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Investigation of the Feasibility of a Novel Heat Stamping Process for Producing Complex-shaped Ti-6Al-4V Panel Components

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Abstract

A novel cost-efficient Heat Stamping (HS) process, combining Heat treatment and fast Stamping, was proposed to produce complex-shaped titanium alloy panel components with low energy consumption and short cycle time. To investigate the feasibility of the HS process for forming Ti-6Al-4V, the stress-strain behaviours of the material under step quenching treatments in HS processes were investigated and compared with those under direct heating treatments in Hot Forming (HF) processes, through uniaxial tensile tests at the temperature range of 800 - 950 ℃ and the strain rate range of 0.01 - 5 /s. To reduce the strain softening, step quenching treatment was designed by soaking the specimen at 950 ℃ and fast quenching it to 800 ℃ for forming. It was found that strain softening in the step quenching tests was reduced as compared to direct heating tests at the strain rate of 1 /s; strain hardening was observed in step quenching test at the strain rate of 0.1 /s, achieved by enhancing the dynamic phase transformation from β phase to secondary α (α_s) during deformation. Strain rate hardening of the material under step quenching treatment was found to be higher than those under direct heating treatment at the same temperature of 800 ℃. To evaluate the novel HS concept, Heat Stamping experiments under step quenching treatments were carried out by using a drawability tool set. A cup-shaped demonstrator with the drawing ratio of 1.3 was produced to prove the feasibility of HS process.

Keywords: Heat stamping; Ti-6Al-4V; Step quenching; Strain softening; Strain rate hardening.

1. Introduction

Titanium alloys have been widely used for aerospace, automotive and biomedical applications due to their high strength to weight ratio, high temperature resistance and excellent corrosion resistance. With regard to their supreme properties, aerospace has been the major field of applications for weight reduction and fuel efficiency improvement [1]. The much higher payoff ratio resulted by weight reduction encourages aerospace industry to adopt more complex-shaped titanium alloy products [2]. The currently used manufacturing methods for producing complex-shaped titanium alloy panels include Superplastic Forming (SPF) [3] and Hot Forming (HF) [4], etc. However, these forming methods are time, energy, and cost intensive.

Panels manufactured using SPF are considerably expensive [5] as SPF requires preheating dies (for up to 24 hours) to a high temperature (above 900 ℃ for Ti-6Al-4V) and very slow forming speed (normally in strain rate range of 10^{-4} - 10^{-2} $/s$ for Ti-6Al-4V) [6], resulting in prohibitively long production cycle, huge energy consumption, and very high tool cost.

The HF process, normally conducted at an intermediate temperature range (750 - 890 ℃ for Ti-6Al-4V) [7], can be classified into isothermal and non-isothermal processes based on the forming tool temperatures. Conventional isothermal HF process requires creep-forming rate [8] and heating of both the panel and forming tool to the forming temperature [9]. Although the cycle time is reduced, the tool cost remains high due to excessive tool wear at a high forming temperature.

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To reduce energy consumption and forming tool cost, efforts have been made on developing non-isothermal HF process using a lower-temperature tool [10][11]. The forming speeds in non-isothermal HF processes are commonly set to be high to avoid excessive temperature drop of the panel during forming due to heat loss to the tool. However, there are drawbacks for fast stamping of titanium alloys at high temperatures. The predominant problem is strain softening of the material under high deformation rates [12]. Material with low hardening properties under deformation could have poor drawability [13]. Therefore, dedicated efforts are needed to minimise the strain softening and enhance the strain rate hardening of Ti-6Al-4V during fast stamping processes.

Hot stamping is a successful forming process which has been traditionally used for forming ultra-high strength steels [13] and recently used for forming high strength aluminum alloys for complex-shaped panels [14]. Relevant studies have rarely been done on titanium alloys. This is because, compared with steels and aluminum alloys, the microstructures and thermo-mechanical properties of titanium alloys are much more sensitive to processing conditions and the forming windows could be much narrower. Therefore, special attention needs to be paid to find out an effective heat treatment and forming strategy that can provide feasible work windows to allow successful forming of titanium alloy sheets into complex shapes.

