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Feasibility study of a novel hot stamping process for Ti6Al4V alloy

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Abstract. To investigate the feasibility of a novel hot stamping process for the Ti6Al4V titanium alloy using low temperature forming tools, mechanical properties of the material were studied using hot tensile tests at a temperature range of 600 - 900°C with a constant strain rate of $1s^{-1}$. Hot stamping tests were carried out to verify the feasibility of this technology and identify the forming window for the material. Results show that when the deformation temperature was lower than 700°C, the amount of elongation was less than 20%, and it also had little change with the temperature. However, when the temperature was higher than 700°C, a good ductility of the material can be achieved. During the forming tests, parts failed at lower temperatures (600°C) due to the limited formability and also failed at higher temperatures (950°C) due to the phase transformation. The post-form hardness firstly decreased with the temperature increasing due to recovery and then increased due to the phase transformation. Qualified parts were formed successfully between temperatures of 750 - 850°C, which indicates that this new technology has a great potential in forming titanium alloys sheet components.

Key words: titanium, hot stamping, metal forming

1 Introduction

In order to meet fuel consumption targets for the aviation sector, increasing demands for low density and high strength materials were observed. Due to applications of such lightweight materials in aircraft vehicles, a considerable weight reduction could be achieved [1]. Therefore, titanium alloys are found in aircraft applications because of the combination of weight, strength, corrosion resistance and temperature stability [2]. However, titanium alloys are considered as difficult-to-form materials thus the forming of complex-shaped components is time, energy and cost intensive. Only a few conventional techniques could enable aircraft companies to produce qualified complex-shaped components. Superplastic forming is definitely one of the leading titanium forming techniques. Other known techniques including superplastic forming with diffusion bonding, hot stretch forming, creep forming, hot gas-pressure forming or isothermal hot forming [2]. It is unquestionable that components formed by these techniques have a high quality, however these components are achieved under conditions of a very high temperature, slow strain rate and simultaneous heating of tools and sheet during the process. As a result, the low efficiency of the forming process and simultaneous high production cost are observed. Recent development of forming technologies such as the solution heat treatment, forming and in-die quenching (HFQ) [3], the Quick-plastic forming [4], and the hot stamping using rapid heating [5] could lead to the increase of productivity and become an alternative to conventionally used techniques. Hamedon et al. [6] proposed a hot stamping process to form titanium components from sheet metal utilizing cold dies and resistance heating. This solution led to the reduction of the tool wear and is more efficient and economical in comparison to conventionally used isothermal hot forming techniques. However, this technology was validated by forming a simple U-shaped component under resistance heating condition.

In order to further study the feasibility of hot stamping process for titanium alloys under furnace heating condition, the hot stamping tests of Ti6Al4V titanium alloy utilizing low temperature forming tools (used at

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room temperature) and a hot blank was carried out. To investigate the formability of Ti6Al4V alloy, the uniaxial tensile tests were performed at temperatures ranging from 600°C to 900°C with constant strain rate of 1 s^{-1}. Ti6Al4V components were successfully formed at temperatures ranging from of 750°C to 850°C. Microstructure of formed components was characterized by Scanning Electron Microscope (SEM).

It was found that this new technology has a great potential in forming titanium alloys sheet components and a qualified part could be formed successfully. Proposed hot stamping process to form components from sheet metal using cold dies, promises to be a more efficient and economical process than the traditionally used isothermal hot forming techniques [6]. Moreover the post-form mechanical properties and microstructure can be tailored by the adjustment of heating temperature and application of low temperature forming.

