MODELLING HOT DIE FORGING PROCESS OF THE Ti-10V-2Fe-3Al ALLOY

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Abstract

In this paper, an analysis of the press forging process of a complex shape forming from the Ti-10V-2Fe-3Al alloy forged at the temperature of 900°C was conducted. It is a high-strength titanium alloy, and, metalurgically, a near-beta alloy. A major advantage of this alloy is its good hot-die forgeability. Ti-10-2-3 is often used for near-net-shape forging applications, which include aerospace airframes hot-die and conventional forgings, and other forged parts in a wide variety of components. The preferred forging process is controlled β forging. The characteristics of the hot deformation behaviour of Ti-10-2-3 were studied with the use of processing maps obtained on the basis of flow stress data generated in a compression test conducted over the temperature range of 800 - 1100 °C and strain rate from 0.01 s^{-1} to 100 s^{-1}. For true strain equal to 0.9, one domain of flow instability was found to be present and three processing windows were isolated. The high sensitivity of the strain rate of this alloy was found. In support of processing maps, the observations of microstructures while being delivered and after deformation in controlled conditions was conducted using a Gleeble 3800 simulator, and the numerical analysis of forming the analysed alloy in industrial conditions was designed. Numerical calculations were conducted using a program based on the finite element method realized in QForm 3D. The high compatibility of numerical calculations results with the industrial test was found.

Keywords: processing maps, numerical modelling, forging, titanium alloy

1. INTRODUCTION

Titanium alloys are widely used in the aerospace industries, mostly due to their low density and attractive combination of strength, crack resistance and corrosion resistance [1]. Ti-10Fe-2V-3Al is a high-strength, metastable, near-beta alloy. A major advantage of this alloy is its very good forgeability and lower crack sensitivity in forging than in the case of the $\alpha+\beta$ Ti-6Al-4V alloy [1,2]. Titanium alloys are more difficult to process in comparison to other engineering materials such as aluminium and steels. In order to effectively conduct the forging process, it is important to investigate and evaluate the material's behaviour over a wide range of temperatures, strain rates and strains. Processing maps [2-9] are a useful tool applied for the optimization of hot-working processes and the evaluation of workability. The maps were prepared on the basis of the dynamic material modelling (DMM) method, and are prepared for many alloys.

The paper presents the results of a complex study of Ti-10Fe-2Fe-3Al alloy, conducted with the application of the dynamic material modelling (DMM) method, in a wide range of temperatures, strain rates and strain and numerical modelling. The numerical modelling of the forging process was performed with application of the finite element method (FEM), using QForm 2D/3D commercial software. On the basis of data obtained by the numerical analysis, the appropriate thermo-mechanical conditions of the hot die forging of a product with determined geometry were estimated. The designed parameters of forging technology were verified by the trials performed in industrial conditions.

2. MATERIALS AND METHODS

The composition of the alloy investigated in the present study is given in **Table 1**. While being delivered, the material was in the form of a bar of the diameter of 76 mm. For developing processing maps, cylindrical compression samples (∅ 10 x 12 mm) were machined from the alloy.

Table 1 Chemical composition (% weight) of the Ti-10V-2Fe-3Al alloy

C	V	Al	Fe	N	O	H	Y	Ti
0,024	9,76	3,37	1,84	0,016	0,10	0,0001	<0,005	balance

2.1 Hot compression testing

High temperature compression tests were conducted on a Gleeble 3800 thermo-simulator applying argon protective atmosphere. The specimens were heated at 2.5 °C/s heating rate up to the specified temperature, and finally subjected to uniaxial compression. The research was conducted over the temperature range of 800 - 1100 °C and the strain rate range of 0.01 - 100 s^{-1} up to the constant final true strain value of 0.9. The inverse method was applied for the interpretation of the results obtained from axisymmetric compression tests. This method was described in detail by D. Szeliga et al. [5].

