Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 1117–1122

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

The cliff-valley approach in the P-maps of PM/W joints for manufacturing the dual-alloys turbine disc

Yongquan Ning[a*], Bingchao Xie[a], Zekun Yao[a], Hongzhen Guo[a],M.W. Fu[b]

[a]*School of Materials Science & Engineering, Northwestern Polytechnical University, Xi'an 710072, P.R. China*
[b]*Department of Mechanical Engineering, the Hong Kong Polytechnic University, Kowloon, Hong Kong, P.R. China*

Abstract

In present work, hot deformation behavior of Ni-based dual-alloys has been investigated using processing map (P-map) at the temperatures of 1020-1140°C and strain rates of 0.001-1.0s^{-1}. The processing map approach was further adopted to optimize hot forging process of dual-property turbine disc. Optimum processing condition is (T_{opi}: 1140°C, $\dot{\varepsilon}_{opi}$: 1.0s^{-1}) with the peak efficiency of 0.55 for processing dual-alloys. In addition, a new method to find the instability criterion (Cliff-Valley) from power dissipation map has been reported. The "cliff" and "valley" features are the sufficient condition of flow instability. The results indicate that P-map approach could be used to optimize the forging parameter for dual-alloys.

Keywords: Processing maps; Instability criterion; Microstructure evolution; Ni-based superalloys; Dual-alloys turbine disc

1. Introduction

Deformation temperature (T_d, °C) and strain rate ($\dot{\varepsilon}$, s^{-1}) are the most important parameters that can affect microstructure and mechanical property for heavy forging process. How to optimize the processing parameters becomes the major problem in actual forging process. It has been widely accepted that processing-maps (P-maps) could provide the basis for parameter optimization in forging process. P-map is developed on the basis of dynamic

* Corresponding author. Tel.: +86 2988493744; fax: +86 2988492642.
E-mail address: ningke521@163.com

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.1069

materials model (DMM). P-maps can be obtained through combining the efficiency of power dissipation (η) and instability parameter ($\xi(\dot{\varepsilon})$). Based on the analysis of P-maps, the flow stability regions and the flow instability regions could be delineated at specific deformation temperature and strain rate. Then hot processing could be conducted with preferable parameters in flow stability regions. Prasad detailed how to generate the P-map and use it to explore the deformation mechanism and to optimize processing parameter[1–3]. By using P-maps, Ning[4] investigated hot deformation behavior and optimized the processing parameters of FGH4096 superalloy. Those articles are all about P-maps of metallic materials in single alloy system (viz. only one alloy in deformation system). However, no P-map of dual-alloys (viz. two or more alloys in deformation system) has even been constructed. In present work, the P-map approach was adopted to optimize the forging parameter of dual-alloys. In addition, a new instability criterion for processing Ni-based dual-alloys has been given.

2. Material and experimental procedure

The as-received materials used in this research are wrought superalloy and PM superalloy. Two kinds of superalloys with the same dimension of 30×30×6mm were prepared by using the mechanical polishing for electron-beam welding (EBW). Mechanical polishing was performed according to the following procedure: after a surface grinding with 30μm grained diamond disc, the specimen was polished with a diamond paste of 18, 9 and 3μm granulation for 30 minutes. Finally, a polishing with a 0.1μm colloidal silica solution was done for 30 minutes. Then EBW was conducted by using a KS55-G150 with an accelerating voltage of 150kV. The electron current was 32mA and the welding speed was selected as 2mm/s. Fig.1 shows a typical microstructure of dual-alloys fabricated by EBW, which presents previous particle boundaries (PPBs) network in base metal (PM), dendrite microstructure in fusion zone and equiaxed microstructure in base metal (W). Cylindrical compression specimen with a dimension of Ø8 × 12mm was machined from the central position of the dual-alloys. A series of isothermal compression tests were conducted in a Gleebe-1500D thermo-simulation machine at the deformation temperature (T_d) of 1020, 1050, 1080, 1110 and 1140°C. Temperature control is within ±2°C. The strain rate ($\dot{\varepsilon}$) is 0.001, 0.01, 0.1 and 1.0s^{-1}, respectively, and the height reduction is 50%. All of the specimens were heated at the heating rate of 10°C/s and soaked for 3.0min at the deformation temperature to obtain a uniform temperature across the specimen. The strain-stress curves were automatically recorded in the compression process. Upon compression, the specimens were cooled down to room temperature by spraying them with water. They were sectioned parallel to the compression axis, and the microstructure examination was conducted by an OLYMPUS-PM3 optical microscope (OM) and with the chemical etchant of $CuSO_4$ (10g) + H_2O_2 (10mL) + HCl (40mL) + H_2O (50mL).