2 Experimental details

2.1 Uniaxial tensile test and microstructure examination

Ti6Al4V titanium alloy sheet with initial thickness of 1.5 mm is used throughout the research. A Gleeble 3800 thermo-mechanical testing machine was used to characterize the properties of material through uniaxial tensile test at elevated temperatures. Dog-bone shaped specimens with a gauge length of 46 mm, a width of 12 mm and a thickness of 1.5 mm were used. During the tests, flat samples were heated up with the heating rate of 2°C/s to the testing temperatures ranging from 600°C to 900°C and deformed. After tensile tests, samples were air quenched immediately. Hardness of the samples after hot forming tests was measured using Vickers hardness tester. Hardness tests were carried out at room temperature by applying 10kgf load on indenter for 10 seconds. Microstructures were examined via scanning electron microscopy (SEM) using backscattered electron (BSE) mode. Metallographic specimens were prepared by standard mechanical polishing method.

2.2 Hot forming test

The forming tests on the titanium alloy were conducted using a 250 tonne Instron press (Fig.1). Rectangular samples of Ti6Al4V with dimension of 90 x 8 x 1.5 mm were first heated in the furnace to the target temperatures ranging from 600°C to 950°C.Temperature of the samples was monitored using a thermocouple wire attached to them. After reaching the target temperature, the sample was quickly placed in the tool for 10 seconds, which was stamped at a speed of 10 mm/s when the press was activated. The formed part was held in the low temperature die after forming to quench it to room temperature.

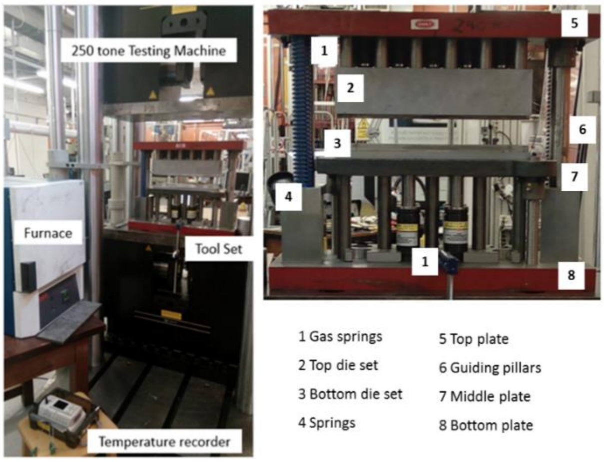


Fig. 1. Testing setup.

3 Results & discussion

3.1 Effect of heating temperature and strain rate on mechanical properties of Ti6Al4V alloy

In order to determine the best forming condition, tensile tests were conducted at temperatures ranging from 600°C to 900°C with a constant strain rate of $1s^{-1}$ (Fig.2). Simultaneous increase of elongation with the temperature was observed. Strain hardening could be found during deformation at temperatures ranging from 600°C to 700°C, but only slight change in elongation was found. However, over the temperature of 700°C, material softening and subsequent increase of elongation from 20% to 60% at 900°C were observed (Fig.3). High temperatures enhance dislocation mobility resulting in ductility increase during deformation. It was concluded that the investigated titanium alloy has a good formability over the temperature of 700°C.

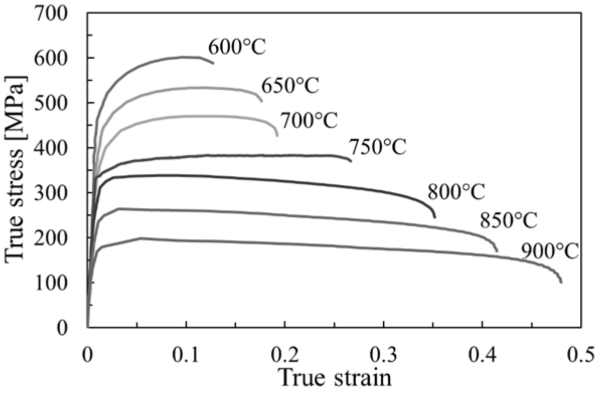


Fig. 2. Representative flow stress - strain curves of Ti6Al4V titanium samples tested under the range of 600 - 900°C.