2.2 Generation of processing maps

The results of compression test were used for plotting a processing map. For the dependence: log flow stress versus log strain rate, for the constant value of deformation and every analysed temperature, cubic equations were selected. Conducting the differentiation of these equations in relation to strain rate, m (strain rate sensitivity exponent) was calculated [6,7]. Afterwards, on the basis of the equation: $\eta=2m/(m+1)$ [6-9], the power dissipation efficiency parameter was calculated. Power dissipation as the function of temperature and strain rate maps were plotted in the form of the isoclines of the power dissipation efficiency parameter expressed in %. Power dissipation maps exhibits various domains in which the power is dissipated by the material through micro-structural changes. The instability criterion (Eq. 1) was used to identify the regimes of unstable flow [6,7,9-12]. Flow process instability is a complex notion referring to particular temperature and strain rate, and, therefore, to the conditions in which the process of shaping a material occurs. The variations of parameter ξ as a function of strain rate and temperature make it possible to plot the instability maps.

$$\xi(\dot{\varepsilon}) = \frac{\partial \log\left(\frac{m}{m+1}\right)}{\partial \log \dot{\varepsilon}} + m \leq 0 \qquad (1)$$

Deformability maps are plotted by overlaying a flow instability map on a power dissipation map [6,7].

2.3 Numerical modelling and industrial testing

The numerical modelling of the process of high-current contact tip forging was conducted in a numerical commercial program based on MES - QForm 3D [13]. In **Fig. 1**, the model of a forging is shown. The following boundary conditions were adopted: the temperature of workpiece heating: 920 °C, the temperature of tools: 210 °C, the time of transporting a workpiece to the press station: 5 s, the time of cooling in the tools before starting forging: 2 s, the height of flash land: 1 mm. One-operation forging process was conducted on a screw press of the maximum energy of 20 kJ and maximum speed of 450 mm/s. For the calculations, a lubricant in the form of graphite-water emulsion, of the friction factor m = 0.5, was adopted. The effective heat transfer coefficient between the workpiece and tools was adopted at the level of 4000 $W \cdot m^{-2} \cdot K^{-1}$. The dimensions of the material were ∅35 mm x 49 mm. The distributions of mean stress, effective strain, and also effective strain rate, were determined. Moreover, the Zener-Hollomon parameter (Eq. 1) was calculated numerically (Eq. 2) [14]. The parameter was calculated with the use of the following formula:

$$Z = (\dot{\varepsilon})\exp\left(\frac{Q_{EW}}{R \cdot T}\right) \tag{2}$$

where: $\dot{\varepsilon}$ - strain rate, s^{-1}, Q_{EW} - activation energy (Eq. 3), J/mol, R - gas constant (8.3145 J/mol/K), T - temperature, °C. Every material is characterized by its specific activation energy. However, the general relationship can be given as follows:

$$Q = C_1 + C_2 \cdot T + C_3 \cdot \bar{\varepsilon} \tag{3}$$

where: T - temperature, °C, $\bar{\varepsilon}$ - effective strain, C_1, C_2, C_3 - coefficients. Industrial forging tests were conducted in one of Polish forges on the basis of the best thermal-mechanical parameters determined in the simulation of forging the tested alloy were conducted. The stock was heated in an induction furnace to the temperature of about 920 °C, and afterwards, it was transferred to a forging position. The temperature was measured using a thermocouple, with 5 °C measuring accuracy. The test was conducted with the use of a graphite-water emulsion for covering dies and a silica based Thermex GL lubricant for securing the billet. After the forging process, forges were cooled with the use of air.

