Numerical and experimental investigation of process parameters in non-isothermal forward extrusion of Ti–6Al–4V

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Abstract Ti–6Al–4V is the most common Ti alloy that may be worked at supra or subtransus temperatures, conventionally or isothermally. In this article, the effect of extrusion process parameters and die geometry on the extrusion force and adiabatic temperature rise is investigated. The process is considered to be non-isothermal. The results show that the non-uniform effective strain field inside the workpiece generates more elongated grains near the surface of the extrudate. The results also indicate that the ram velocity has the highest effect on both extrusion force and adiabatic temperature rise. The study suggests that in non-isothermal extrusion of Ti–6Al–4V, die and billet temperatures have stronger effect on the extrusion force compared with the die angle. However, effect of the die angle on the adiabatic temperature rise is considerable and cannot be neglected. Effect of the billet temperature on adiabatic temperature rise is more than the effect of die angle. The simulation model and analytical results are verified by experimental investigations that shows good agreement between the corresponding results. The provided insights using the approach and the results presented in this article gives a better understanding of forward extrusion of Ti–6Al–4V material. The results can be used by the tool designers and process planners in developing the tools and the processes that gives better yield and reduces the manufacturing costs.

Keywords Non-isothermal extrusion · Ti–6Al–4V · Adiabatic temperature rise · Extrusion force

1 Introduction

Ti–6Al–4V is the most common Ti alloy. It is a two-phase alloy, with low density, high specific strength and attractive corrosion resistance that make it an ideal choice for many aerospace applications [1]. Process of ingot breakdown takes place at temperatures above β transus and is followed by a combination of supra and subtransus operations and appropriate heat treatment to achieve desired microstructure and mechanical properties. Above the β transus temperature, Ti–6Al–4V has a single phase of β (bcc), and below it, two phases of α (hcp) and β are present [2, 3]. Cooling from single phase of β, produces the lamellar microstructure that might be unsuitable in some applications; so the process of forming should be designed in a way to prevent the material temperature exceeding the β transus temperature. Flow stress of Ti–6Al–4V is very sensitive to temperature and strain rate change [4] and with the presence of die-chilling in non-isothermal processes causes some operational difficulties.

Extrusion is a basic manufacturing process that is used to fabricate the parts with constant cross section. In the extrusion of Ti alloys, glass is applied to the workpiece as a lubricant that also acts as a thermal insulation to reduce the effect of die-chilling. The results of a few studies about the non-isothermal forward extrusion of Ti–6Al–4V are published. Udagawa et al. investigated the effect of process parameters upon Ti–6Al–4V tubes quality during extrusion numerically [5]. Srinivasan and Venugopal studied the warm open-die extrusion of Ti-64. Open-die was used to reduce the workpiece-die contact and reduce the process force [6]. Investigations of Zhang et al.
showed that non-isothermal backward extrusion of Ti-15-3 alloy was not successful and instead of it, isothermal backward extrusion was used [7]. Li et al. studied extrusion of Ti–6Al–4V numerically and experimentally. They concluded that the heat generated in Ti alloy extrusion is significant [8]. Bergamini et al. studied the extrusion of T- and U-shape cross section Ti-64 extrudates. Their conclusion is that the temperature of hot plastic deformation should be slightly higher than the β transus [9]. Considering extrudate distortion after hot extrusion of titanium billets, Damodaran and Shivpuri have performed a sensitivity analysis of the effect of process parameters on the distortion of Ti–6Al–4V billet in hot asymmetric extrusion [10]. Shin et al. studied the non-isothermal backward extrusion of Ti–6Al–4V and optimized the process to prevent the defect formation [11]. Considerable refinement of the microstructure is the result of extrusion of Ti–6Al–4V in the range 600–700 °C with a lamellar microstructure that is reported by Zherebtsov et al. [12].

Surveying the published literature reveals that the number of publications concerned with extrusion of Ti–6Al–4V is limited. There is not any thorough study of the effect of process parameters on the extrusion force and adiabatic temperature rise and interaction of process parameters. In this paper, the effect and significance of process parameters and die geometry on the extrusion force and adiabatic temperature rise is presented. For this purpose, a 2D axisymmetric FEM model of forward extrusion is developed and validated by experimental work. Then this model is used to simulate the non-isothermal forward extrusion of Ti–6Al–4V with various parameters. The investigated parameters include two groups, i.e., process parameters (ram velocity, die, billet and punch temperature) and die geometry parameters (die semi-angle (α), entrance and exit fillet radius). Effect of each parameter on the extrusion force and adiabatic temperature rise is analyzed and discussed.

2 Modeling and simulations

2.1 FEM model development

A coupled thermomechanical modeling based on the rigid-viscoplastic finite element method (FEM) is developed to simulate the extrusion process with different design parameters. Some of these parameters are related to die, i.e., die angle, entrance and exit fillet radius of the die zone and others are related to process, i.e., die, punch, and workpiece temperature and the ram velocity. Die-related parameters are depicted in Fig. 1.

A commercially available FEM package is utilized to perform the simulations. Because of axisymmetric geometry of the workpiece, 2D axisymmetric modeling is used. Simplification of 3D model to 2D axisymmetric is shown in Fig. 2.

The flow stress of material is determined as a function of strain rate, temperature, and strain by isothermal hot compression tests. The flow data are corrected for the effect of friction and adiabatic temperature rise and are implemented in the simulations. Variation of true stress as a function of true strain, strain rate, and temperature is presented in Fig. 3.

Fig. 1  Die parameters

Heat transfer coefficient at tool/workpiece interface as a function of contact pressure [13], friction factor as a function of temperature [14], and material properties are extracted from the literature [15, 16] and presented in Table 1. The geometry of workpiece, die and punch are modeled in a CAD package and imported to the FEM software via the standard format...