Materials Science & Engineering A 615 (2014) 497–510

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Evolution of flow stress and microstructure during isothermal compression of Waspaloy

A. Chamanfar [a,b,*], M. Jahazi [b], J. Gholipour [c], P. Wanjara [c], S. Yue [a]

[a] Department of Materials Engineering, McGill University, 3610 University Street, Montreal, Quebec, Canada H3A 0C5
[b] Département de Génie Mécanique, École de Technologie Supérieure, 1100 rue Notre-Dame Ouest, Montreal, Quebec, Canada H3C 1K3
[c] National Research Council Canada, Aerospace, 5145 Decelles Avenue, Montreal, Quebec, Canada H3T 2B2

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form
24 July 2014
Accepted 25 July 2014
Available online 31 July 2014

Keywords:
Waspaloy
Isothermal hot compression
Friction
Adiabatic heating
Flow stress
Microstructure

ABSTRACT

The evolution of the flow stress and microstructure for Waspaloy was studied in the 950–1140 °C temperature range under constant true strain rate conditions of 0.001–1 s^{-1} up to a true strain of 0.83 using isothermal hot compression testing. The impact of friction at the sample/anvil interface and adiabatic heating during deformation on the flow stress evolution was also examined. Mathematical models relating the flow stress to the deformation temperature and strain rate were derived using a power–law relationship. The strain rate sensitivity and the activation energy for hot deformation of Waspaloy were found to be considerably different for deformation in the subsolvus and supersolvus temperature ranges. According to the microstructural investigations, at 950 °C dynamic recovery (DRV) was the main softening mechanism. By contrast, dynamic recrystallization (DRX), partial or complete, occurred at temperatures above 950 °C and resulted in flow softening.

1. Introduction

Waspaloy is a nickel-base superalloy commonly used in the forged and heat treated condition for aircraft and land-based gas turbine engine components, such as blades and disks, that must endure long-term service at high temperatures (up to 650 °C) under high stresses (up to 500 MPa) in severe corrosive environments [1,2]. The high temperature strength of Waspaloy is provided by Al and Ti through precipitation of γ', $Ni_3(Al, Ti)$, in the γ matrix and by Co, Fe, Cr, and Mo through solid solution strengthening. Moreover, Ti, Co, and Cr form carbides that further strengthen the alloy through pinning of the grain boundaries and decreasing grain boundary sliding at high temperatures [3]. Also, Cr and Al provide corrosion resistance for the alloy through formation of impermeable Cr_2O_3 and Al_2O_3 oxide films.

The different stages of industrial thermomechanical processing for the manufacture of Waspaloy components include ingot homogenization, ingot-to-billet conversion (cogging), open and closed-die forging, and heat treatment [4,5]. Overall, hot working of Waspaloy is relatively difficult, since the material is designed to resist deformation at elevated temperatures [6,7]. The high level of the dissolved alloying elements (40 wt% in Waspaloy) at the elevated deformation temperatures leads to high flow stresses and a high recrystallization temperature, which narrows the hot working temperature range to 1000–1100 °C [6,7]. The very high flow stresses usually define the lower limit of the hot working temperature range, and incipient melting and/or severe grain growth establish the upper limit [8].

Knowledge of the flow stress curves at high temperatures is essential for the reliable design and simulation of the industrial hot deformation processes [9], assembly technologies that involve deformation, *e.g.* friction welding [10,11], as well as advanced manufacturing technologies such as additive manufacturing, incremental forming, metal injection molding (MIM), and laser assisted spinning. Moreover, during high temperature deformation, adiabatic heating induced by deformation, as well as the incidence of DRV, DRX, and grain growth affect the flow stress, microstructure, and properties [12]. For industrial thermomechanical process design, simulation, optimization, and achievement of the desired microstructure in the final product, it is essential to understand the mechanisms of high temperature deformation and correlate the flow stress and grain size evolution to the deformation variables (temperature, strain, and strain rate) using constitutive equations. These mathematical constitutive equations are often generated by isothermal hot compression testing due to the simplicity of the sample geometry and the similarity of the stress state in this test to that in most hot deformation processes [7].

In the literature, the evolution of the flow stress and grain size for Waspaloy with the deformation variables has been investigated mostly by means of *nonisothermal* or Gleeble compression testing

* Corresponding author. Tel.: +1 514 396 8800x7868; fax: +1 514 396 8530.
E-mail address: ahmad.chamanfar@mail.mcgill.ca (A. Chamanfar).

http://dx.doi.org/10.1016/j.msea.2014.07.093
0921-5093/

[13–15]. Specifically, in Gleeble testing, there is a considerable thermal gradient along the sample height [15]. Therefore, the flow stress data obtained during nonisothermal compression testing cannot be used for deriving the flow stress constitutive equations, which are essentially obtained under isothermal conditions. Also, although the variation of the flow stress in Waspaloy at some limited temperatures, strains, and strain rates has been investigated in another study [16] using isothermal compression testing, the flow stress constitutive equation was not formulated. Consequently, a comprehensive study covering the temperature, strain, and strain rate ranges that would allow the determination of the flow stress constitutive equations for Waspaloy was undertaken in this work. Once developed, such equations should serve as key material input parameters for predicting the flow behavior and microstructural evolution during industrial hot deformation to effectively support process development, optimization and control especially for advanced manufacturing technologies such as linear friction welding, additive manufacturing, incremental forming, metal injection molding, and laser assisted spinning.