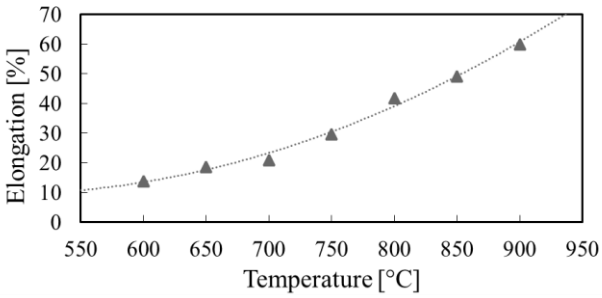


Fig. 3. Variations of elongation of Ti6Al4V titanium alloy with heating temperature obtained by tensile test.

Satisfactory elongation of investigated material (>30%) was observed during testing at temperatures ranging from 750°C to 900°C. In order to investigate the effect of strain rate on material property, tensile tests were carried out at temperatures of 750°C - 850°C, strain rates of 0.1s^{-1} - 5s^{-1} and the same heating rate of 2°C/s. Evolution of elongation with the different strain rates was presented in Fig.4. It could be observed that the elongation increased with the increasing temperature from 0.2 - 0.35 at 750°C to 0.5 - 0.6 at 850°C and decreasing strain rate from 0.2 at strain rate of 5s^{-1} to 0.35 at strain rate of 0.1s^{-1} (at testing temperature of 750°C). The same tendency is observed for temperatures of 800°C and 850°C.

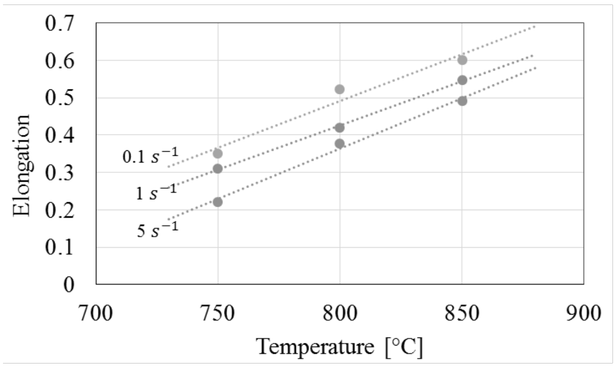
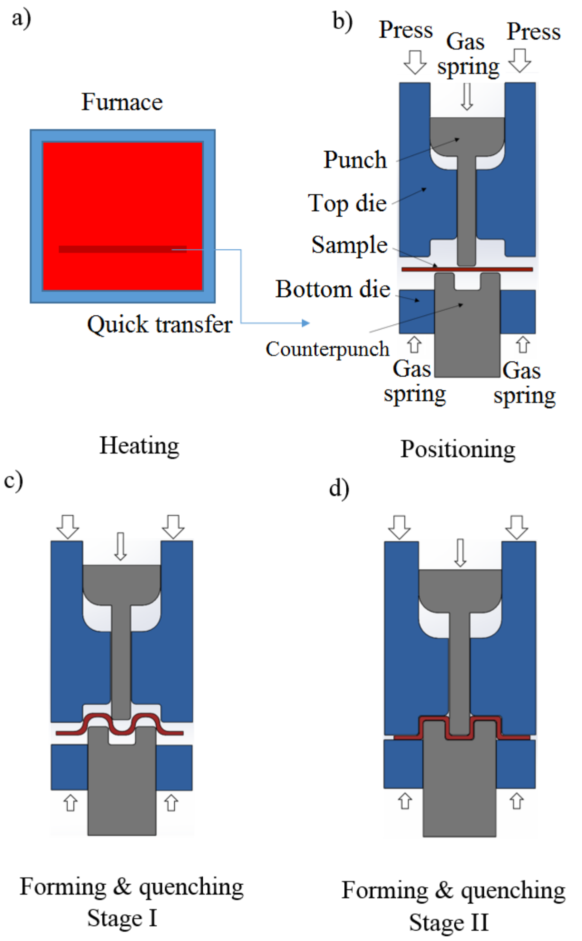


Fig. 4. Elongation evolution of Ti6Al4V titanium samples tested under different strain rates at temperatures ranging from 750 - 850°C.

