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Investigation of Mechanical and Microstructural Properties of Ti-6Al-4V Alloy Depending on Hot Forging Process Parameters

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Abstract

Ti-6Al-4V is widely used alloy in advanced industrial applications such as bio-compatible implant manufacturing, aerospace and power generation systems. Lower density and superior mechanical properties, like high strength, corrosion and fatigue resistance at elevated temperatures, enables manufacturing of lighter components. Due to the high cost of the raw material forging of Titanium is becoming more desirable rather than machining with excessive chip scrap. This article presents a numerical modelling of Ti-6Al-4V forging process and investigates the effect of the process parameters on mechanical and microstructural properties of alloy. The simulation of the forging process is vital, because Ti-6Al-4V has a temperature dependent dual structure and phase transformation affects thermo-mechanical properties of the alloy. The influence of the heat treatment process on forged parts is experimentally analysed by mechanical and microstructural analyses.

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Keywords: Hot forging; Heat treatment; Process modelling; FEM modelling; Titanium; Ti-6Al-4V; Ti64;

1. Introduction

During the last decade Titanium became a commonly used engineering material employed in biomedical systems, implants, aerospace and automotive industries. Components used in these industries generally demand extreme functionality and reliability. Therefore, detailed investigation, control and repeatability of the manufacturing processes is vital. To fulfil demanded process stability modelling and understanding influence of the parameters is important. Beside relatively low density and superior mechanical properties, the ability of adaptation of material properties to specific applications is what makes Titanium alloys preferable for various applications. Different stabilizer elements like Vanadium and Aluminum are added to Titanium for different metallurgical reasons [1-2]. Depending on crystalline structure Titanium alloys can be classified in three groups: α type having a hexagonal packed structure, β type having a body-centred cubic structure and α-β type having a mixed structure.

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The most commonly used Titanium alloy is Ti-6Al-4V, which has an α-β type structure [3]. The presence of mixed structure means that mechanical properties and microstructures can be achieved by variation of forging temperature and heat treatment process. The machining of Titanium was thoroughly investigated [4,5], but there is a few research done in hot forging field. Due to the high cost of the raw material and mechanical properties advantage forging of Titanium is becoming more desirable rather than machining with excessive chip scrap. On the other hand, Ti-6Al-4V alloy is known for poor formability due to narrow forging temperature range, temperature and strain rate dependent Yield stress, which requires careful selection of the process parameters. Literature presents two different approaches (a) α-β forging, where forging temperature is below the β-transus and (b) β forging, where forging temperature is above the β-transus [6, 7]. Presented study evaluates the effect of both α-β and β forging on microstructure and mechanical properties of alloy. Another reason limiting formability of Titanium alloys is high affiliation to oxidation and forging defects. Therefore, it is essential to control the process parameters to avoid formation of shearing bands, internal and surface cracks, folds and anisotropy [8].

Several groups of researchers have been working on forging modelling and heat treatment investigations of Ti-6Al-4V. Kukuryk [9] presented a finite element model, which predicts a deformation parameters during the forging. The focus of the research was on determining of optimal parameters for hot forging process. Bruschi et al.[10] developed a numerical model of turbine blade forging and investigated phase transformation effect on process mechanics. Also, the relationships between mechanical properties and microstructural features of titanium alloys have been investigated by Kim et al. [11] and Hu et al. [12]. From conducted research it is clear that formed microstructure is dependent on process history and heat treatment applied. Microstructure in its turn has high influence on the material flow stress. In this case, correctly built numerical simulation shows material flow behaviour and estimates process parameters like internal temperature distribution and strain-stress distribution.

This paper presents numerical modelling of the forging process and forging experiment of Ti-6Al-4V connecting rod used in automotive industry. The effect of the forging temperature and heat treatment is deeply investigated. The increase of the temperature generated by the deformation is analysed and different heat treatment processes are introduced to investigate changes in microstructure and mechanical properties.

2. Materials and methods

2.1. Modelling of hot forging process

The material used for simulations and experimental validations is the most commonly used α-β Titanium alloy – Ti-6Al-4V. The chemical analysis of the alloy is reported in Table 1 and flow stress curves used for simulation by Forge NxT finite element modelling software are presented in Figure 1.

