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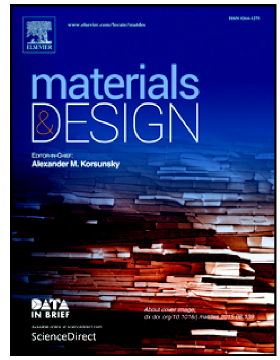

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Enhanced formability and forming efficiency for two-phase titanium alloys by Fast light Alloys Stamping Technology (FAST)

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Abstract

During hot stamping of titanium alloys, insufficient forming temperatures result in limited material formability, whereas temperatures approaching the β phase transus also result in reduced formability due to phase transformation, grain coarsening and oxidation during the long-time heating. To solve this problem, Fast light Alloys Stamping Technology (FAST) is proposed in this paper, where fast heating is employed. Effects of heating parameters on the formability and post-form strength were studied by tensile tests. Forming of a wing stiffener was performed to validate this new process. Results show that microstructure of TC4 alloy after fast heating was in nonequilibrium state, which could enhance ductility significantly compared with the equilibrium state. When TC4 alloy was first heated to 950 ℃ with heating rate of 100 ℃/s and then cooled to 700 ℃, the elongation at 700 ℃ was more than 3 times that of a slow heating rate with soaking. Nano-scaled martensite with high dislocation density transformed from β phase was observed under fast heating condition. A complex shaped wing stiffener was successfully formed from TC4 titanium alloy in less than 70 seconds including heating, transfer and forming, and the post-form strength was almost the same with the initial blank.

Key Words: Titanium alloys; Fast heating; Hot stamping; Formability; Post-form strength

1. Introduction

Titanium alloys are extensively used in the aviation industry because of their outstanding mechanical properties [1, 2]. However, they are seldom used in the commercial field due to the prohibitively high cost [3]. It is reported that the cost of a product made from titanium alloy is 40 times greater than steels and 20 times greater than Aluminium alloys [4]. The price pressure of titanium alloy products is becoming more pronounced with the continued expansion of the aviation and aerospace industry. The cost contribution to manufacturing titanium alloy products can be subdivided into sponge titanium, additive alloys, melting and manufacturing cost [5]. It is difficult to further reduce the price of processes such as sponge titanium, additive alloys and melting due to the mature production lines and increasing environmental pressure [6]. Therefore, reducing the manufacturing cost of titanium alloy products is becoming increasingly important as it is the area that can benefit most from new technologies.

Titanium alloys have strong deformation resistance at room temperature and a high level of springback, resulting in titanium alloy sheet components being generally formed at elevated temperatures [7, 8]. In the traditional hot pressing process, both forming tools and blank are heated in a furnace attached to the press [9]. When the forming tools have a large mass, significant amounts of energy and time are required. Extended heating times also impose strict requirements on the tool material, as it must exhibit high temperature performance, which results in high tooling cost. Moreover, tool wear and galling are also critical at elevated temperatures, which will reduce tool life. Due to these reasons, it is necessary to develop new technologies to improve the forming efficiency and reduce the cost of manufacturing titanium alloy components.

Hot stamping technology has already been widely used in the automobile industry [10], which uses cold forming tools to form and quench the hot (austenized) steel blank. In this hybrid forming technology, forming and heat treatment are conducted simultaneously, and one could obtain a part with martensite structure after forming [11]. However, the application of hot stamping to titanium alloys has not yet achieved widespread adoption in industry. Compared with the traditional hot forming process for titanium alloys, hot stamping has the advantages of higher heating and energy efficiency, improved production efficiency, lower tool cost and improved post-form properties.

In the authors' previous work [12], a feasibility study on hot stamping of titanium alloy was performed. Results show that the processing windows for TC4 titanium alloy during hot stamping are very narrow and one could only achieve a qualified part without surface cracking between 750 and 850 °C. The sheet blank was first heated to the designated temperature in a furnace and soaked for approximately 2 minutes, followed by rapid transfer to the cold forming dies and forming. The temperature decreased rapidly in the transfer and forming process. It is known that the microstructure of titanium alloys is sensitive to the thermal-mechanical processing conditions [13, 14]. During the heating and soaking process, α phase would transform to β phase; and the reverse transformation would occur during the subsequent forming and cold die quenching processes. The heating temperature and soaking time will determine the content of β phase at the specific heating temperature; the cooling path will determine the volume fraction and morphology of different phases after quenching. Hence, the formability and properties of titanium alloys after forming are primarily controlled by the material heating and cooling history. If the heating temperature is low (<750 °C), titanium alloys have limited elongation under the hot stamping condition, which will lead to crack failure and severe springback. Regarding the hot stamping of steels, the steel blank is heated to the single-phase zone, where all the other phases are transformed to austenite. However, if the titanium alloy is heated to the single-phase zone and formed at a lower temperature, forming will be unsuccessful due to the poor ductility caused by the coarse β grain size and the martensite, which is different from steel [15]. A qualified part could not be formed if the microstructure of the blank is β phase dominant which reduces ductility. It should be noted that increasing the temperature is one of the most effective approaches to reduce the springback [16]. However, for titanium alloys, the rates of β phase transformation, grain coarsening and oxidation increase with temperature, especially when the temperature is near the β phase transus temperature. Therefore, there is a dilemma between reducing the springback and improving the formability. Due to the above limitations, it is challenging to form complex-shaped components through hot stamping technologies.

Recently, a novel data driven forming technology namely FAST (Fast light Alloys Stamping Technology) [17] was proposed to address the technological challenges of hot stamping [18] and to support the multi-material mix for the next-generation vehicles [19]. In this new technology, a two-phase titanium alloy blank with customised equiaxed microstructure was heated rapidly to the specified temperature, then formed and quenched immediately in the room temperature dies. The innovation of the FAST technology lies in the precise control of the phase transformation, grain growth and oxidation at elevated temperatures by the combination of tailored initial microstructure, precisely controlled heating, transfer, forming and in-die quenching, which could solve the dilemma discussed above and improve the formability and reduce the springback simultaneously. In addition, the forming efficiency could also be improved.

Ozturk et al. [20] and Maeno et al. [21] studied the hot stamping of titanium alloys utilising resistance heating, where the heating rates ranged from 108 to 132 °C/s. During the resistance heating, the materials in contact with the electrodes were not heated, and when the shape of the blank was not rectangular, the temperature was non-uniform [22]. Therefore significant efforts have been devoted to solving this heating problem [21]. However, in these studies, the effect of heating rate on the formability and material properties was not studied. Other studies regarding fast heating of titanium alloys focused on the kinetics of the phase transformation from α to β [23], and it is reported that the diffusion distance of β stabilizer elements such as V decreases with the increasing heating rate [24], which leads to a higher β-transus temperature under fast heating conditions [25]. The microstructure of the rapidly heated titanium alloy does not have sufficient time to reach equilibrium, which will therefore affect the formability and post-form properties greatly. However, little research has been performed in this field, and in particular under the FAST conditions.

Therefore, the effect of heating history on the ductility of titanium alloys under both FAST and hot stamping conditions was studied in this paper. The mechanical properties were evaluated through thermo-mechanical testing, and the post-form properties were characterized by Vickers's hardness testing. The microstructure evolution under the FAST conditions was examined by Scanning Electron Microscope (SEM). A wing stiffener made from TC4 titanium alloy was successfully formed by FAST.

2. Material and experimental procedure

2.1 Material

A two-phase TC4 titanium alloy sheet was employed in this study, which is the most commonly used titanium alloy worldwide. The average thickness of the as-received sheet was 1.6 mm. The chemical composition of the as-received sheet is shown in Table 1. The initial microstructure was customised to be equiaxed to guarantee the thermo-ductility, and the microstructure is shown in **Fig. 1**, where the white region shows the β phase and the dark region the α phase. The initial microstructure consists of equiaxed α phase and fine β phase. Both volume fraction and average grain size of β phase are much smaller than that of the α phase in the initial microstructure. The yield strength, ultimate tensile strength, Young's modulus and elongation of the as-received sheet at room temperature are 870 MPa, 1056 MPa, 97 GPa and 14% respectively. Two-phase titanium alloys with lamella dominant microstructure, near β or β titanium alloys with β phase dominant microstructure are not discussed for this technology in this paper.

