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Effect of Temperature and Strain Rate on Deformation Behavior of Zirconium Alloy: Zr-2.5Nb-0.5Cu

K. K. Saxena\textsuperscript{a}, S. Sonkar\textsuperscript{a}, R. Kumar\textsuperscript{a}, V. Pancholi\textsuperscript{a}, G. P. Chaudhari\textsuperscript{a}, D. Srivastava\textsuperscript{b}, G. K. Dey\textsuperscript{b}, S. K. Jha\textsuperscript{c}, N. Saibaba\textsuperscript{c}

\textsuperscript{a}Department of Metallurgical and Materials Engineering, Indian Institute of technology, Roorkee-247667, Uttarakhand, India
\textsuperscript{b}Materials Science Division, Bhabha Atomic Research Center, Mumbai-400085, India
\textsuperscript{c}Nuclear Fuel Complex Limited, Hyderabad-501301, India

Abstract

Hot workability of Zr alloy has been investigated by means of hot compression test using Gleeble-3800. Hot compression test was performed in the temperature and strain rate range of 700 to 925°C and 0.01 - 10 s\(^{-1}\), respectively. Deformation behavior was characterized with the help of processing maps using Dynamic Material Model (DMM). From the power dissipation map peak efficiency of 48-55\% was obtained at temperature of around 750°C and strain rate of \(1 \times 10^{-2}\) s\(^{-1}\), in (\(\alpha + \beta\)) phase field. High efficiency suggests dynamic recrystallization and therefore is preferred processing condition. A domain of unstable flow was obtained at temperature range 700-730°C and strain rate range of \(8 \times 10^{-2}-1\) s\(^{-1}\) in which instability parameter is negative. This region should be avoided during hot working. Effect of Cu in addition to Zr-2.5Nb also studied by power dissipation and instability map in this present study.

Keywords: Zr-2.5Nb-0.5Cu, Hot deformation, Thermomechanical Processing, Processing maps.

1. Introduction

Zirconium based alloy are preferred structural materials for nuclear reactors because of properties like, adequate strength and ductility, low thermal absorption cross section, long term dimensional stability in an irradiation environment, good corrosion resistance.

* Corresponding author. +98-911-121-4008
E-mail address: vivekfmi@iitr.ac.in
The manufacturing of such structural components consist large amount of deformation and bulk deformation processes are usually carried out at high temperature, i.e. above 0.5Tm where Tm is the absolute melting point of the material. Generally these deformation processes involve large amount of strain and high speed of deformation, which leads to achieve good production rate. The high temperature process helps to achieve large strain in a single step without any failure, thus a product can be finalized in fewer steps. During hot deformation microstructure of material changes, so it is an important objective to obtain microstructure which show better properties. The development of strong control system for Zr material processing requires good understanding of the constitutive behavior of the different element.

Addition of small amounts of copper to Zr-2.5Nb alloy improves its strength further by precipitation of Zr2Cu. Secondary hardening is also obtained due to β-Nb precipitate at twin and grain boundaries. The corrosion properties of Zr-2.5Nb are also improved considerably by copper addition. Zr-2.5Nb-0.5Cu is a two phase alloy containing α phase (HCP) and softer β phase (BCC). This alloy is used as a garter spring material in pressurized Heavy Water Reactor systems (PHWRs). As per its specific use, it is now required to understand the deformation behavior of above said material. Hot compression test have been developed already to characterize the plastic flow behavior of material, thus experimental testing of material are important for process simulation and optimization. After the deformation, microstructures and mechanical aspects are then correlated to test parameters.

In correlation of test parameters to microstructure and mechanical aspects, processing map is a powerful tool to identify stable or unstable hot working condition for plastic deformation, which is developed by Dynamic Material Model. Several unstable mechanisms were found to be related to process such as adiabatic shear band formation, flow localization and dislocation-solute interaction (DSA); the final product with these defects shows poor mechanical properties. Thus the unstable domain should be avoidable in case of hot working process. The safe domain observed in the processing map, associated with DRX is favored since DRX enhances intrinsic workability.