A new hybrid forming method combining Heat treatment and fast Stamping, named Heat Stamping (HS), was invented by Li's group [15]. The idea was to decouple the heat treatment temperature and start forming temperature, in order to achieve a more favourable microstructure for deformation. To further develop the HS process, metallurgical and thermo-mechanical responses, as well as their interactions, of titanium alloys under HS conditions need to be comprehensively studied. In this paper, Ti-6Al-4V was used to investigate the HS process as it is the most widely used titanium alloy due to its good balance of high temperature strength, creep resistance and fracture toughness [1].

To identify the feasible work window for HS of Ti-6Al-4V, the softening mechanisms and the effect of microstructure on thermomechanical properties of the material under HS conditions need to be understood. Commonly reported strain softening mechanisms of Ti-6Al-4V under hot deformation can be classified into recovery and recrystallization [16], globularization [16][17], phase transformation [18], adiabatic heating [16][19][20] and texture softening [20][21]. This study focused on enhancing dynamic phase transformation, from β phase to secondary α phase (α_s), through step quenching treatment in the HS process, to achieve reduced strain softening compared with the material under direct heating treatment which is usually adopted in a HF process.

2. Experimental Methods

2.1. Material and specimen design

The Ti-6Al-4V sheet material with a thickness of 1.6 mm was supplied by Doncaster Group Limited Company. The β transus temperature of the material was 995 ℃. The design of dog-bone shaped specimens for uniaxial tensile tests is shown in Fig. 1. All specimens were machined from the same batch of material through laser cutting and milling.

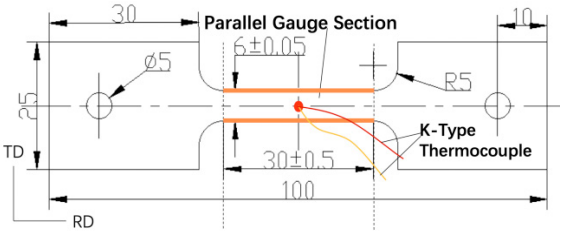

Fig. 1. Specimen geometry for uniaxial tensile tests (RD and TD represent rolling direction and transverse direction respectively). Unit: mm.

Hitachi 3400 Scanning Electron Microscope (SEM) operated under Backscattered Electron (BSE) mode and Bruker e-flash Electron Backscatter Diffraction (EBSD) were used to for microstructural analysis. The samples were cut from the dog-bone shaped specimens using ATA Brillant 220 cut off machine and were ground using P800, P1200, P2500, P4000 SiC papers. Subsequently, the samples were polished, using Metprep Chemicloth M with a mixed solution of colloidal silica solution and 30 % hydrogen peroxide, for 30 min. The volume fraction and grain size of primary α (α_p) phase were

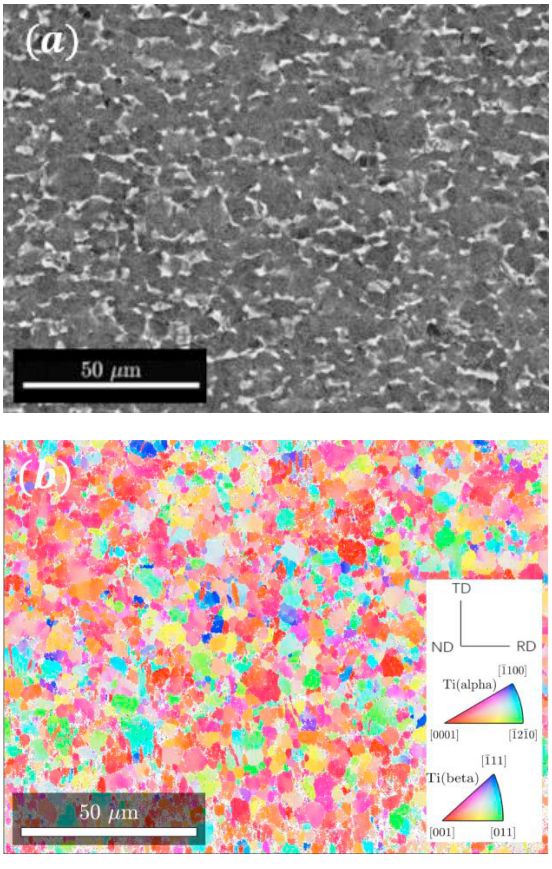

Fig. 2. Microstructure of as received Ti-6Al-4V material, obtained through: (a) SEM operated under BSE mode (the α phase is dark and β phase is bright in the image) (b) Inverse Pole Figure (IPF) from EBSD.