Table 1. The chemical composition of the as-received Ti6Al4V

Wt %	Al	V	C	N	O	H	Fe	Ti
Ti6Al4V	6.09	4.01	0.02	<0.01	0.12	<0.015	0.16	Bal.

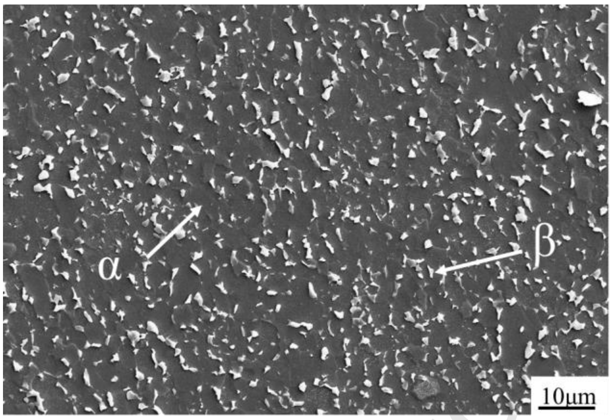

Fig. 1 Microstructure of the as-received TC4 titanium alloy

2.2 Forming of the wing stiffener panel components

To validate the FAST technology and extend the forming processing windows for hot stamping, a complex-shaped wing stiffener component was selected as the demonstrator. A rectangular-shaped initial sheet with thickness of 1.6 mm was machined from the rolled blank with dimensions shown in **Fig. 2 (a)**, where the rolling direction was along the longitudinal direction. The geometry of the component is shown in **Fig. 2 (b)**. To avoid complications arising from optimizing the blank shape, a section of the component containing the most complex features was formed. Further details regarding the full-size wing stiffener can be found in [26].

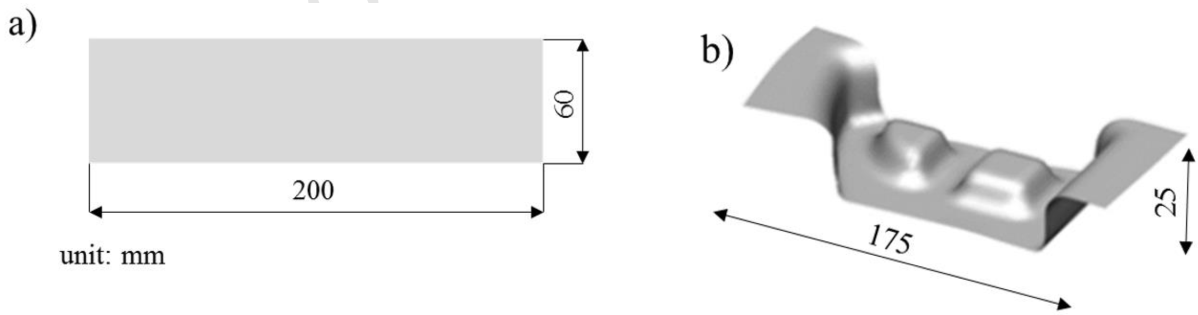

Fig. 2 The dimensional information of the initial sheet (a) and formed component (b)

The forming tests were performed on a 25-tonne press. The forming tool is shown in **Fig. 3**. The sheet was rapidly heated by the use of contact heaters. The sheet was lubricated by boron nitride on all surfaces and was heated to 900 °C at an average heating rate of 15°C/s. The temperature of blank was monitored by a K-type thermocouple. Once the value reached 900 °C, the blank would be transferred quickly from the hot platen to the forming die and immediately formed. The formed part would be taken out after 5 s holding in the forming die. After the forming, the material thinning and post-form hardness along the cross-section was measured. The wing stiffener was also formed by hot stamping for comparison, where the blank was heated to 900 °C at an average heating rate of 4°C/s and then soaked for two minutes. The punch speed was 250mm/s under both conditions. The temperature reduction during the transfer of the heated blank was almost the same in both the FAST forming and conventional hot stamping, where the temperature dropped from 900 to 761 °C just before forming. As a result, the formed part cracked in two corners under hot stamping with slow heating condition as shown in **Fig. 4**.

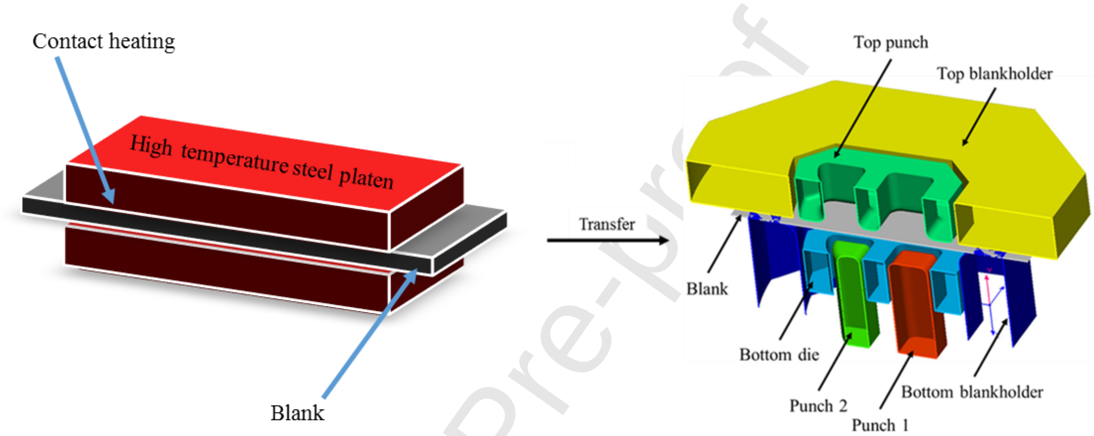

Fig. 3 The schematic for FAST forming of titanium alloy wing stiffener

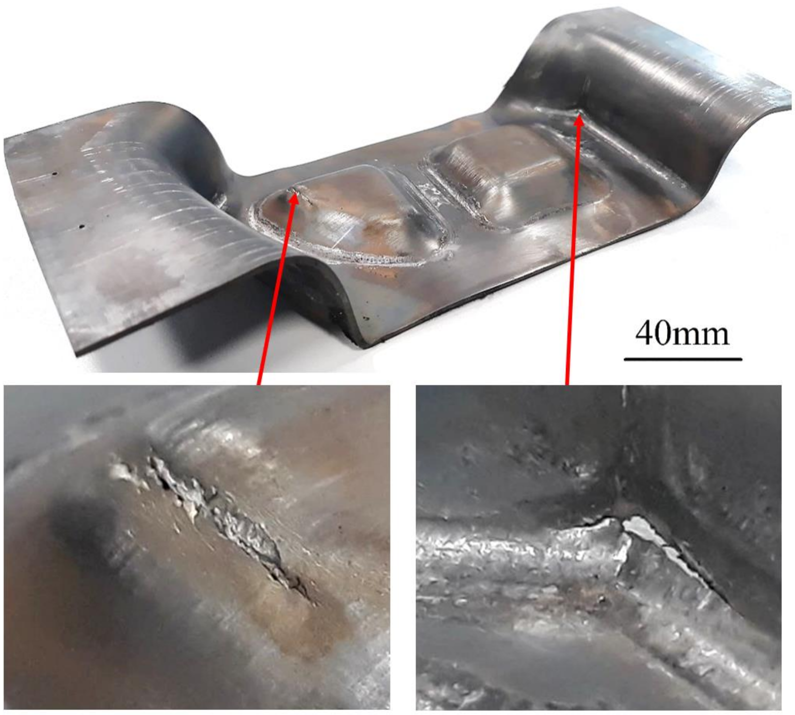

Fig. 4 Crack failures in the corners of the part formed by hot stamping with slow furnace heating

2.3 High-temperature uniaxial tensile tests and characterization of microstructure and properties

To examine the effect of heating history on the ductility, tensile tests were performed by a Gleeble thermo-mechanical simulator to replicate the forming processes. The samples were first heated to an elevated temperature (850 to 950 °C) at a range of heating rates (0.5 to 150 °C/s). After soaking for a period (0 and 2 min), the samples were cooled down to 700 °C, at which tensile tests were performed at a constant strain rate of 1 s-1 as shown in Fig. 5. It should be noted that strain rate varied differently in different areas during hot stamping, and the maximum strain rate could reach as high as 20 s^{-1} according simulation results, but tensile test with such a high strain rate is very difficult. As strain rate of 1 s^{-1} is close to the average value, and therefore tests were performed under this condition. After the tensile test, samples were cooled immediately by pressurised air to room temperature within 10 s. A dog-bone shaped specimen was used with a gauge length of 46 mm, a width of 12 mm and a thickness of 1.6 mm.