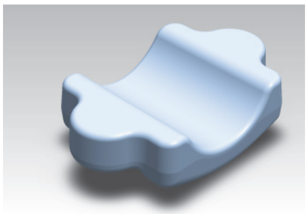


Fig. 1 High-current contact tip forging model

3. RESULTS AND DISCUSSION

On a processing map, it is possible to separate three processing windows (I, II, III) of the highest power dissipation efficiency parameter, and also one „unsafe” domain IV (**Fig. 2**) [15]. The first processing window of the efficiency η = 34 - 38% and the parameter ξ ≤ 0.25 are observed in the case of strain rate of 0.08 - 0.01 s^{-1}, at the temperature of 800 - 816 °C. The second processing window (II) of the efficiency η = 24 - 50% and the parameter ξ = 0.05 - 0.25 for the strain rate of 0.01 - 5 s^{-1} at the temperature of 816 - 889°C. The separated III processing window has the efficiency η = 25 - 35% and the parameter ξ = 0.09 - 0.27 for the strain rate 10 - 100 s^{-1} at the temperature of 1012 - 1054°C. The window has a favourable system of the isoclines of process efficiency and the parameter identifying the flow instability. Domain IV, shown in the **Fig. 2**, is connected with flow process instability, and it may not be used in forging processes. It is set at the temperature of 800 - 859 °C, which means that occuring the transformation: α + β → β for the strain rate 5.5 - 100 s^{-1} and the decreasing parameter ξ between zero and (-0.39). Designing the technological process of high-current contact tip forging, it was assumed that the process should be conducted in the range of the second domain, which means the temperature of forging of approximately 890 °C.

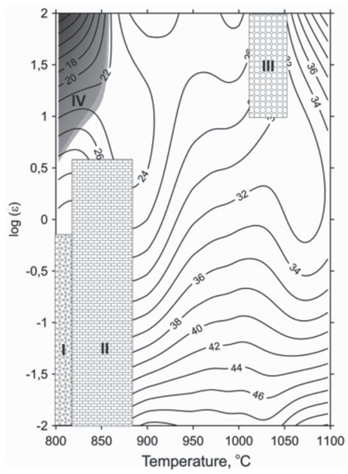


Fig. 2 Processing maps plotted for true strains of 0.9, with process frames and domains [15]

Taking under consideration the material flow kinematics, the finishing impression is filled by means of upset forging and extrusion. Forging is characterized in its volume by the areas of various degree of forging reduction ratio, and, simultaneously, constitutes a compact forging, which makes it possible to obtain differentiated thermal-mechanical conditions during forging and after it is concluded. In **Fig. 4**, mean stress distribution (**Fig. 3a**) was presented, together with effective strain (**Fig. 3b**), effective strain rate (**Fig. 3c**) and also the Zener-Hollomon parameter (**Fig. 3d**) in characteristic cross-section of the forging obtained from numerical calculations. Over the entire volume of the forging, compressive stresses dominate. The highest values of mean stresses are ascertained in the central part of the forging (**Fig. 3a**). Tensile stresses occur only in the forging. The numerically-set effective strain distribution is characterized by a high degree of homogeneity. The maximum values of effective strain, connected with relocating the large quantities of material, are confined to the area of transition of a impression die into the flash, and also in the area of changes to the cross-section. They reach the value equal to 4 - 5. The lowest values of effective strain (no more than 1) may be observed in the lower part of the forging. The values of the Z parameter are characterized by substantial changeability over the volume of a forging. The highest values may be observed in the area of corner radii (LogZ = 24), and also on the flash gab (LogZ = 18) (**Fig. 3d**). In the central part of a forging, the Z parameter reaches the values near 12.