In this regard, the influence of friction and adiabatic heating during plastic deformation on the flow stress of Waspaloy is also important, but, as neither has been addressed in the open literature, the current work included corrections for these phenomena. It is noteworthy that an important impediment to the development of process–microstructure interrelationships is an effective and consistent methodology for revealing the grain boundaries in hot deformed Waspaloy [14,16], which was addressed by the current authors in an earlier work [17] on the development of the grain size constitutive equations for Waspaloy under isothermal compression testing conditions. In the present work, these findings have been extended for identifying the hot deformation mechanisms and the operative hardening and softening processes for Waspaloy.

2. Experimental material and procedures

In this study, for the hot compression experiments cylindrical samples with dimensions of 6 mm in diameter and 9 mm in height were prepared by wire electrodischarge machining from a Waspaloy disk. It is noteworthy that to have a similar initial microstructure, the cylindrical samples were machined at the same distance from the center of the disk. The disk was in a solution heat treated and double aged condition with a hardness of 420 ± 5 HV. The chemical composition of the disk was determined to be (wt%): Ni–17.08 Cr–12.87 Co–1.00 Fe–4.12 Mo–3.35 Ti–1.07 Al–0.07 B–0.01 Zr–0.04 C.

The isothermal hot compression tests were conducted using a computer controlled 250 kN servohydraulic MTS testing machine equipped with a radiant cylindrical furnace that had a heating capability to 1200 °C. A K-type thermocouple in contact with the compression sample was employed to control the temperature during the experiments using a digital controller. The furnace was capable of maintaining the temperature of the sample, anvils, and surrounding atmosphere within ±5 °C during the entire thermal cycle of the hot compression testing experiments. The sample and anvils were enclosed in a quartz tube through which a constant flow of argon gas was passed to increase the temperature uniformity in the sample and minimize oxidation of the sample and anvils.

Graphite, mica sheet, and boron nitride were used as consecutive lubricant layers between the anvils and sample during hot compression testing to minimize friction, and thus, barreling of the samples. To produce the graphite layer, graphite powder was compacted in an Al mold to form a disk with a thickness of 0.1 mm and diameter of 10 mm. The mica sheet was also disk-like in shape with a thickness of 0.08 mm and diameter of 10 mm. The boron nitride layer was uniformly applied by spraying each end of the sample and both sides of the mica sheet for five seconds from a distance of 30 cm. Trials to control the friction effect also included the utilization of Deltaglaze applied to the sample ends. This latter lubricant, however, was found to be less effective than boron nitride.

Each thermal cycle during hot compression testing involved an initial solution heat treatment at 1100 °C for 15 min, which was conducted in two stages; the furnace temperature was raised from ambient to 1000 °C at a rate of 1.5 °C/s, and then to 1100 °C at a rate of 0.5 °C/s. After solutionizing, the sample was heated or cooled to the deformation temperature at a rate of 0.5 °C/s. To ensure temperature uniformity, the sample was held at the deformation temperature for 5 min. Then, at a constant temperature and strain rate, the sample was deformed to a true strain of 0.83 (corresponding to an engineering strain of 56%), immediately followed by water quenching to retain the hot worked microstructure. To maintain the deformation at a constant strain rate, the speed of the lower actuator was adjusted to the changes in sample height using the control software of the MTS machine. Upon completion of each hot compression testing cycle, the load and displacement data were extracted from the data acquisition system for conversion into true stress–true strain curves. The deformation temperatures studied were subsolvus (950 °C, 980 °C, and 1020 °C) and supersolvus (1060 °C, 1100 °C, and 1140 °C). It is noteworthy that the γ' solvus is defined as the temperature above which all the γ' particles dissolve and no γ' can thermodynamically form [18]. For Waspaloy the γ' solvus was determined to be 1030 °C [19]. Also, the applied strain rates were 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1} and 1 s^{-1}.

The effect of friction on the flow stress was considered using the following equation [20,21]:

$$\sigma = \frac{C^2 P}{2[\exp(C) - C - 1]} \tag{1}$$

with

$$C = \frac{2\mu r}{h} \tag{2}$$

In Eq. (1), σ and P are the flow stresses of the material without and with friction, respectively. In Eq. (2), μ, r, and h are the friction coefficient, the radius, and the height of the compression sample, respectively. Since the geometry of the sample varies during hot compression testing, friction coefficient also changes. Therefore, to calculate friction coefficient and relate it to the instantaneous hot compression sample geometry the following equation was used [22]:

$$\mu = \frac{(R/h)b}{(4/\sqrt{3}) - (2b/3\sqrt{3})} \tag{3}$$

with

$$b = 4\frac{\Delta R}{R}\frac{h}{\Delta h} \tag{4}$$

In Eq. (3), R is the theoretical frictionless radius of the sample after deformation calculated based on volume constancy during plastic deformation and b is the barreling factor. In Eq. (4), ΔR determines the difference between the maximum and minimum radii of the deformed sample. As well, Δh is the difference between the initial and final heights of the hot compression sample. Therefore, considering the initial and final geometry of the compression sample, b was calculated using Eq. (4). The calculated value of b was inserted into Eq. (3) to determine μ. Considering the calculated μ and the final geometry of the compressed sample, C was calculated and inserted into Eq. (1) to determine the flow stress for