collected from SEM images and analysed using ImageJ software. The results were compared with EBSD results. As can be seen from Fig. 2, the initial microstructure of the as delivered material was equiaxed with an average primary α (α_p) grain diameter of 8 μm.

2.2. High temperature uniaxial tensile tests

High temperature uniaxial tensile testes were carried out on Gleeble 3800 thermo-mechanical testing machine. The temperature of specimens was controlled and monitored through a pair of K-Type thermocouples spot-welded at the surface centre of the parallel gauge section. The step quenching with designated cooling rate (50 ℃/s) was carried out by the combination of compressed air flow and resistance heating system. A C-gauge was used to measure the width changes at the middle of the parallel gauge section of the specimen, which was used to derive strain and actual strain rate using the method adopted by N. Li [22]. Tests under different conditions were conducted three times to ensure good repeatability. The errors of peak stress under each condition were within 2%, indicating good repeatability.

Two sets of high temperature uniaxial tensile tests were designed with different heat treatment routes which are named direct heating and step quenching, illustrated in Fig. 3, to simulate the processing conditions in Hot Forming (HF) and Heat Stamping (HS) processes using low temperature tools,

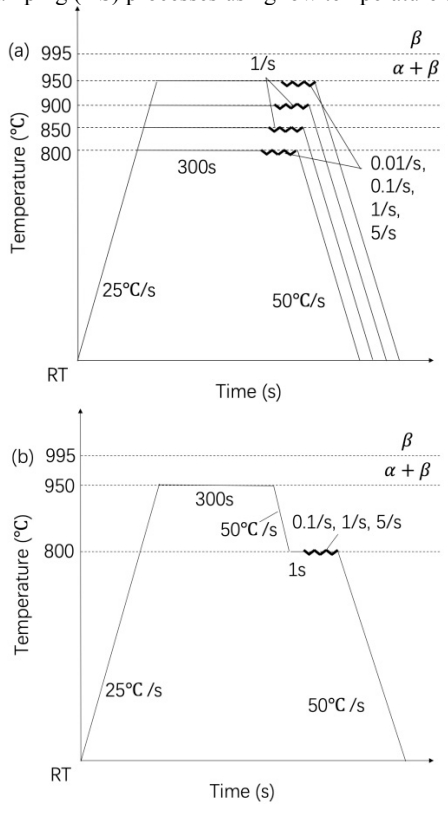

Fig. 3. Schematic illustration of temperature profiles and test conditions of uniaxial tensile tests under two different heat treatment routes: (a) direct heating; (b) step quenching.

respectively. The fractured specimens were fast quenched to room temperature for microstructural characterisation.

The effect of forming temperatures in HF was investigated by direct heating tests at temperatures of 800, 850, 900 and 950 ℃ and the strain rate of 1 /s. Strain rate sensitivity tests were conducted to investigate the strain rate hardening properties of the material under direct heating at temperatures of 800 ℃ and 950 ℃ and strain rates of 0.01, 0.1, 1, and 5 /s, as shown in Fig. 3 (a).

The step quenching tests were designed to evaluate the feasibility of the HS process as shown in Fig. 3(b). First, fast quenching (50 ℃/s) specimen from a higher soaking temperature of 950 ℃ to a lower forming temperature of 800 ℃, which is referred as step quenching test 950 ℃ ⟶ 800 ℃, was designed, in order to reduce strain softening. This was assumed to be realized by enabling a dynamic phase transformation from the softer β phase to a harder secondary α phase (α_s) to occur during material deformation. It was expected that the composition of primary α (α_p) phase and β phase was retained the same right after the step quenching. It means that the primary α (α_p) would keep the same (or very similar) volume fraction at it was at 950 ℃; the β phase was expected to be the same while have a high level of supersaturation. Given time, the supersaturated β phase would start to transform to harder α_s at 800 ℃, which could lead to reduction of strain softening during material deformation. Second, the strain rate sensitivity tests (0.1, 1, and 5 /s) were designed to study the strain rate hardening properties of the material under the step quenching 950 ℃ ⟶ 800 ℃ condition. An additional test, direct heating without deformation was carried out by directly quenching the specimen to room temperature right after soaking at 950 ℃ for 300s to set up a benchmark of volume fraction of primary α (α_p) prior to step quenching or deformation.