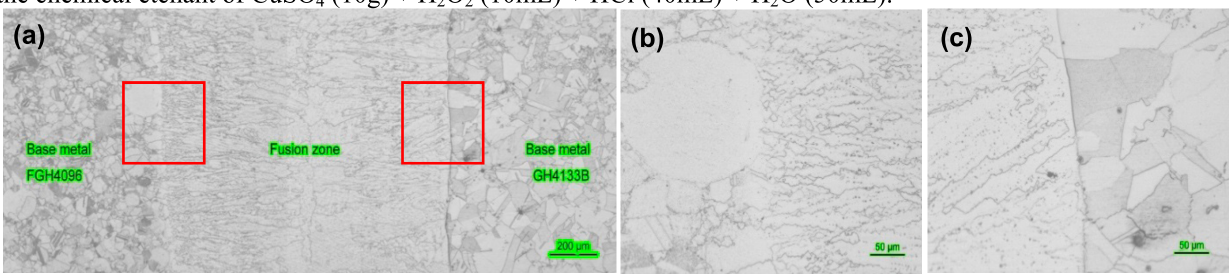

Fig.1. Typical microstructure of PM/W joints fabricated by electron beam welding which showing previous particle boundaries (PPBs) network in base metal (PM), dendrite microstructure in fusion zone and equiaxed microstructure in base metal (W).

3. Results and discussion

Strain rate sensitivity (SRS) exponent m is very important for forging process, which is related to different deformation mechanisms. Many researchers have used different methods to measure the value of m. Some researchers reported that m varies with the processing parameters. Romhanji[5] investigated the effect of deformation temperature on the strain rate sensitivity exponent m of high strength Al-Mg alloy sheet, and observed that m increases with deformation temperature. Picu[6] found m is a function of deformation temperature and strain. Chiou[7] studied the effect of deformation temperature, strain and strain rate on the value of m. Del Valle[8] explored the effect of grain size on m, and observed that it increases strongly with grain size if it is below 15μm. Moreover, strain rate sensitivity exponent m contributes to the variation of processing map's parameters including efficiency of power dissipation η and instability parameter $\xi(\dot{\varepsilon})$. The m-value at different compression conditions were calculated based on the fitted cubic splines for logσ Vs. log $\dot{\varepsilon}$. Obviously, the effects of deformation temperature and strain rate on the m-value of dual-alloy are significant. Generally, the m-value varies irregularly with strain, strain rate and deformation temperature. In order to reveal the detailed response of m-value to the compression condition such as strain, strain rate and deformation temperature, the m-values at different conditions are plotted and shown in Fig.2. The strain rate sensitivity exponent m at the strain of 0.7 and the strain rate of 1.0s^{-1} firstly tends to decrease with the increasing deformation temperature. When a minimum value is reached, the m-value begins to increase with the deformation temperature. The main reason may be clearly interpreted on the basis of the variation of grain size. The minimum m-value is obtained at 1050°C, close to the recrystallization temperature. The present variation of m-value with deformation temperature could be reasonably explained based on the microstructural evolution.

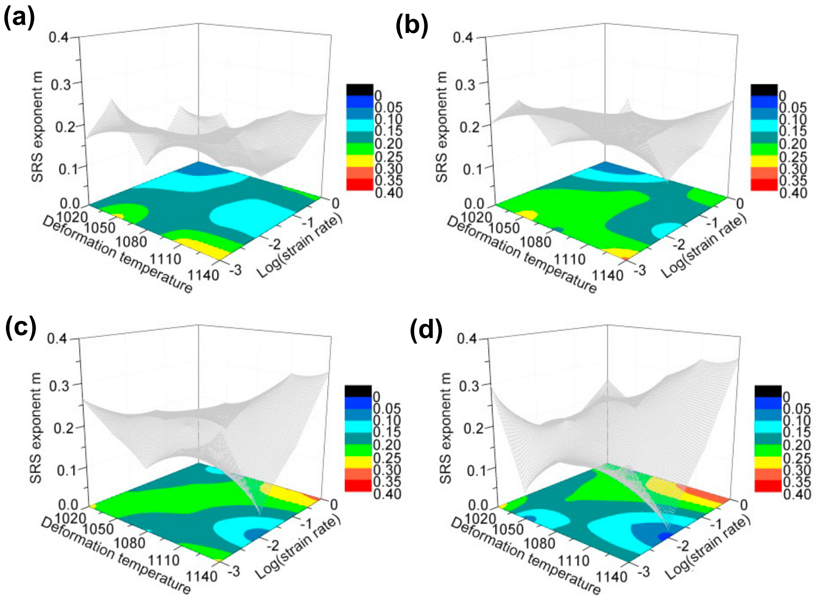

Fig.2. Response 3D surfaces of m-values to deformation temperature and strain rate as true strain (a) 0.1, (b) 0.3, (c) 0.5 and (d) 0.7.