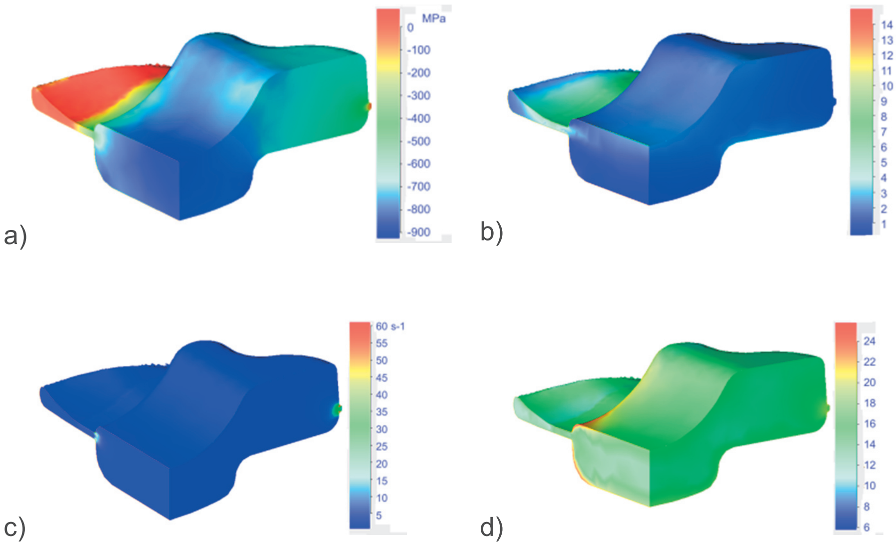


Fig. 3 Numerically determined distributions: a) mean stress, b) effective strain, c) effective strain rate, d) log Z

The analysis of the forging process indicates as well that in the majority of the volume of a forging, the effective strain rate amounts to approximately 1 s^{-1} (**Fig. 3c**). The simulation of such a strain rate for the temperature of 900 °C in a Gleeble thermo-mechanical simulator (heating rate 2.5 °C/s, heating time 10 s, cooling in compressed air, true strain: 0.9), results in the complete dissolution of the α phase and the occurrence of a healing process (**Fig. 4**). Such a microstructure was found to be appropriate for the final forging. Therefore, the above-described forging conditions were found to be appropriate for conducting an industrial test.

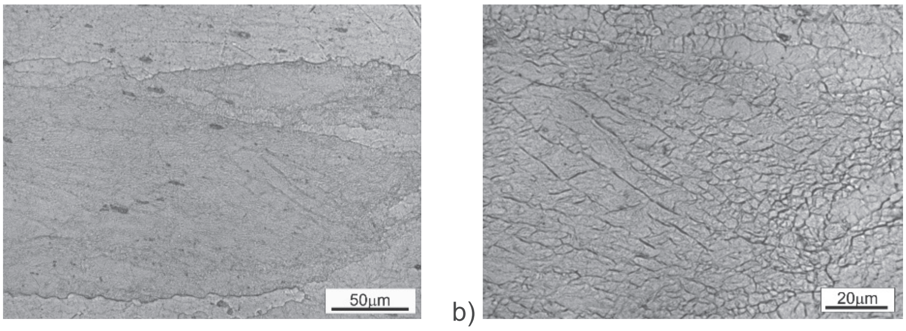
a) b)


Fig. 4 Microstructure of the Ti-10V-2Fe-3Al alloy after deformation in a Gleeble 3800 thermo-simulator at the temperature of 900 °C with strain rate of 1 s^{-1}

The developed thermal-mechanical conditions of forging the Ti-10V-2Fe-3Al alloy were used in industrial tests. The obtained forging is presented in **Fig. 5**. After the forging process, the forgings were not thermally processed; they were only cooled in controlled conditions in the air. A defect-free forging of full dimensional and structural stability was obtained.

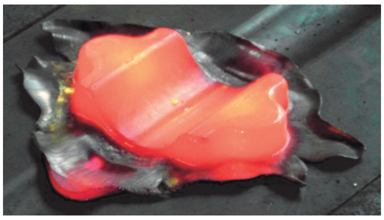


Fig. 5 View of the hot cover plate of a forging

CONCLUSION

The applied methodology of developing a technology of making forging of the Ti-10Fe-2Fe-3Al alloy made it possible to obtain a forging of high technical quality. The optimum parameters (as for computational engineering and analyses) of the thermo-mechanical plastic working process, in structural-energetic quantification were determined for the investigated alloy. The combination of the classical methods of material's workability testing, such as uniaxial compression test, the dynamic material modelling (DMM) method and numerical modelling, was applied to the complex analysis of hot-working processes. On the basis the results of numerical simulations of the investigated forging process, the optimal technological parameters of forging the Ti-10Fe-2V-3Al alloy in designed thermo-mechanical conditions were determined. The results of the simulations were compared with the results of forging in industrial conditions. The results of the simulations showed to be in very good agreement with the experimental observations.

ACKNOWLEDGEMENTS

The research project was financed by the Polish Ministry of Science and Higher Education (AGH-UST statutory research project no. 11.11.110.292) and Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project WND-POIG.01.03.01-12-004/09.

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