however, the variations in yield stress values are attributed to the variations in W content. With different W content, the strain hardening behavior is essentially unchanged under low strain rates at room temperature.

1.2 SHPB compression test

1.2.1 Principle of SHPB test

The SHPB system was used to study the deformation of Ta-2.5W and Ta-10W at high strain-rates, which comprised three bars 14.5 mm in diameter. The bullet was 300 mm long and the length of the incident and transmitted bars were both 800 mm. The striker bar was propelled at a specified velocity, hitting the incident bar and causing compression of the specimen. Prior to impact, near the impact area, the velocity was measured using an electronic velocity measurement unit consisting of two pairs of photodiodes and light sources. Strain gauges were used to measure the elastic wave within the bars which were then used to analyze the specimen response. In this study, a method to combine the incident, reflected and transmitted strain pulses was adopted for data analysis of the SHPB experiments.

1.2.2 SHPB compression test results

The strain circuit outputs of the incident, reflected and transmitted waves in Ta-W alloys at different strain rates are shown in Fig.2. The left top trace gives the incident pulses and right bottom trace gives the reflected strain pulse. The right top trace gives the transmitted strain pulse. The lengths and diameters of the initial and final specimens from each experiment, and corresponding velocity and strain rate are listed in Table 2.

Based on the recorded incident, reflected and transmitted waves, the relationships of the true stress and true strain with