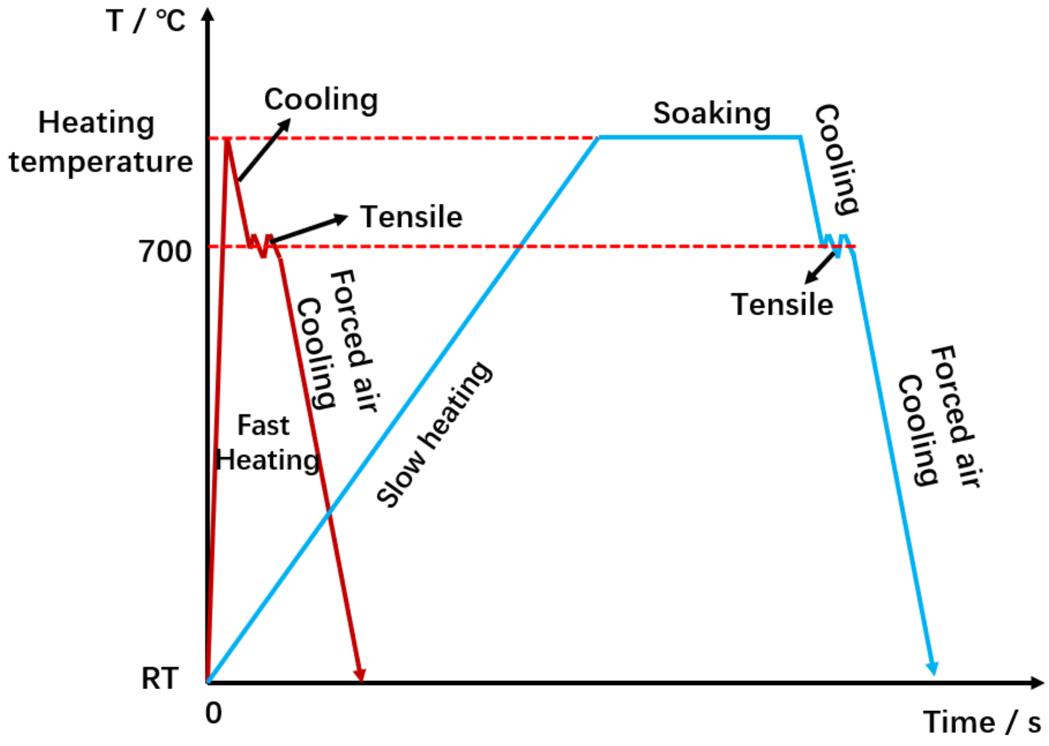

Fig. 5 High-temperature uniaxial tensile tests program – investigation of the heating history effect on ductility

To study the influence of heating rate on the ductility of the TC4, uniaxial tensile tests with different heating rates at a heating temperature of 900 °C were performed. During the tests, the sample was first heated to 900 °C with heating rates ranging from 4 to 150 °C/s. When the temperature reached the target value, the sample was subsequently cooled to 700 °C with an average cooling rate of 60 °C/s and deformed immediately to failure. The sample was further cooled with pressurised air to room temperature within 10 s after failure. The microstructure of samples after testing were examined by transmission electron microscope (TEM) and scanning electron microscope (SEM) to reveal the evolution mechanisms. A Vickers hardness test machine was used to test the hardness with a load of 10 kgf force and duration of 10 s. The microhardness of the sample after tensile tests was measured near the fracture area.

3. Results and discussion

3.1 Effect of heating temperature on ductility and post-form strength of TC4 titanium alloy

The formability of the material decreased when the heating temperature exceed 850 °C during the hot stamping. Tensile tests under hot stamping and FAST conditions were first carried out to reveal the corresponding mechanisms and to study effects of heating temperature on formability and mechanical properties of the TC4 titanium alloy. For the hot stamping condition, the sample was first heated to the target temperature at a heating rate of 4 °C/s, and was followed by soaking for 2 minutes, cooling to 700 °C and finally deforming immediately to failure at a constant strain rate of 1 s^{-1}. The sample was cooled with high pressure air to room temperature within 10 s after failure. As for the FAST condition, the sample was first heated to the target temperature at a heating rate of 100^{o}C/s, and when the temperature reached the target value, the sample was cooled to 700 °C and deformed immediately to failure with a strain rate of 1 s^{-1}. After failure, the same cooling rate and method was used, and the stress-strain curves are shown in **Fig. 6**.

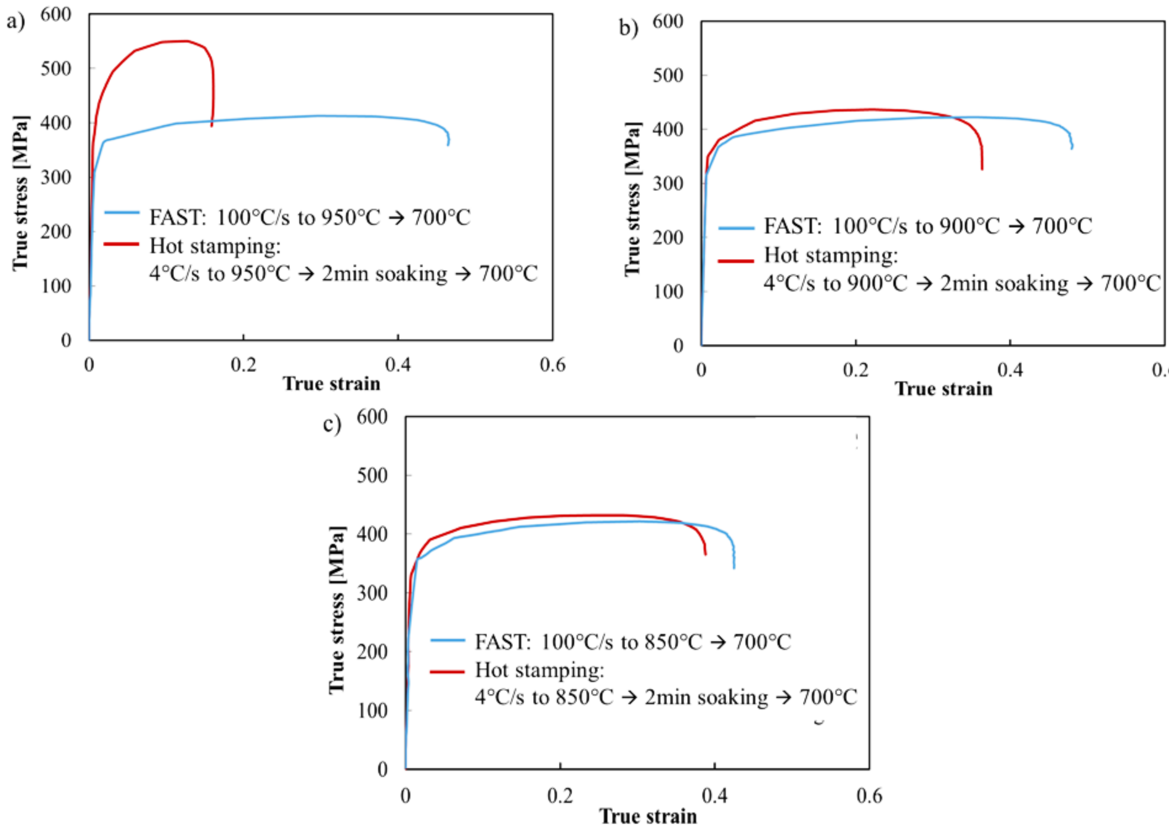

Fig. 6 Effect of heating temperature a) 950 °C; b) 900 °C; c) 850 °C on the ductility of investigated titanium alloy tested under both hot stamping and FAST conditions