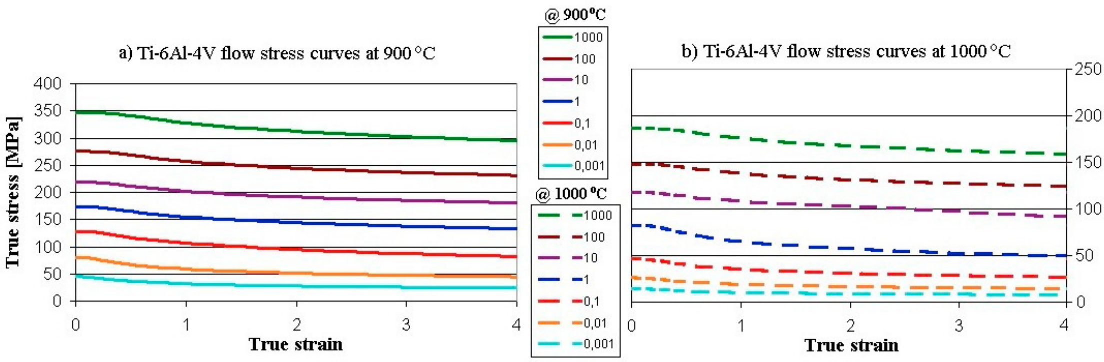

Fig. 1. Ti–6Al–4V flow stress curves at a) 900ºC, b)1000ºC at different strain rate values [13]

Table 1. Chemical composition of Ti-6Al-4V

	Elements									
	Ti	Al	V	Fe	C	O_2	N_2	H_2	Rest each	Rest total
Weight % (Max)	balance	6.16	4.09	0.127	0.0155	0.158	0.0135	0.0007	≤0.1	≤0.4
Weight % (Min)	balance	6.12	4.03	0.115	0.0152	0.155	0.0090	0.0005	≤0.1	≤0.4

The numerical model has ability to perform coupled thermo-mechanical analysis of hot forging process, using a large library of Ti-6Al-4V stress curves defined at various temperatures and strain rates, which are key physical data to perform precise analysis. Beside flow stress curves simulation requires temperature dependent Elasticity modulus $E(T)$, Poisson's ratio $\upsilon(T)$, Density $\rho(T)$, thermal conductivity $k(T)$ and specific heat coefficient $c_p(T)$. FEM software uses an interpolation to select corresponding values from the database and substitute them into visco-plastic flow law according to the "Hansel-Spittel" model [14] to calculate stress and strain generated in the workpiece. The "Hansel-Spittel" law applies to visco-plastic behaviour. The model enables a universal flow stress prediction in the whole range of strains. It is temperature-dependent and takes strain hardening or softening phenomena into account.

3. Experimental set-up and validation

The above described model was used to simulate the forging process on hammer press. Process parameters and geometries were properly set in order to reproduce the experimental methods. In the presented model thermo-mechanical behaviour of a Ti-6Al-4V alloy was investigated during hot forging at 920 ºC and 1020 ºC temperatures which correspond to α-β forging and β forging processes. Later, the effect of the heat treatment operation on microstructure and mechanical properties of the alloy was studied. Experiments were performed in broad range heat treatment conditions. The heat treatment conditions were selected in order to study the influence of the beta transformation on the final microstructure and determine effect of the process parameters on mechanical properties of the forged product. After heat treatment microstructure, Yield strength ($R_{p0.2}$), ultimate tensile strength (R_m) and percentage of total extension at fracture ($A5_m$) of the forged specimens were evaluated, by means of optical microscope and tensile testing. The results obtained showed that the heat treatment conditions have a great influence on the final microstructure and mechanical properties. A hammer press with 110 kJ maximum energy and 4500 kg drop weight was utilized for the experiments. Upsetting and two step forging was performed to form the final shape. Lubrication was performed by water based graphite lubricant. An FEM simulation of each process step was performed in order to prevent forging faults like incorrect material flow, flap and underfill. Another important issue analysed in simulations is temperature distribution. Forging operation introduces a temperature increase inside the workpiece due to deformation. As it is seen in the simulation for forging operation performed at 920ºC, temperature at some regions of the part exceed β-transus, 995ºC, which means that microstructural integrity of the part is has changed. The detailed temperature analysis was performed for each step and temperature simulation results are presented in Figure 2.