2.3. Heat Stamping (HS) experiments

Forming experiments, by using a drawability tool set as shown in Fig. 4, were conducted to test the feasibility of producing a Ti-6Al-4V component in a cup shape through a HS process combining step quenching heat treatment and fast stamping. The circular shaped panels with a diameter of 130 mm and thickness of 1.6 mm were laser cut from the same

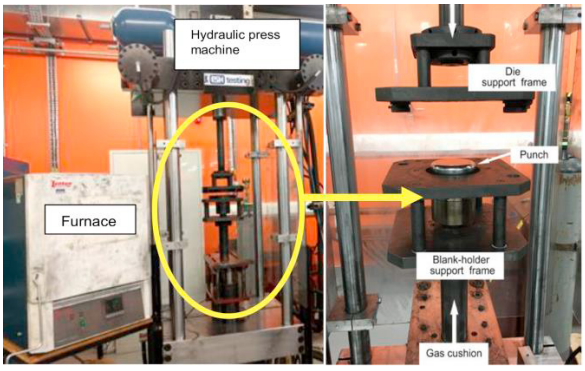

Fig. 4. Heat Stamping experimental setup: a 250KN hydraulic press machine with a drawability tool set installed and a furnace.

panel used for manufacturing dog-bone shaped uniaxial tensile test specimens. The panels were heated to 950 ℃ and soaked for 5 min in a furnace before transferring. The forced air-cooling of panels was carried out using fans before forming, to achieve step quenching to approx. 800 ℃ . K-Type thermocouples were spot-welded at the centre and the flange of a panel to measure the temperature profiles. The forming speed was set to be 200 mm/s.

3. Results and Discussion

3.1. Hot tensile behaviours of Ti-6Al-4V

Fig. 5 (a) shows that the deforming temperature has a great effect on the strain at fracture (ductility) in direct heating tests. It can be seen that the ductility increases with increasing temperature until 900 ℃. The decrease of ductility at 950 ℃ was consistent as reported and believed to be affected by severe oxidation and formation of micro-cracks on the specimen surfaces [12]. Strain softening was found to increase with increasing deforming temperature. Fig. 5 (b) and (c) show that the material is strongly strain rate sensitive. For each deforming temperature after direct heating treatment, the ductility of the material increased with decreasing strain rate