It could be observed that the material had a higher failure strain but lower flow stress at FAST conditions, indicating greater ductility. Under the FAST condition, the flow stresses were almost the same; while at hot stamping conditions, the flow stress increased dramatically after heating to 950 °C. The elongation and post-form hardness distribution is shown in **Fig. 7**. It is clear that the heating temperature affects the elongation significantly. The elongation decreased gradually with increasing heating temperature at hot stamping conditions; while the elongation first increased and eventually decreased at FAST conditions. The elongation enhancement obtained at FAST condition increased from 17% at 850 °C to 241% at 950 °C. The post-form hardness increased gradually with the increasing heating temperature at both hot stamping and FAST conditions, although hardness at hot stamping condition is greater than that at FAST condition. Nevertheless, the formability of TC4 alloy decreased with increasing heating temperature under hot stamping conditions, especially when the temperature was greater than 900 °C, indicating that the maximum heating temperature for hot stamping of TC4 alloy should be lower than 900 °C as shown in **Fig. 8**, which also provides an explanation for the crack failures in **Fig. 4**. Therefore, the processing windows for hot stamping of TC4 alloy could be extended to at least 950 °C by FAST, enabling the achievement of both improved formability and reduced springback.

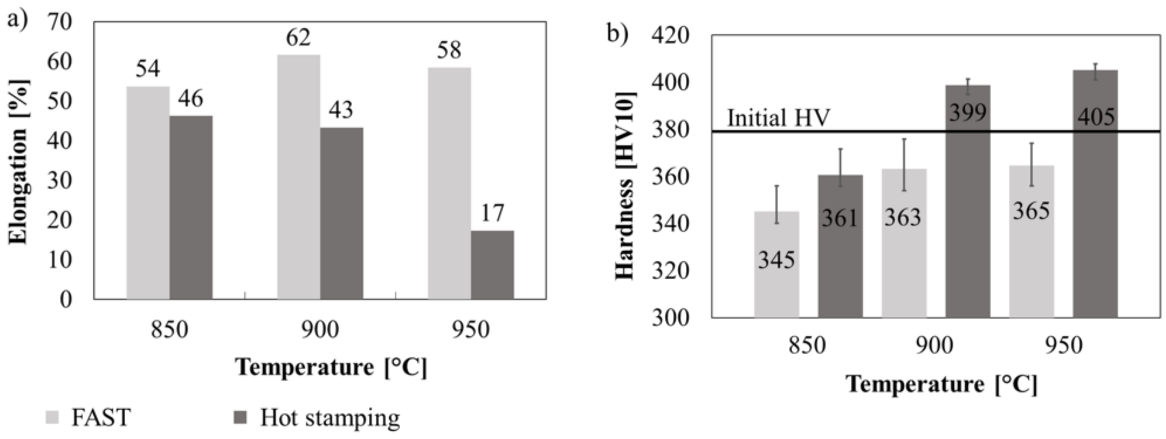

Fig. 7 Effect of heating temperature on elongation (a) and post-form hardness (b)

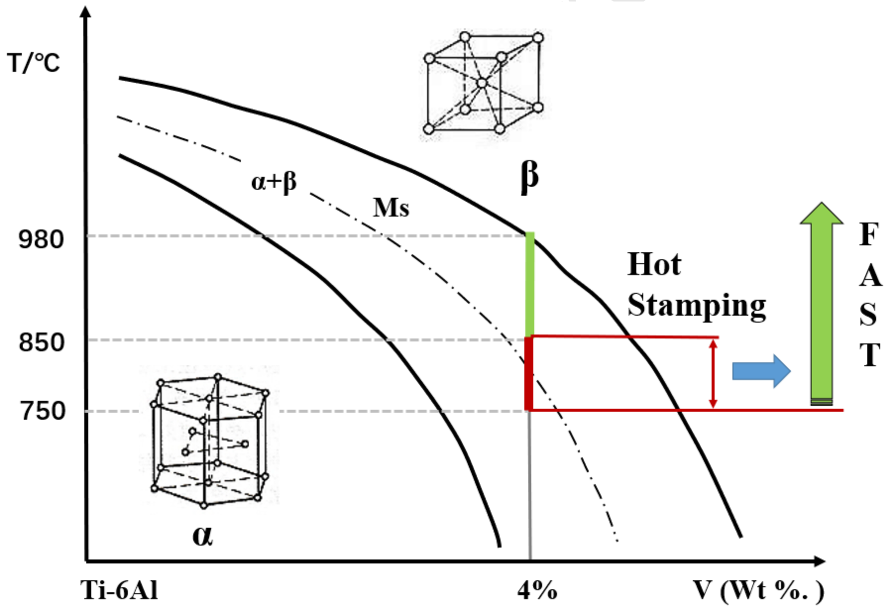

Fig. 8 Comparison of processing windows between FAST and hot stamping with slow heating

To reveal the evolution mechanism of elongation and post-form hardness, the post-form microstructure near the fracture area and fracture morphology were characterised and the results are shown in **Fig. 9** and **Fig. 10** respectively. A greater number and larger β phase appeared with the increase of heating temperature. Under the FAST condition, the volume fraction of prior β phase at elevated temperature is much lower than that under the hot stamping condition. This is because of the insufficient time for element diffusion under the FAST condition to generate more β phase, although the β phase grew coarser than the initial state [27]. It can also be found that the difference between the microstructures after fast heating and slow heating became larger with increasing temperature. Secondary α appeared under the hot stamping condition as the temperature was greater than 850 °C; while no visible secondary α could be found in the SEM figures under the FAST condition. This is because the element diffusion rate increased with the temperature. Therefore, the elongation enhancement by fast heating would be more obvious at higher temperature range (> 850 °C) for titanium alloys at hot stamping condition.