Table 2. Forging and heat treatment parameters

Case 1	920 ºC (α-β forging)	As forged
Case 2	1020 ºC (β forging)	As forged
Case 3	920 ºC (α-β forging)	1 h. furnace heating at 927ºC → water quenching → 3 h. furnace aging at 537ºC
Case 4	1020 ºC (β forging)	1 h. furnace heating at 927ºC → water quenching → 3 h. furnace aging at 537ºC
Case 5	920 ºC (α-β forging)	1 h. furnace heating at 927ºC → furnace cooling to 720ºC → water quenching
Case 6	1020 ºC (β forging)	1 h. furnace heating at 927ºC → furnace cooling to 720ºC → water quenching
Case 7	920 ºC (α-β forging)	3 h. furnace heating at 927ºC → water quenching → 24 h. furnace aging at 480ºC
Case 8	1020 ºC (β forging)	3 h. furnace heating at 927ºC → water quenching → 24 h. furnace aging at 480ºC

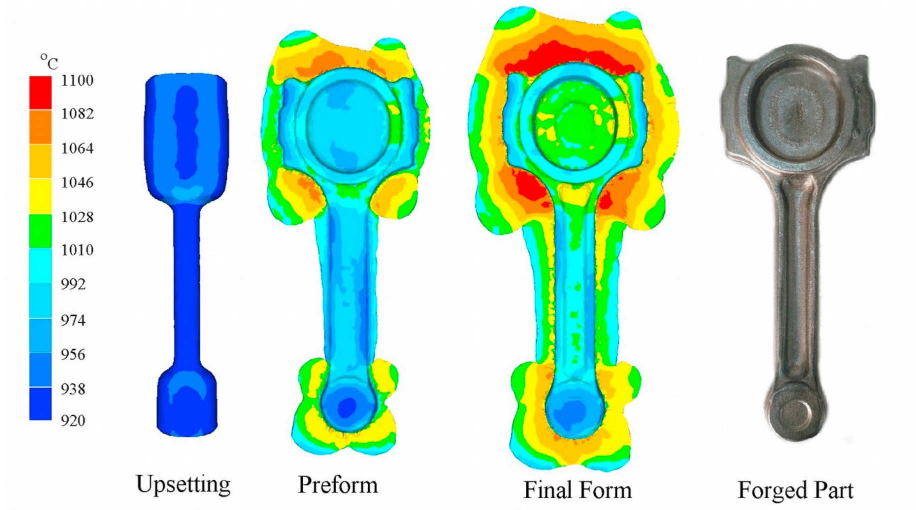

Fig. 2. The temperature results of the connecting rod forging operations at 920°C and final forged geometry

To provide microstructural integrity though the part heat treatment should be applied. This study investigated heat treatment operations applied to the forged part and their effect on microstructure and mechanical properties. Forged parts were cooled in steel air and heat treatment operations shown in Table 2 were applied to investigate effect of the parameters on microstructure and mechanical properties. The microstructure characterisations were performed via optical micrographic images from cross sections of the forged parts. A fine grinding, polishing with 0.3 µm alumina solution and etching with 100 ml H_2O + 3 ml HF + 6 ml HNO_3 solution for 10 s were applied to specimens. The micrographic images and mechanical testing results are presented in Figure 3 and Figure 4, respectively. The mechanical test were performed in laboratory environment under controlled circumstances and the measurement uncertainty is %2 for R_{p02} and %1.5 for R_m at maximum.