3.2 Hot forming of Ti6Al4V

During the hot stamping of titanium alloys, three main stages may be distinguished: heating, transferring, and forming and quenching (Fig.5*)*. The effective control of temperature at each stage is required since the temperature affects not only the formability of the material during deformation but also the post-form properties of the formed component. In order to monitor the temperature evolution during the whole process, a thermocouple wire was attached to the specimen. At the first stage, titanium sample was heated to the targeted temperature and then soaked within 180 s, until the temperature became stable. Then, titanium sample was placed in the tool, stamped by low temperature dies and quenched to room temperature within tool.



Heating

Positioning

Forming & quenching Stage I

Forming & quenching Stage II

Fig. 5. Schema of the forming process during heating of the sample (a), at the positioning stage (b), during forming (c) and at the final stage (d).

Ti6Al4V components formed at temperatures ranging from 600°C to 950°C on hydraulic press utilizing low temperature forming tools are shown in Fig.6a-e. However, parts were successfully formed only in the temperature range of 750°C to 850°C. Macroscopic observations reveal that sample formed at 600°C has cracks on the surface. The occurrence of cracks is probably caused by the limited ductility of the material (Fig.7a). Evident cracks were also observed in feature formed at 900°C as shown in Fig.7*b*. As the heating temperature reached 950°C, the forming also failed resulting in the fracture of the sample into pieces (Fig.6e). It was found that during the uniaxial tensile test, elongation increased with the temperature increasing. However, the uniaxial tensile tests were performed at isothermal conditions. During actual forming, there is a considerable drop of temperature during the transferring and the forming. Because the microstructure and mechanical properties of material are strongly temperature dependent, such a drop of temperature led to decrease of formability.

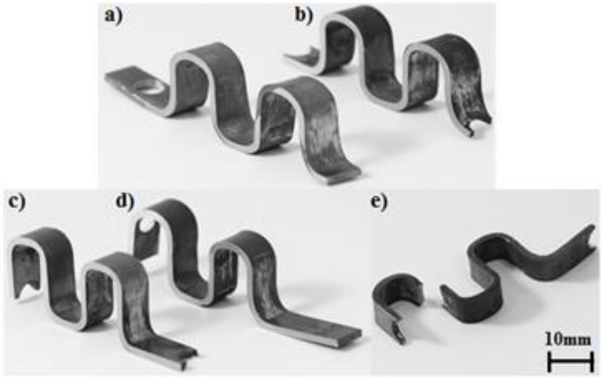


Fig. 6. View of parts formed at 600°C (a), 750°C (b), 850°C (c), 900°C (d), and 950°C (e).

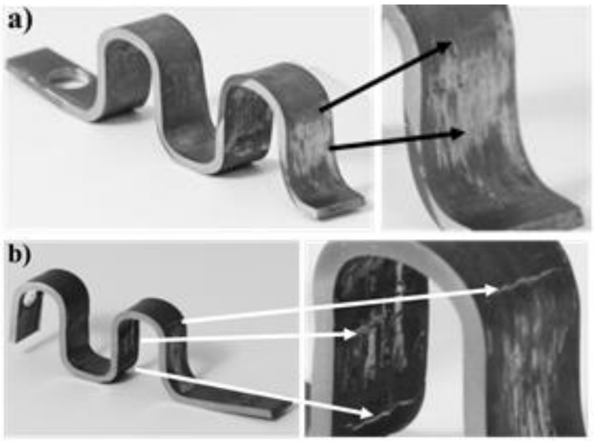


Fig. 7. View of cracks of parts formed at 600°C (a) and 900°C (b).