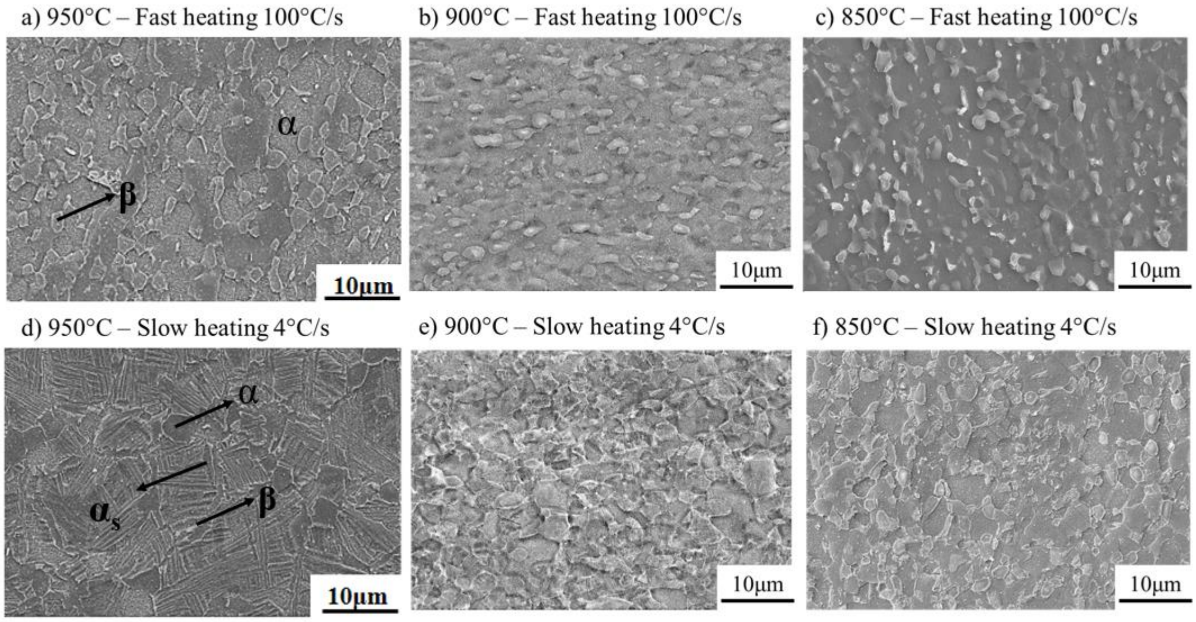

Fig. 9 Microstructure of the investigated titanium alloy after deformation at different conditions

The fracture morphology demonstrated ductile fracture with various dimples at all conditions. More larger and deeper dimples were observed in FAST condition than under the hot stamping condition, indicating that more plastic deformation occurred under the fast heating condition. However, this difference reduced at 900 and 850 °C which is in good agreement with the stress-strain curves. Based on the above results, it can be concluded that the fast heating could restrain α transforming to β during the heating and therefore improve the formability of the TC4 titanium alloy under hot stamping condition.

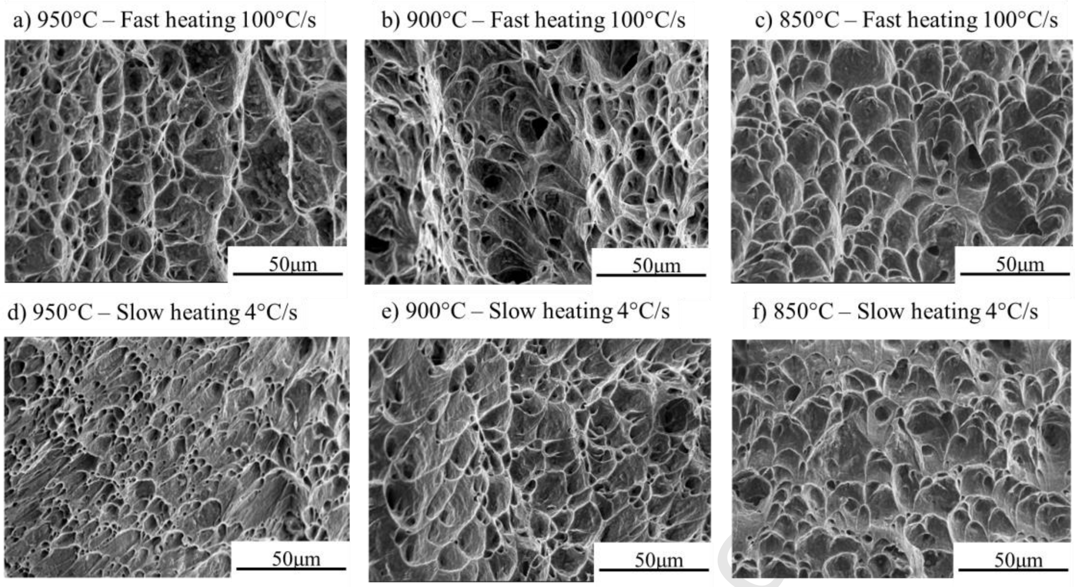

Fig. 10 Fracture morphology of the investigated titanium alloy after deformation at different conditions

3.2 Effect of heating rate on the ductility and post-form strength of TC4 titanium alloy

From the above results, 900 °C is an effective heating temperature for TC4 titanium alloy at FAST condition. In order to reveal the effects of heating rates on ductility and post-form strength, the investigated material was tested under different heating rate conditions ranging from 0.5 to 150 °C/s, and the test results are shown in **Fig. 11**. It is clear that heating rate affects the ductility of the material, where an increased heating rate increases the tensile elongation.

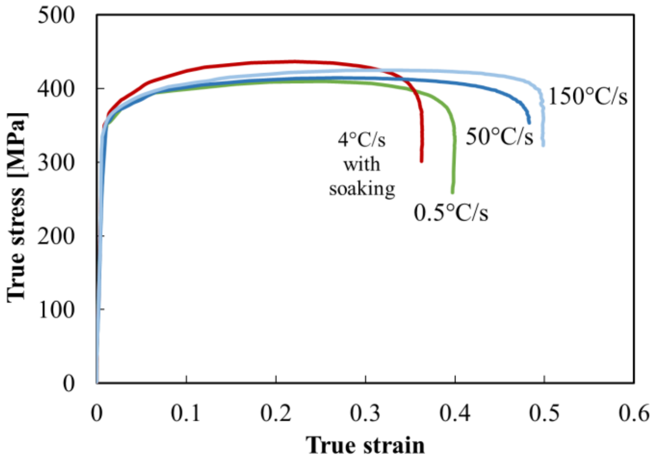

Fig. 11 Stress-strain curves for material tested with different heating rates

The distribution of elongation-to-failure with different heating rates is shown in **Fig. 12(a)**. The elongation increased from 49.2% at the heating rate of 0.5 °C/s to 64.9% at the heating rate of 150 °C/s, which was increased by 31.9%. However, the elongation enhancement decreased with increasing heating rate. When the heating rate is greater than 50 °C/s, the elongation exhibits negligible changes. The sample demonstrating the lowest elongation was at a heating rate of 4 °C/s followed by two minutes soaking. Therefore, it would be very important to avoid extensive soaking during hot stamping to guarantee formability. The post-form strength was evaluated by Vickers hardness and the result is shown in **Fig. 12(b)**. The post-form strength decreased with increasing heating rate. Approximately 94.7% of the original hardness was retained even after deformation at a heating rate of 150 °C/s. Therefore, it could be concluded that FAST could maintain the material post-form strength.

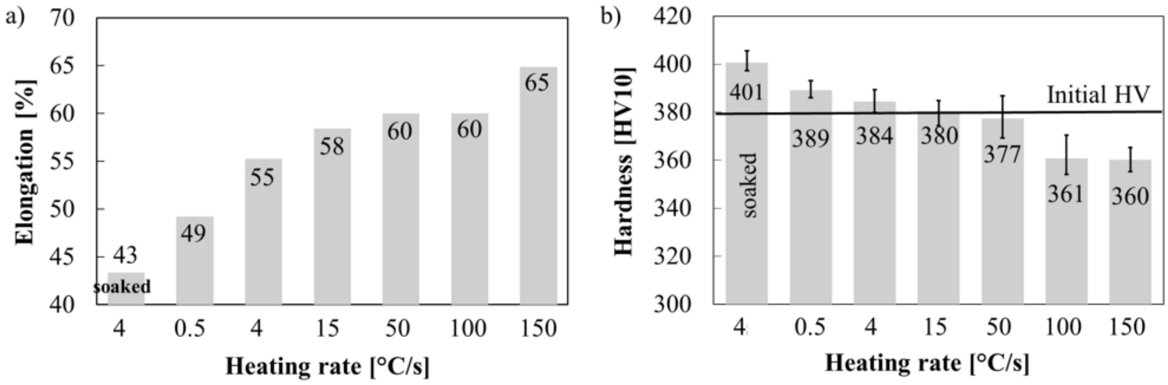

Fig. 12 Effect of heating rate on elongation (a) and post-form hardness (b)

The microstructures near the fracture area after tensile tests are shown in **Fig. 13**. Both volume fraction and size of β phase increased with decreasing heating rate, and fine secondary α phase formed at heating rates of 0.5 and 4 °C/s with 2 min soaking. The microstructure of the sample after fast heating was in nonequilibrium state including the volume fraction and size of the two phases, because of the heating time was too short for element diffusion to reach the equilibrium state. Hence, it can be summarised that more α transformed to β phase under the hot stamping condition and the corresponding average grain size was also larger, which decreased the ductility but increased the hardness by more transformed microstructure.