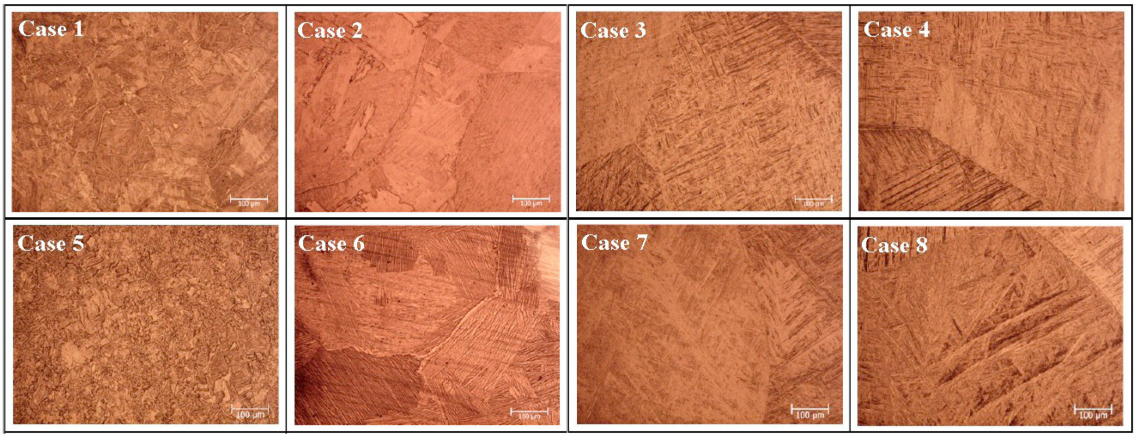

Fig. 3. The micrographic images

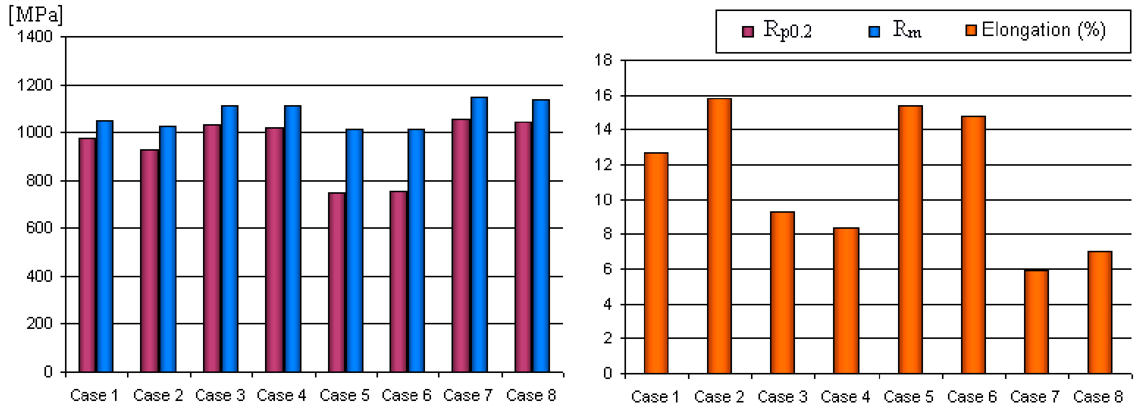

Fig. 4. The mechanical testing results

Conducted experiments showed that forging temperature and heat treatment affects both mechanical properties and microstructure. From Case 1 and Case 2 it is seen that forging above β-transus temperature increases grain size, which result in increase of elongation. Case 1 has an acicular α grains in transformed β matrix that contains small amount of bimodal α grains. Case 2 contains acicular α grains in transformed β matrix. Case 3, Case 4, Case 7 and Case 8 contain martensitic structure, effect of the forging temperature is not seen, martensitic structure increased the Yield and Tensile strength and decreased elongation. Case 5 presents α-β matrix structure with high elongation and highly decreased Yield strength. Microstructure of Case 6 shows acicular α phase in transformed β matrix, with precipitated thin α phase on grain boundaries. From microstructure evaluation it can be conducted that mostly the effect of forging temperature 920ºC and 1020ºC degrees is eliminated by heating of the samples to 927ºC during the heat treatment operations. Especially this phenomena is clearly seen in quenched samples.

The determination of proper heat treatment operation highly depend on application field. From experiments it is seen that for applications which require high strength water quenching and ageing can be considered, but for applications which require toughness and high elongation martensitic microstructure should be avoided. The ageing at high temperature (537ºC) is more efficient than, ageing at low (438ºC) temperature. The effect of the long ageing at 438ºC is neglectable.

4. Conclusion

This paper presents an investigation of mechanical and microstructural properties of Ti-6Al-4V alloy depending on hot forging process parameters. The effect of forging temperature and finite element modelling of the forging process were studied, in order to control microstructural transformations depending on deformation initiated internal temperature generation. Based on performed work following conclusions can be done:

1) Performed finite element simulation estimated temperature higher than β transus, which expected to result in microstructural transformation. The microstructural integrity of the part is essential criteria especially in aerospace industry. Therefore, heat treatment operation should be applied to the part.

2) The results of the heat treatment experiments showed that for applications which require high strength water quenching and ageing combination can be considered, but for applications which require toughness and high elongation martensitic microstructure should be avoided.

3) Further investigation on co-relation of the microstructure variation inside the part due to the temperature increase during forging and simulation will be conducted.

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