Fig.3 gives the m-values and the microstructures of the samples processed with the strain rate of 1.0s^{-1}. It can be seen that the nuclei of recrystallization is predominant at the deformation temperature of 1050°C, which leads to a lower value of m. The nuclei began to grow up into equiaxed grains with the increase of deformation temperature, resulting in the strain rate sensitivity exponent m at the deformation temperature of 1140°C, which is higher than that at the deformation temperature of 1050°C. In general, fine grain size is beneficial to grain boundary sliding, so the variation of grain size finally results in the increase of m at the deformation temperature ranging from 1050 to 1140 °C. The power dissipation map is constituted by the three-dimensional variations of the efficiency of power dissipation η with deformation temperature and strain rate at a constant strain, and can be considered as a contour map representing efficiency contours in the deformation temperature-strain rate frame. This map articulates the manner in which the power is dissipated through microstructural change during the hot deformation process, and hence reveals the region in which a specific mechanism may become attractive for minimizing the energy of the dissipated state. Each contour presents the same value of the efficiency of power dissipation η, and the number of contour indicates the dimension of efficiency of power dissipation in the same hot deformation conditions. Study on processing map is one of the most important applications when optimizing hot deformation process.

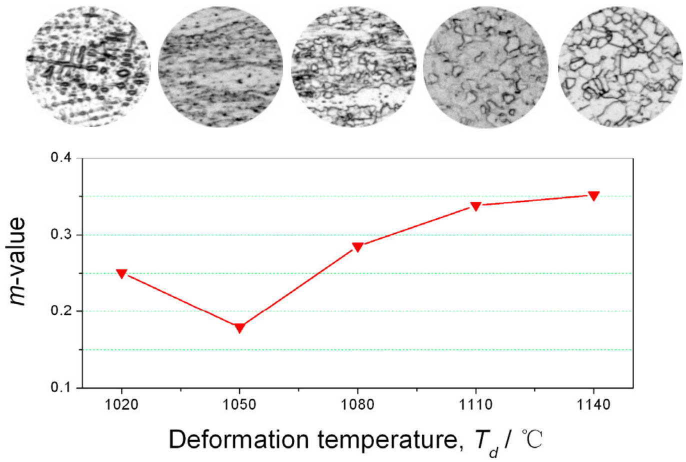

Fig.3. Microstructures and *m*-values of PM/W joints processed with the strain rate of $1.0s^{-1}$.

Based on the dynamic material model (DMM), different instability criteria are applied to studying the hot compression deformation of metal materials and the valuable conclusions are derived by analyzing these instability criteria. Prasad's criterion[9] is derived carefully by the maximum entropy generation rate principle and big plastic deformation. However, when this criterion is put into application, it is needed that the established constitutive equation during high temperature compression deformation meets the three-order derivability of the strain rate ($\dot{\varepsilon}$). Gegel's and Malas's criterion[10-11] is derived on the basis of thermodynamics theorem and its theoretical basis is strict. However, as compared with the requirement of Gegel's criterion in which the strain rate sensitivity exponent (m) value is a constant parameter, Malas's criterion does not need to consider m value as a constant. The entire derivation process of Murty's criterion[12] does not consider the issue whether m value is a constant or not. While, in calculation of the efficiency of power dissipation (η), the definition-formula of η value must be used and the calculation process is tedious. Semiatin's criterion[13] is an empirical formula derived based on the microstructure observation of titanium and its alloys. As compared with other criterions, this criterion does not have the strict theoretical basis. Fig.4 presents the power dissipation map. The efficiency of power dissipation (η) flows from mountain to valley, finally into the bottom. This shift of efficiency predicts the decrease in hot workability of dual-alloy. In this paper, a new method to find the instability criterion from power dissipation map is presented. Firstly, there is a local region in which the η significantly changes from high to low value (in Fig.4 marked cliff). Secondly, a valley with a low η value is under the cliff. Generally, in the valley, there are some "bottoms" (η<0.1). Between cliff and valley, an instable region is predicted. When the hot deformation process is carried out under the condition located in this region, the flow instability might occur. The "cliff" and "valley" are sufficient condition, but not necessary one. There are still other conditions which could result in the flow instability. Meanwhile, it should be pointed out that only "cliff" or "valley" might not lead to the occurrence of flow instability. Further investigations are still needed to provide the evidence of microstructure mechanism and mathematical equation.