3.4 Effect of hot stamping conditions on post-form properties of the formed components

In order to investigate the effect of heating temperature on the post-form hardness and microstructure of the as-formed part, hardness tests and SEM observations were conducted on shaped components. Hardness measurements were performed in the longitudinal direction of formed parts as it shown in Fig.8. For each part, 20 indentations were used for calculation of an average hardness value. It could be observed that the hardness values firstly decreased from 356HV10 to 341HV10 at 750°C, and then increased to 392HV10 at 950°C (Fig.8). It was concluded that during forming at temperatures up to 950°C, phase transformation occurred and the content of β-phase increased significantly as shown in Fig.9. As the sample was cooled within low temperature dies, transformed beta phase and secondary α‘ phase formed, which improved the hardness of the material at the room temperature (Fig.8). The fraction of transformed beta and α‘ phase increased with the temperature (Fig.9c), resulting in the simultaneous hardness increase [7, 8]. The increasing fraction of transformed beta and α‘ phase formed during the forming process may also decrease the formability of the material, which resulted in the forming failure at temperatures ranging from 900 to 950°C [9].

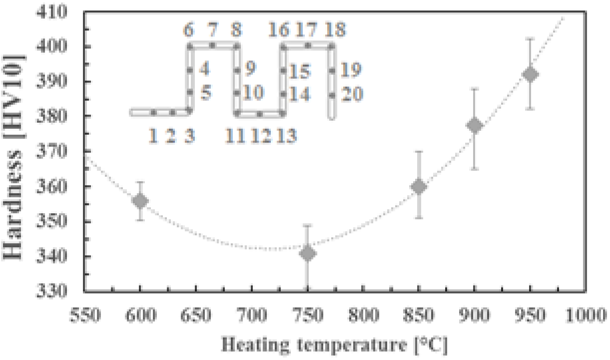


Fig. 8. Effect of heating temperature on post-form strength of formed components.

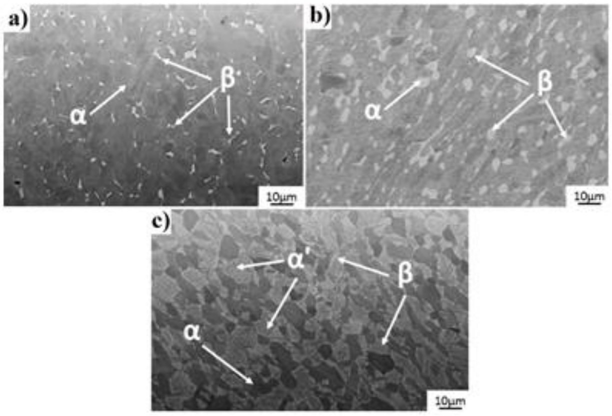


Fig. 9. Microstructures of the Ti6Al4V alloy formed at 600°C (a), 850°C (b), and 950°C (c).

4 Conclusions

In this paper, an innovative forming technology to shape Ti6Al4V titanium alloy utilizing low temperature forming tools and a hot blank was studied through uniaxial tensile test and hot stamping process. The uniaxial tensile properties of Ti6Al4V alloy at temperatures from 600°C to 900°C with the strain rate of $1s^{-1}$ have been obtained. The results of tensile tests showed that the investigated material has a good formability over the testing temperature of 700°C. It was observed that during deformation at temperatures from 600°C to 700°C, work hardening occurred. As the temperature increase to 750°C, the hardening rate decreased and the flow stress curve became flat due to recovery. With the temperature increase to 900°C, an obvious material softening during the tensile test occurred. Ti6Al4Vcomponents were successfully formed at temperatures ranging from 750°C to 850°C. The hardness of formed parts firstly decreased from 357HV10 at 600°C to 341HV10 at 750°C due to recovery and then increased to 392HV10 at 950°C as a result of phase transformation. It was found that through the adjustment of the heating temperature, the post-form mechanical properties can be tailored, which indicates that this new technology has a great potential in forming titanium alloys sheet components.

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