In dynamic material models, material is considered as a power dissipator. Constitutive flow behavior of material is the basis for power-dissipation characteristics of the workpiece, which follows a power law equation.

\[ \sigma = k \dot{\varepsilon}^m \]  

(1)

Where the flow stress is \( \sigma \), strain rate is \( \dot{\varepsilon} \), strain rate sensitivity is \( m \) and \( k \) is a constant. At any instant, the power dissipation occurs through rise in temperature (G content) and microstructural change (J content). Strain rate sensitivity \( m \) of the flow stress \( \sigma \) is the factor that partitions the power. So \( J \) at a particular temperature and strain is given by

\[ J = \sigma \dot{\varepsilon} \cdot \frac{m}{m+1} \]  

(2)

The value of \( J \) for non-linear dissipater is normalized with that of linear dissipater (\( m=1 \)) to obtained efficiency of power dissipation, which is a dimensionless parameter and is given by:

\[ \eta = \frac{J}{J_{\text{max}}} = \frac{2m}{m+1} \]  

(3)

The variation in \( \eta \) with temperature and strain rate represents the characteristics of power dissipation in terms of different domains, and these domains represent the specific microstructural mechanism, which dominates in the work piece during hot deformation. The processing map composed by superimposition of an instability map to power dissipation map. A continuum instability criterion is developed on the basis of extremum principles of irreversible thermodynamics, which is given by

\[ \xi(\dot{\varepsilon}) = \frac{\partial \ln(m/(m+1))}{\partial \ln \dot{\varepsilon}} + m < 0 \]  

(4)
The objective of this study is to construct power dissipation and instability maps on the basis of the dynamic material model in order to obtain the optimum hot working condition for Zr-2.5Nb-0.5Cu alloy.

2. Experimental Procedure

The starting material Zr-2.5Nb-0.5Cu alloy was obtained in the extruded and β quenched state, cylindrical specimens with 10 mm diameter and 15 mm height were machined parallel to the extrusion direction. A 1 mm chamfer of 45° was given to the edge of the face to avoid fold over in the initial stages of compression. Concentric grooves of 0.5 mm depth were machined at the both faces of samples to hold the lubricant properly. Graphite foil (5mil) was used to reduce the friction and avoid barreling.

Hot compression tests were conducted at the temperatures of 700, 750, 815, 850 and 925°C and at the constant true strain rates 0.01, 0.1, 1, 5 and 10 s⁻¹ with the help of Gleeble-3800 Thermo Mechanical Simulator. The specimens were deformed to apply true strain of about 0.69 and load-stroke data were recorded. Load-stroke data were converted to true stress-true plastic strain curves using standard equations. The flow stress values were obtained as a function of temperature, strain rate, and strain. The deformed specimens were sectioned along the compression axis and the cut surface was prepared by standard procedure for microstructural examination.

3. Results

3.1 Power dissipation maps

Power dissipation maps are shown in Fig.1 and Fig.2, drawn at strain of 0.2 and 0.5 respectively. The power dissipation maps were developed using Dynamic Material Model (DMM) and flow stress data obtained from hot compression test at different temperatures and strain rates. Domains with peak efficiency at different strains are summarized as follows.

- At strain of 0.2, power dissipation map exhibits a domain with peak efficiency of 48-55% at temperature of around 730-770°C and strain rate of 1×10⁻² which lies in (α+β) phase field.
- At strain of 0.5, power dissipation map exhibit a domain with peak efficiency of 48-55% at temperature range 700-765°C and the strain rate around 1×10⁻² s⁻¹. This domain also lies in (α+β) phase field.

![Power dissipation map at strain 0.2](image_url)
Comparison of power dissipation maps at strain of 0.2 and 0.5 brings out that range of strain rates and temperature having higher efficiency of power dissipation increase as a function of strain. Thus at strain of 0.5, temperature range for peak efficiency is higher than at strain of 0.2 at almost same strain rate. Higher efficiency of power dissipation is usually associated with DRX. Initiation of DRX process requires a critical density of dislocations which require certain amount of strain to accumulate. This is probably the reason for increase in DRX region in the processing map with increase in strain.