Typical microstructures of Ni-based dual-alloys processed after hot compression under different conditions are shown in Fig.5, which give the evidence of DRV, DRX and grain growth. Typical microstructures compressed at the low temperature of 1050°C and high strain rate of $0.1–1.0s^{-1}$, result in the DRV as shown in the figure. The lower-left region presents a typical DRX microstructure, processed at the suitable temperature of 980–1140°C and strain rate of $0.1–1.0s^{-1}$. However, the coarse microstructure exists at the lower-right region, with the temperature of 1110–1140°C and the lower strain rate of $0.001–0.01s^{-1}$. Meanwhile, the wavy (or corrugated) boundaries can be easily seen in the grain growth microstructure. In general, the elevated deformation temperature is beneficial to fabricate the formation of homogeneous microstructure. However, the grain growth and the strengthened phase coarsened after hot compression process with the lower strain rate. In order to obtain the fine homogeneous microstructure, hot deformation should be carried out under the condition of (T_{opi}: 1140°C, $\dot{\varepsilon}_{opi}$: $1.0s^{-1}$) with the peak efficiency of 0.55. This result indicates that P-map approach could be used to optimize the forging parameter for dual-alloys system.

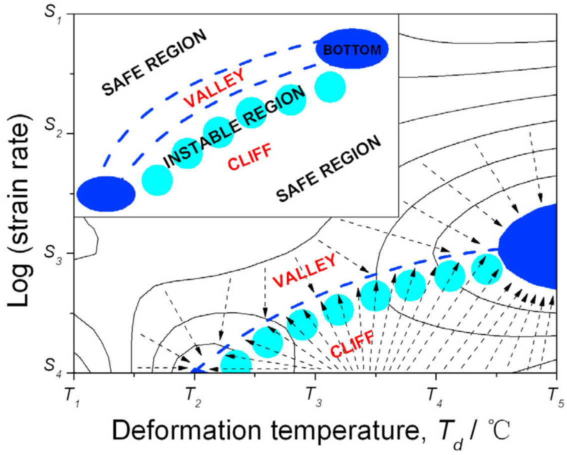

Fig.4. Schematic illustrating the instability criterion of Ni-based dual-alloys.