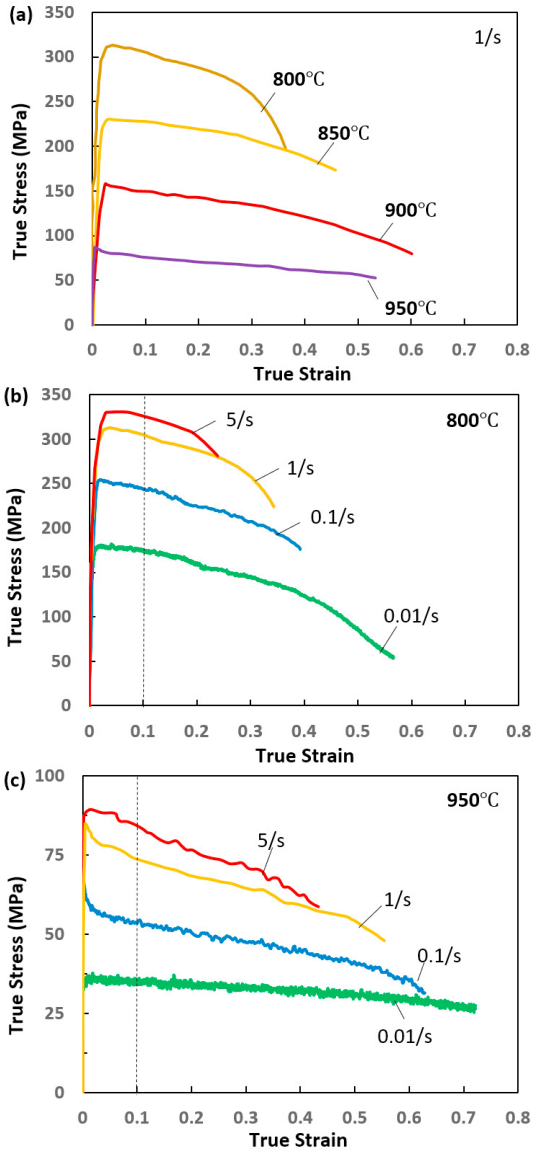

Fig. 5. Hot tensile true stress-strain curves of Ti-6Al-4V, after direct heating treatments, at different temperatures and strain rates: (a) 800 - 950 ℃ and 1/s; (b) 800 ℃ and 0.01 - 5 /s; (c) 950 ℃ and 0.01 - 5 /s.

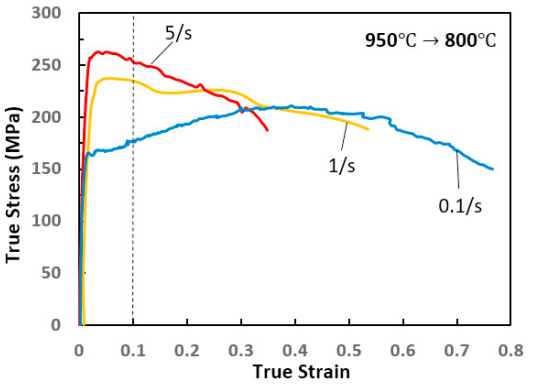

Fig. 6. Hot tensile true stress-strain curves of Ti-6Al-4V, after step quenching treatments from 950 ℃ to 800 ℃ (noted 950 ℃ → 800 ℃), at different strain rates.

Fig. 6 shows that the ductility of the material after step quenching treatment was improved as compared to direct heating test at the same deforming temperature of 800 ℃ for every tested strain rate. The true stress-strain curve at 0.1 /s exhibited a strain hardening stage up to a true strain of 0.4. The ductility of specimen tested under this condition was even higher than direct heating test at 950 ℃ and the same strain rate of 0.1 /s.

In order to better compare the strain softening properties in a quantitative manner, the commonly used strain hardening exponent n was adopted. The value of n at the start of softening for each true stress-strain curve, shown in Fig. 7, was calculated. All values are negative and a higher value means less strain softening. For example, in Fig. 7 (a), the curve with n = -0.013 represents the least strain softening.

For tests after direct heating, it can be seen from Fig. 7 (a) and (b) that, at the same temperature (800 or 950 ℃), specimens deformed at the strain rate of 5 /s had less strain softening than those tested at the strain rate of 1 /s; at the same strain rate (1 or 5 /s), the strain softening of specimens deformed at a lower temperature of 800 ℃ is less than those tested at a higher temperature of 950 ℃.

For tests after step quenching of 950 ℃ ⟶ 800 ℃, the material showed the least strain softening when deformed at the strain rate of 1 /s and the greatest strain softening when deformed at 5 /s, compared to the direct heating tests at 800 ℃ and 950 ℃ at the same strain rates (1 /s for Fig. 7 (a) and 5 /s for Fig. 7 (b)). The mechanisms behind the phenomena will be discussed in section 3.2.