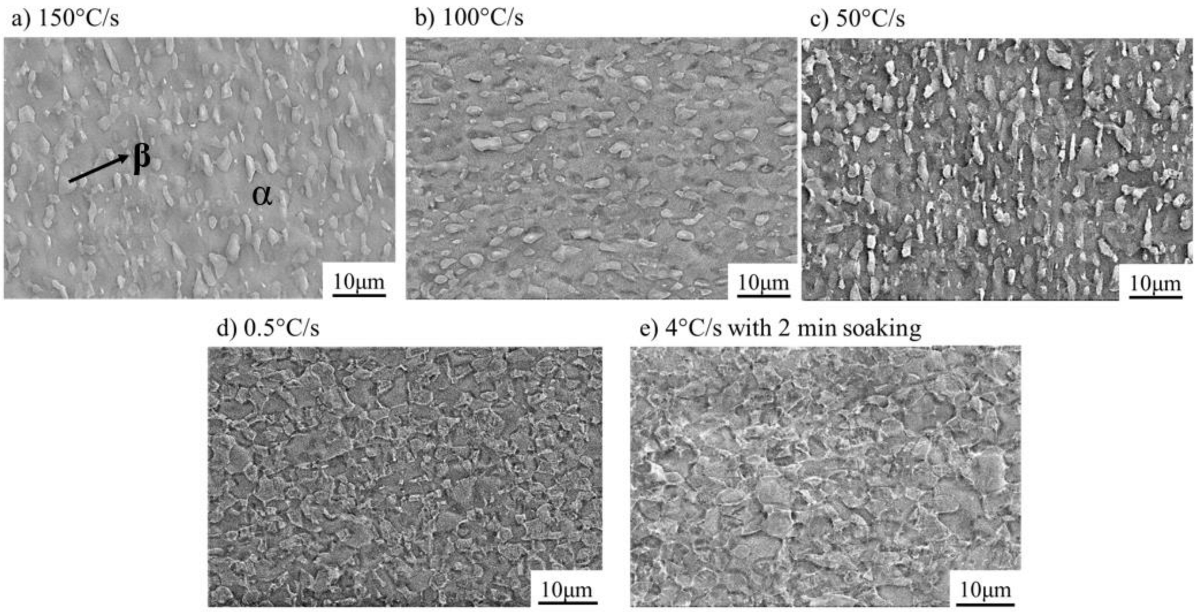

Fig. 13 Microstructure near the fracture area of the sample after tensile tests with a heating rate of 150 °C/s (a), 100 °C/s (b), 50 °C/s (c), 0.5 °C/s (d) and 4 °C/s with 2 min soaking (e)

3.3 Validation of FAST by forming of a wing stiffener

Based on the above discussion, it can be summarized that when the TC4 titanium alloy was heated at a high temperature range in the two-phase zone (e.g. > 850 °C), the formability and efficiency will be improved under the FAST condition, although post-form strength may decrease slightly. Under the hot stamping condition, the post-form strength may be improved, but this may negatively impact the formability and efficiency. Hence, an appropriate heating rate is very important. According to the elongation and post-form hardness distribution, heating rates ranging from 4 °C/s to 50 °C/s at 900 °C is suggested for the investigated TC4 titanium alloy.

To validate the feasibility of FAST for titanium alloys, forming tests of a wing stiffener were performed. According to the high-temperature uniaxial tensile tests, a relatively good forming condition was determined to be a heating rate ranging from 4 °C/s to 50 °C/s at 900 °C, because in this range, the material exhibited a relatively good elongation and the post-form strength was similar with the initial material. In the actual forming, the blank was heated to 900^{o}C with an average heating rate of 15 °C/s through contact heating. After reaching the target heating temperature, the blank was immediately transferred and formed. A qualified wing stiffener was successfully formed with fully formed local features as shown in **Fig. 14**. However, when the initial sheet was soaked in the furnace for 2 minutes at target temperature of 900 °C, the formed part failed due to the cracks occurring on the surface as shown in **Fig. 4.** The longer heating time led to more phase transformation, grain coarsening and surface oxidation, which resulted in the cracks.

Fig. 14 TC4 wing stiffener formed by FAST (heating temperature 900 °C)

In order to investigate the post-form hardness of the as-formed part, the hardness of the formed wing stiffener was tested, and the measurement positions and results are shown in **Fig. 15**. The post-form hardness distributed uniformly along the longitudinal direction and the average value was 370HV±10, which was almost the same as the initial material.

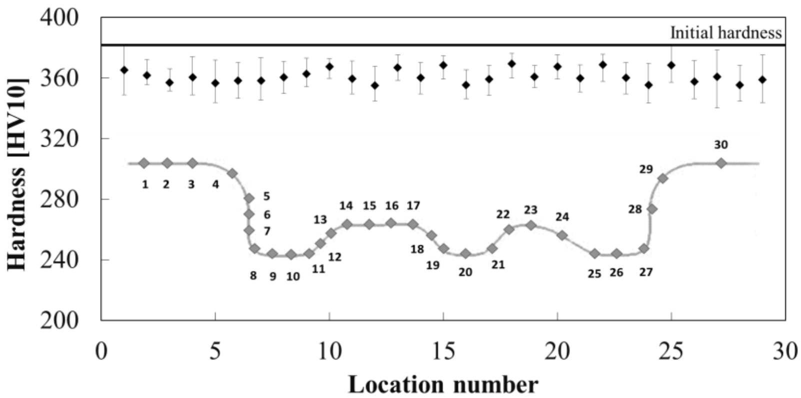

Fig. 15 Post-form strength distribution of the investigated TC4 titanium alloy wing stiffener formed by FAST

The thickness distribution along sections AB and CD from the wing stiffener is shown in **Fig. 16**. The thickness was distributed non-uniformly. In the flange area, there was some thickening; whereas localized thinning can be observed in other areas. With an initial thickness of 1.6 mm, the minimum wall thickness is approximately 1.27 mm resulting in a 20% thickness reduction. The maximum thickness reduction occurred at the corner regions due to the local deformation. The same wing stiffener made of AA5754 aluminium alloy was once formed by HFQ technology by El-Fakir et al. [26], where similar thickness distribution tendency and amplitude were also reported, although the AA5754 alloy wing stiffener was formed at a much lower temperature. This demonstrates that titanium alloys could achieve both good formability and thickness accuracy under FAST condition as aluminium alloys under hot stamping condition.

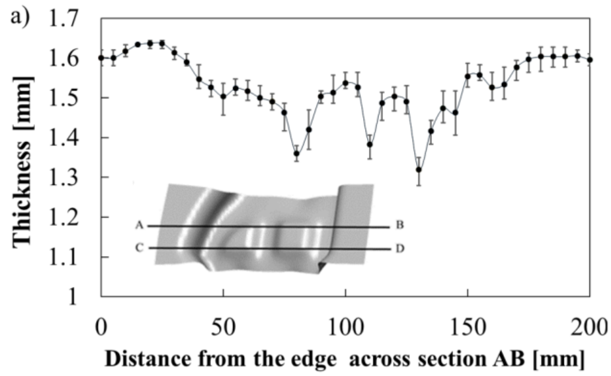

Fig. 16 Thickness distribution along the cross sections of AB (a) and CD (b)

Temperature is one of the most important parameters affecting springback during hot stamping. Fast heating could enhance the formability of titanium alloys under hot stamping condition by obtaining nonequilibrium microstructure after heating at elevated temperature. The principle of reducing springback by FAST is that titanium alloys components could be formed at higher temperature by FAST than by traditional hot stamping. It is well-known that higher forming temperature could reduce the springback during hot stamping. However, with regard to the forming of wing stifferner, it was difficult to form it at lower temperature because of the crack failure. Therefore, the authors did not perform the forming tests at lower temperature for comparison. The prediction of springback during FAST and the forming tools compensation design will be studied in the future work.