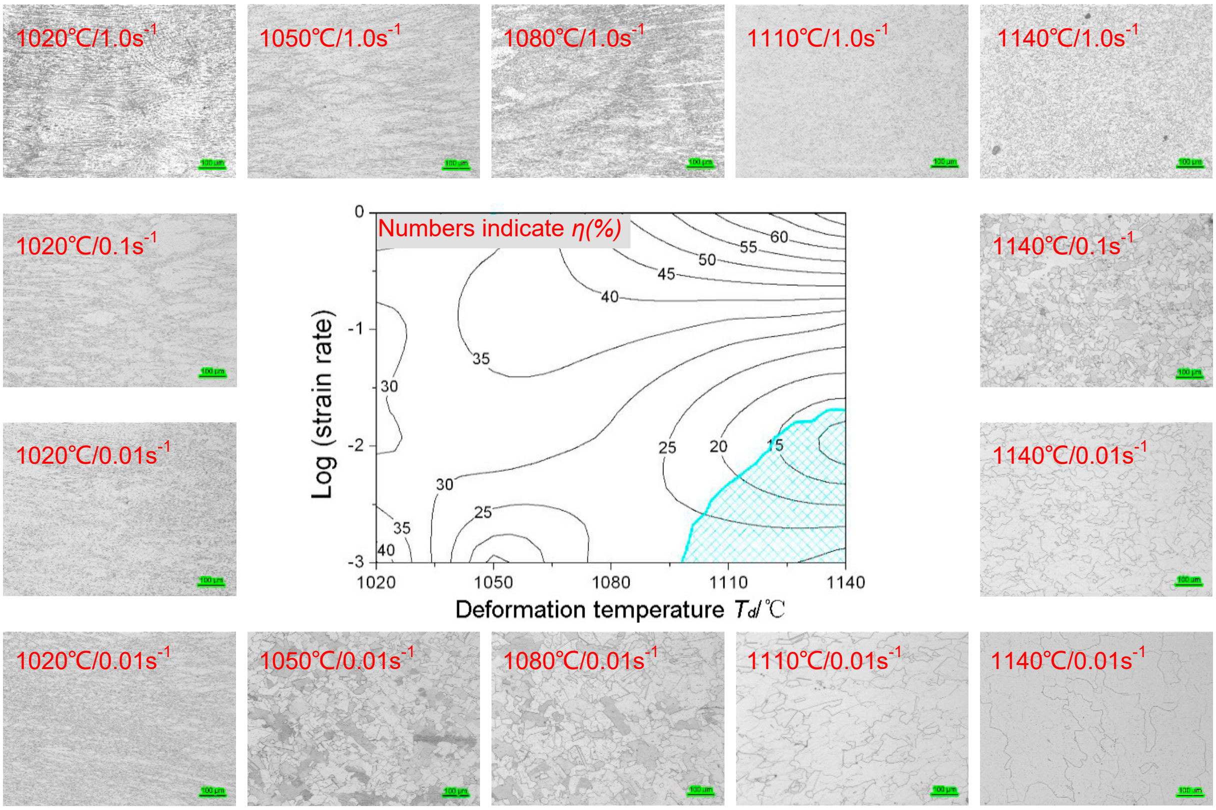

Fig.5. Typical Microstructures of Ni-based dual-alloys processed after hot compression processes

4. Conclusion

Hot deformation behavior of Ni-based dual-alloys has been investigated using processing map (P-map) at the temperatures of 1020-1140℃ and strain rates of 0.001-1.0s^{-1}. Based on the theoretical analysis and microstructural observation, the following conclusions are drawn:

(1) The processing map approach can be adopted to optimize the forging parameter for dual-alloys.

(2) Optimum processing condition is suggested to be (T_{opi}: 1140℃, $\dot{\varepsilon}_{opi}$: 1.0s^{-1}) with the peak efficiency of 0.55 for processing dual-alloys.

(3) A new method to find the instability criterion (Cliff-Valley) from power dissipation map has been reported. The "cliff" and "valley" features are the sufficient condition of flow instability.

Acknowledgements

This work was financially supported by Fundamental Research Funds for the Central Universities (Grant No. 3102016ZY012), Natural Science Foundation of Shaanxi Province (Grant No. 2016JQ5039), China Postdoctoral Science Foundation (Grant No. 2015M570851) and Shaanxi Postdoctoral Science Foundation. Also, we would like to thank the funding support by the Hong Kong Scholar Program (Grant No. XJ2014047 and G-YZ68).

References

[1] Y.V.R.K. Prasad, Recent advances in the science of mechanical processing, Indian J. Technol. 28 (1990) 435–451.
[2] Y.V.R.K. Prasad, T. Seshacharyulu, Processing maps for hot working of titanium alloys, Mater. Sci. Eng. A 243 (1998) 82–88.
[3] Y.V.R.K. Prasad, Processing maps: A status report, J. Mater. Eng. Perform. 12 (2003) 638–645.
[4] Y. Ning, Z. Yao, H. Li, H. Guo, Y. Tao, Y. Zhang, High temperature deformation behavior of hot isostatically pressed P/M FGH4096 superalloy, Mater. Sci. Eng. A 527 (2010) 961–966.
[5] E. Romhanji, M. Dudukovska, D. Glišić, The effect of temperature on strain-rate sensitivity in high strength Al-Mg alloy sheet, J. Mater. Process. Technol. 125–126 (2002) 193–198.
[6] R.C. Picu, G. Vincze, F. Ozturk, J.J. Gracio, F. Barlat, A.M. Maniatty, Strain rate sensitivity of the commercial aluminum alloy AA5182-O, Mater. Sci. Eng. A 390 (2005) 334–343.
[7] S.T. Chiou, H.L. Tsai, W.S. Lee, Impact mechanical response and microstructural evolution of Ti alloy under various temperatures, J. Mater. Process. Technol. 209 (2009) 2282–2294.
[8] J.A. del Valle, Q.A. Ruano, Influence of the grain size on the strain rate sensitivity in an Mg-Al-Zn alloy at moderate temperatures, Scripta Mater. 55 (2006) 775–778.
[9] Y.V.R.K. Prasad, S. Sasidhara, Hot Working Guide: A Compendium of Processing Maps, ASM International, Materials Park, 1997.
[10] H.L. Gegel, E.W. Collings, A physical basis for solid-solution strengthening and phase stability in alloys of titanium, Scripta Mater. 7 (1973) 437–443.
[11] J.C. Malas, V. Seetharaman, Using material behavior models to develop process control strategies, JOM 44 (1992) 8–13.
[12] S.V.S. Murty, R.B. Nageswara, B. Kashyap, B.P. Kashyap, Instability criteria for hot deformation of materials, Int. Mater. Rev. 45 (2000) 15–26.
[13] S.L. Semiatin, V. Seetharaman, I. Weiss, Hot workability of titanium and titanium aluminide alloys—an overview, Mater. Sci. Eng. A 243 (1998) 1–24.