In order to better compare the strain rate sensitivity in a quantitative manner, the commonly used strain rate hardening

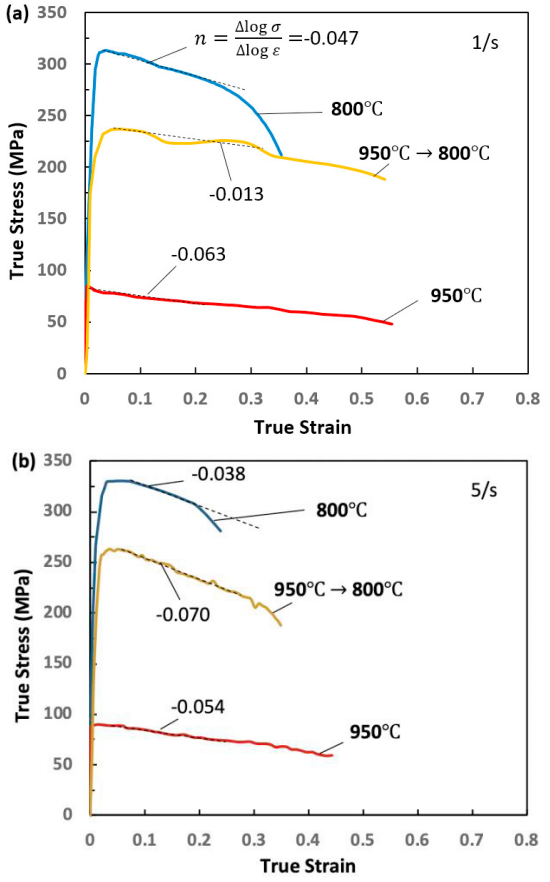

Fig. 7. Strain softening of Ti-6Al-4V, after different heating treatment routes, at the strain rates of (a) 1 /s; (b) 5 /s.

exponent m was adopted. Fig. 8 shows that the strain rate hardening properties in step quenching test were improved as compared to direct heating tests at 800 ℃. For example, the m value in the strain rate range 0.1 /s - 1 /s increased from 0.09 in direct heating tests to 0.12 in step quenching tests at temperature 800 ℃. The mechanisms of the strain rate hardening improvement will be discussed in section 3.2.

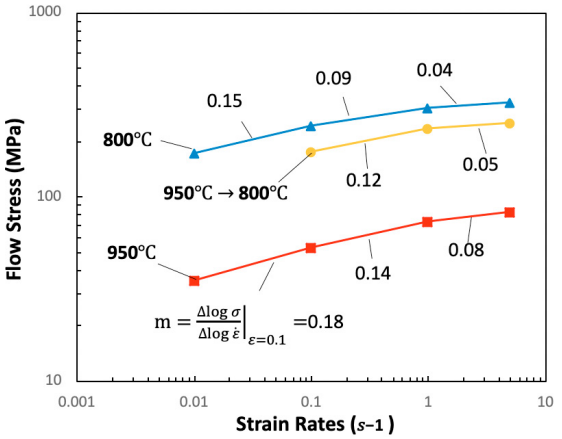

Fig. 8. Strain rate hardening of Ti-6Al-4V tested under different heat treatment routes and deforming conditions.

3.2. Microstructural evolution

Fig. 9 shows the microstructure of the material after step quenching and tensile tests, 950 ℃ ⟶ 800 ℃, at different strain rates. The microstructure of step quenching test at strain rate of 0.1/s as shown in Fig. 9 (a) has globularized α_s distributed in the metastable β phase. In contrast, the grain size of globularized α_s was smaller in high strain rate tests at 1 /s and 5 /s, as can be seen in Fig .9 (b) and (c) respectively. Martensite phase α' was also found in these two conditions.

The strain softening properties from step quenching tensile tests varied greatly with different strain rates. This was believed to be due to the different deforming mechanisms after the step quenching. In the test at 0.1 /s, the high supersaturation of β phase and the relative slow strain rate could introduce