3.4 Mechanisms of phase transformation during FAST

Heating rate is an important parameter during the thermal-mechanical processing of titanium alloys, which will affect the mechanisms and kinetics of phase transformation [24]. Rapid heat treatment has been adopted to tailor the properties of titanium alloys because of its great potential in refining β grain size by rapid heating. It is reported that the β grain size could be refined from 40 μm to 8 μm with heating rate increasing from 10 °C/s to 50 °C/s during the rapid heat treatment of a TC4 alloy in the single β phase region, and fully martensite microstructure inside the refined β grains could be obtained, resulting in the simultaneous improvement of strength and ductility [28]. Nevertheless, hot stamping of titanium alloys should be performed at the two-phase region and avoid the single β phase region to achieve the best formability. The SEM images in **Fig. 13** do not show any martensite or secondary α microstructure under the fast heating condition. However, the TEM result of the sample after tensile tests with a heating rate of 100 °C/s shows that Nano-scaled martensite formed inside the β phase as shown in **Fig. 17**. The average width of the Nano-scaled martensite is 33 nm (**Fig. 17 b-c**), which is not visible in **Fig. 13 (b)**. Obvious element partition is observed in α and β phase (**Fig. 17 e-g**). The α phase is rich of Al element and the β phase is rich of V element, which is typical for titanium alloys.

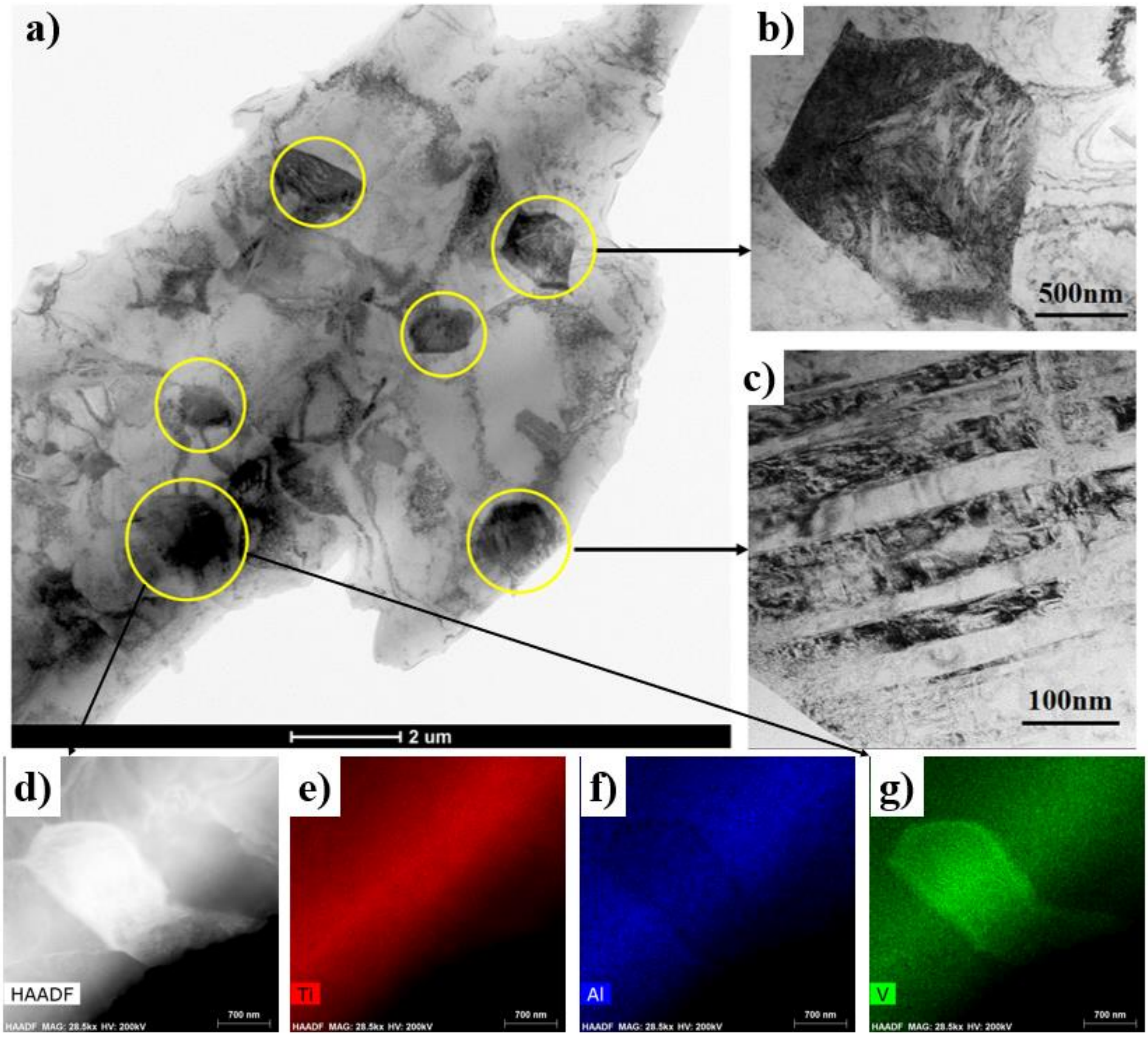

Fig. 17 TEM result of the sample after tensile tests with a heating rate of 100 °C/s at 900 °C. Bright field maps show the martensite microstructure transformed from β phase (a – c), HAADF (d) figure and the element distribution map (e – g).

To further reveal the mechanisms of the phase transformation under FAST condition, the microstructures of the initial material, and sample after fast heating-cooling-deformation were compared in **Fig. 18**. The initial sheet blank was annealed after rolling, and both α and β phase were in the equilibrium state. The average content (Atom %) of V element in the β phase of the initial material was 27.9% and the average content (Atom %) of Al element in the β phase was 2.3%. When the material was heated to 900 °C at a heating rate of 100°C/s followed by cooling and tensile deformation, the β phase grew larger during heating and Nano-scaled martensite with high dislocations density transformed from the β phase after deformation. The content of V element in the β phase reduced greatly with an average value of 8.8% and the content of Al element in the β phase increased accordingly with an average value of 6.8%. The heating time was too short for β phase to reach equilibrium state, therefore larger chemical gradient appeared in the phase boundary region. Thus, the main mechanism for the transformation of α phase to β phase at the two-phase region with fast heating was diffusion. However, when the material was heated to the single β phase region with fast heating, the mechanism may change to diffusionless transformation. Semiatin et al. [27] preformed some fast heating tests where the TC4 samples were first soaked at 704 °C, then heated at a rate of ~ 275 °C /s to 1121 °C followed by immediate water quenching, and found that some prior-α particles transformed into β at or near the peak temperature and then into martensitic α upon water quenching [27]. Those particles demonstrated almost the same composition as that in the primary α in the initial material, indicating no solute diffusion [27].