Effect of addition of Cu can be brought out by comparing power dissipation maps of Zr-2.5Nb-0.5Cu with that of Zr-2.5Nb. Power dissipation map of Zr-2.5Nb at strain of 0.2 exhibits two domain of peak efficiency of 49-54% and 54-60% around strain rate of $1 \times 10^{-2} \text{s}^{-1}$; first domain is located around 925°C and second one around 750°C. At
strain of 0.5 the peak efficiency of 44-50% exhibits for a very small region of temperature at 750°C and strain rate of 1×10^{-2} s^{-1}. In Zr-2.5Nb-0.5Cu alloy the temperature range for peak efficiency is increasing whereas for Zr-2.5Nb alloy it is decreasing. However, deformation conditions of temperature and strain rate for peak efficiency remains same for both the alloys.

3.2 Instability maps
It may be possible that the deformation conditions showing higher efficiency may lead to unstable flow. Therefore it is important to find instable region using DMM model. Figures 3 and 4 show instability maps developed using Eq. 4 at strain of 0.2 and 0.5 respectively. Blue colored areas are instability region in Fig. 3 and 4.

![Instability map at strain 0.5, Blue region is showing instability, as it has negative value for instability.](image)

At strain of 0.2 the instability occurs at lower temperature of 700°C and higher strain rate of 10 s^{-1}, while at strain 0.5, two instable domain exhibits; first at temperature of around 700-730°C and strain rate of 0.1 to 1 s^{-1} and second at temperature of around 850°C and strain rate of around 10 s^{-1}. Increase in instable region may be because of damage accumulation with strain. However, it is not clear why instable region is shifting from low temperature and high strain rate to low strain rates.

4. Discussion
Generally, the domains in processing maps (superimposed map of power dissipation on instability) are determined by two methods; one is correlating the efficiency variation with respect to strain rate and temperature, and the other one is the microstructure changes that occur in the deformed specimens. In the deformed specimen, microstructural evolution depends on dominating deformation mechanism operating in that particular domain.

In the domain of 750°C and strain rate 1×10^{-2} s^{-1}, Zr-2.5Nb-0.5Cu has two phases, so the hot deformation characteristics for both the phases have to be considered. In the case of two phase alloy, hot deformation is controlled by harder phase, which is generally α (hcp) in case of Zr-Nb alloys. According to Raj, dynamic recrystallization (DRX) or superplasticity is favored for hot working. Superplastic deformation show efficiency of power dissipation in excess of 60% and for very fine grained material like Zr-2.5Nb-0.5Cu, the efficiency may reach as high as 90%. Since the observed peak efficiency is 54% in present case, therefore it appears that superplastic deformation may not be operating. It is also reported that β-transformed structure does not undergo superplasticity since the interface sliding is restricted due to a definite crystallographic relationship. In extruded and cold drawn Zr-2.5Nb-0.5Cu, optimum hot working condition was reported at temperature of 750°C and strain rate of 1×10^{-3} s^{-1}, a domain of dynamic recrystallization whereas at temperature of 850°C and strain rate of 30 s^{-1}, instability occurs.
5. Conclusion

The hot deformation characteristics of extruded and β-quenched Zr-2.5Nb-0.5Cu alloy was studied using hot compression testing at temperatures 700, 750, 815, 850, and 925°C and constant true strain rates of 0.01, 0.1, 1, 5 and 10 s⁻¹. Power dissipation and instability maps are drawn with experimentally generated data and interpreted with the help of Dynamic Material Model (DMM). The conclusions drawn are given below.

- At strain of 0.2, domain with peak efficiency of 48-55% was obtained at temperature range of 730-770°C and strain rate of 1×10⁻² s⁻¹, while at strain of 0.5, domain with peak efficiency shifted to temperature range of 700-765°C at almost same strain rate as in 0.2 strain. Range of temperature, where optimum condition for hot working was obtained, increased as a function of strain.
- At 0.2 strain DMM model showed instability at temperature of 700°C and strain rate range of 10 s⁻¹, while at strain of 0.5, two domains of instability were obtained; at temperature of 700-730°C and strain rate of 8×10⁻²-1 s⁻¹ and second at temperature of around 850°C at strain rate of around 10s⁻¹.
- Addition of Cu in Zr-2.5Nb increases the region of peak efficiency of power dissipation and shifts towards the lower temperature at almost same strain rate. Additionally, Cu reduces the strain rate range and temperature for the instability in material of Zr-2.5Nb.

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References