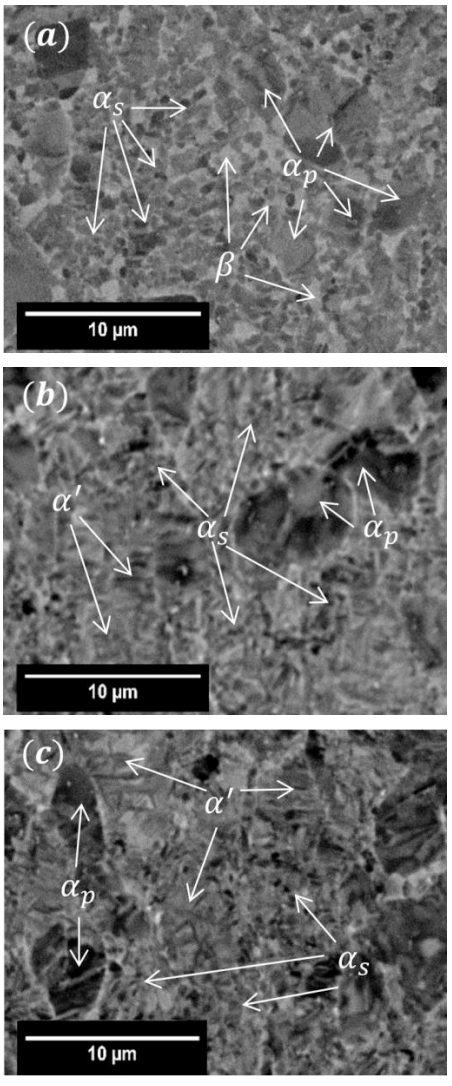

Fig. 9. Microstructures of specimen after step quenching tensile test 950 ℃ ⟶ 800 ℃ at different strain rates: (a) 0.1 /s; (b) 1 /s; (c) 5 /s, obtained through SEM operated under BSE mode (the $\alpha_p, \alpha_s, \alpha'$, β represent primary α phase, secondary α phase, martensite and β phase, respectively).

heterogenous nucleation sites for secondary α_s and allow time for α_s growth. Although the lamellar secondary α_s was globularized during deformation, which could lead to strain softening, the dynamic phase transformation (from β to α_s) still led to strain hardening by generating more harder phase secondary α_s and growth of existing acicular secondary α_s. Strain softening was only expected to be found at a later stage of the material deformation, when the globularization of secondary α_s could not be counterbalanced by hardening effects caused by the dynamic phase transformation from β to α_s. This is in consistence with the tested true stress-strain curve shown in Fig. 6.

Higher strain rates in step quenching tests with strain rates of 1 /s and 5 /s were believed to create more nucleation sites for secondary α_s, resulting in accumulation of smaller acicular α_s at the early stage of the deformation. Due to the short deformation durations in the step quenching tests at the strain rates of 1 /s and 5 /s, the amount of adiabatic heating generated cannot be dissipated to the ambient air in time. As a result, the deforming temperature increase was no longer negligible [20]. The higher deforming temperature combined with shorter deformation time could reduce the amount of secondary α_s that could be generated from β phase. For the step quenching tensile test at 1 /s, the reduced phase transformation, from β to α_s, could not counterbalance the softening from globularization of existing acicular α_s anymore, thus strain softening was found. As for the step quenching test at 5 /s, there was even less time for the heat to be dissipated. The forming temperature increase was measured to be higher than that in the test at 1 /s (average temperatures at fracture were 826 ℃ and 840 ℃ for 1 /s and 5 /s respectively). In addition, small amount of globularized acicular secondary α_s might be transformed to β phase leading to additional strain softening at 5 /s than the test at 1 /s test. For this reason, there was expected to be more β phase at the completion of the test at 5 /s, which can be deduced from the existence of more martensite in Fig. 9 (c) than in Fig. 9 (b). The combined effect of less phase transformation from β to α_s, globularization of secondary α_s, and phase transformation from globularized secondary α_s to β phase results in severe strain softening in step quenching tensile test at the strain rate of 5 /s.

The strain rate hardening improvement was found in step quenching test as compared to direct heating at forming temperature of 800 ℃. This could be because, at the beginning of deformation, there was supersaturated β phase, reserved from the high temperature soaking at 950 ℃.The existence of more β phase, as compared to direct heating test at 800 ℃, could facilitate the grain boundary sliding, resulting in strain rate hardening improvement [24]. In the study of [25], it was found that the globularization of acicular secondary α_s could facilitate grain rotation and grain boundary sliding, which could contribute to the superplasticity. In this study, this was suggested as an additional mechanism contributing to the enhanced strain rate hardening properties of the material under step quenching tensile test, at the strain range of 0.1 /s - 1 /s.

Fig. 10 shows that the volume fraction of primary α_p of the material after direct heating and tensile test at 950 ℃ and 1 /s decreased to 20.9 %, as compared to 22.8 % measured from

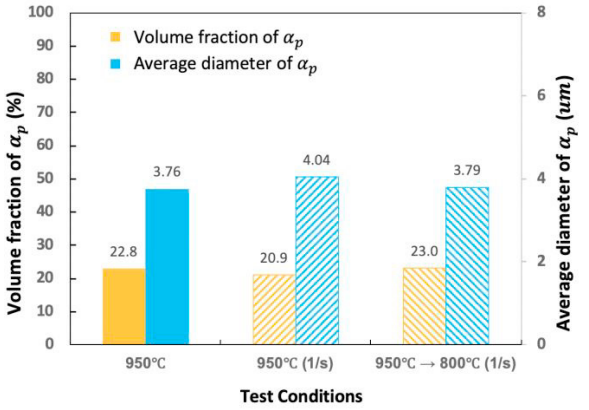

Fig. 10. Volume fraction and average grain diameter of primary α_p under different heat treatment routes and tensile test conditions.

direct heating without deformation test. As it was expected, the material after step quenching 950 ℃ ⟶ 800 ℃ and tensile test at 1 /s showed similar volume fraction of primary α_p (23.0 %) as before step quenching, i.e. direct heating without deformation at 950 ℃.

The decreased volume fraction of primary α_p in the direct heating and tensile test at 950 ℃ and 1 /s, compared with the undeformed benchmark, was believed to be because of the dynamic phase transformation (α_p to β) caused by adiabatic heating during fast deformation; while the volume fraction of α_p remained almost unchanged after the step quenching tensile test, which could be attributed to the supersaturated β phase.

Based on the analysis above, the step quenching heat treatment was proven to be effective in reducing strain softening at strain rate of 1 /s. Strain hardening was even observed at strain rate of 0.1 /s which is a promising property; however, 0.1 /s could be too slow in a Heat Stamping process when cold tool is used. Further studies are needed to refine processing conditions and expend the applicable work windows for HS.

3.3. Heat Stamping of Ti-6Al-4V

The feasibility of HS process using step quenching heat treatment was investigated by forming the cup shape demonstrator with a drawing ratio of 1.3 as shown in Fig. 11. However, the flanges were found to be preferred sites for tiny cracks. This could be because the temperature of flanges

Fig. 11. A cup shape demonstrator formed under step quenching heat treatment 950 ℃ ⟶ 800 ℃.

dropped to around 750 ℃ (which caused β to brittle martensite α' transformation) due to the conductive heat lost through contacting the blank holder before forming, while the temperature of the blank at centre was 800 ℃. Further development is needed for improving the HS process.

To obtain the supersaturation state of β and better microstructural control, more efficient cooling equipment with accurate temperature control is needed. In addition, a faster handling system is to be developed to avoid the initiation and accumulation of α_s during transferring. As a result, the softening caused by globularization of α_s and adiabatic heating induced phase transformation (α_s to β) is hoped to be reduced.

4. Conclusion

The feasibility of novel heat stamping process under step quenching treatment was investigated. Flow stress properties of the studied Ti-6Al-4V sheets under direct heating and step quenching treatment were compared at temperatures of 800 - 950 ℃ and strain rates of 0.01 /s, 0.1 /s, 1 /s, and 5 /s. The following conclusions are drawn from the results:

- Step quenching 950 ℃ ⟶ 800 ℃ can reduce strain softening especially at the low strain rate of 0.1 /s and 1 /s However, at high forming strain rate of 5 /s, severe strain softening was found.
- The varied strain softening properties in the step quenching tensile tests at different strain rates were due to the combined effect of dynamic phase transformation (β to α_s), globularization of α_s, and adiabatic heating.
- The step quenching heat treatment, 950 ℃ ⟶ 800 ℃, can improve the strain rate hardening as compared with the material deformed at the same temperature (800 ℃) after direct heating.
- A better controlled step quenching and handling system should be developed for the Heat Stamping practice.

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