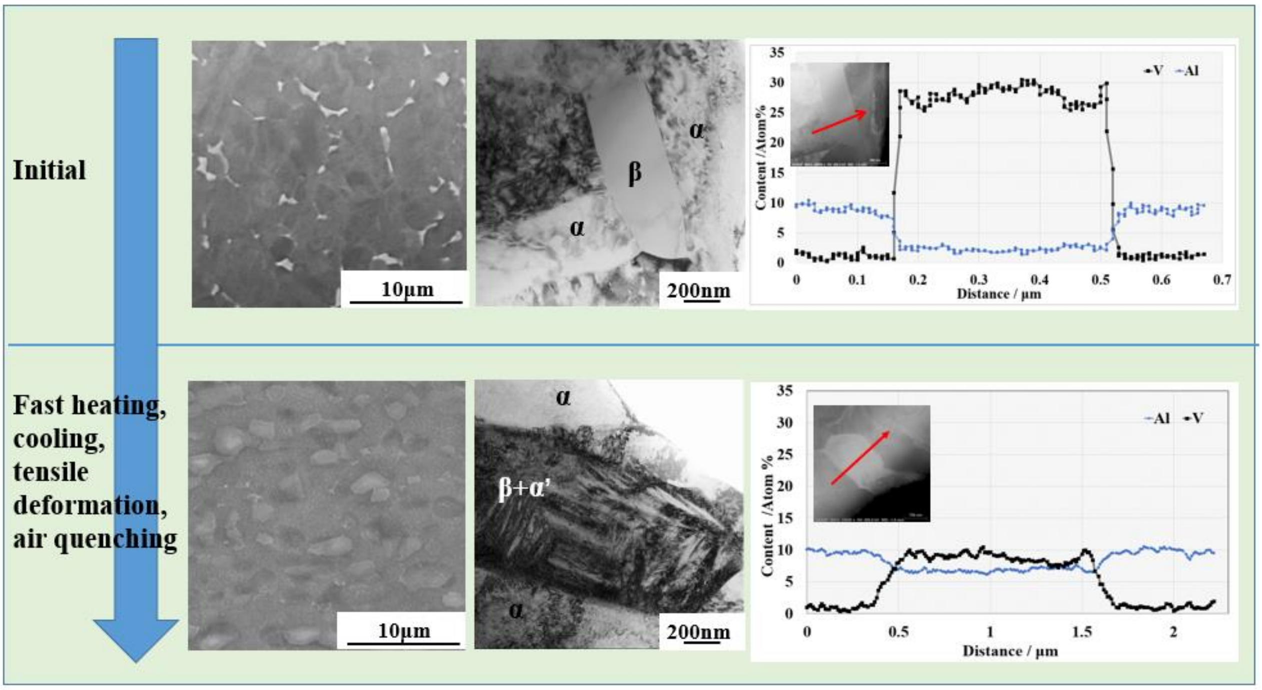

Fig. 18 Comparison of the microstructures of the initial material, and sample after fast heating-cooling-deformation

Fig. 19 shows the schematic figure of the phase transformation under slow and fast heating conditions. The initial material has an equiaxed microstructure with few fine β phase distributed in the boundaries. With the increase of heating temperature, the β phase grows and consumes the α phase gradually. When two adjacent β grains are in contact, they will merge into a single larger grain. With the temperature reaching the β transus point, all of the α phase will transfer into β phase with the original β phase being coarse under the slow heating condition. However, less phase transformation occurs under the fast heating condition and the grain size is also finer. The β transus point could also be delayed depending on the heating rates. Therefore, fast heating could enhance the formability of titanium alloys.

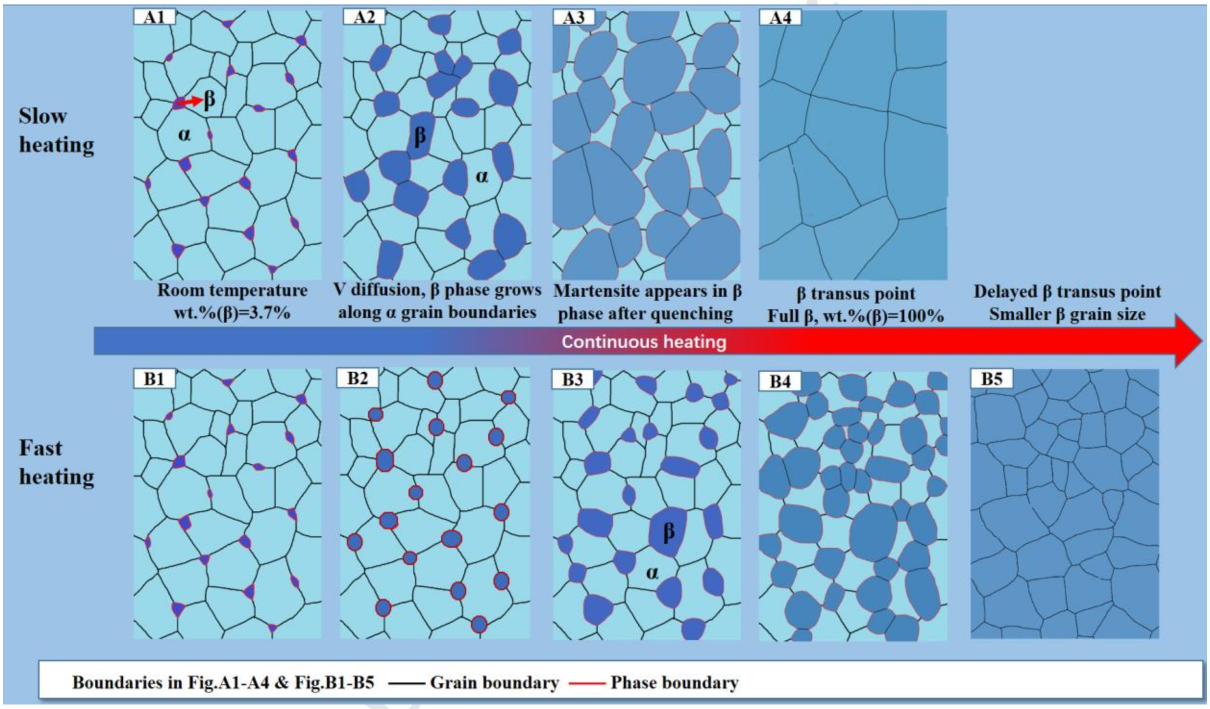

Fig. 19 Schematic figure of the phase transformation under slow and fast heating condition

Conclusions

In this paper, FAST was proposed to extend the processing windows for titanium alloys with a tailored initial microstructure under hot stamping conditions. High-temperature uniaxial tensile tests with different heating rates and different heating temperatures were performed in Gleeble to study the effects of heating parameters on the ductility and post-form strength. Forming tests of a TC4 titanium alloy wing stiffener were performed to verify this new process. The main conclusions obtained in this study are as follows:

(1) Under the fast heating condition, the heating time was too short for full element diffusion, which resulted in a nonequilibrium microstructure with less phase transformation and therefore improved the formability of the TC4 titanium alloy. When the heating temperature was 900 °C, the

elongation was increased by 31.9% when the heating rate increased from 0.5 °C/s to 150 °C/s. However, the elongation enhancement decreased with the increasing heating rate. When the heating rate is greater than 50 °C/s, the elongation change was negligible.

(2) The elongation decreased gradually with increasing heating temperature at slow heating condition; while it first increased and was followed by a reduction at fast heating conditions. The elongation enhancement obtained at fast heating condition improved from 17% at 850 °C to 241% at 950 °C. The post-form hardness also increased gradually with increasing temperature at both slow and fasting heating conditions, although the hardness values were greater at slow heating conditions. The processing windows should be selected by considering both elongation and post-form strength. A qualified wing stiffener part made from TC4 titanium alloys could be formed successfully in less than 70 seconds including heating, transfer and forming, and the post-form strength was almost the same with the initial blank.

(3) Nano-scaled martensite with high dislocations density transformed from the β phase after deformation was observed under fast heating condition, which is beneficial for maintaining the post-form strength but not impairing the formability at the same time. The phase transformation of α phase to β phase in the two-phase region is mainly diffusion controlled.

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1. Nonequilibrium microstructure was obtained after fast heating, which could enhance the formability of TC4 alloy significantly under FAST condition.
2. Nano-scaled martensite with high dislocations density transformed from β phase was observed under fast heating condition.
3. A complex shaped wing stiffener was successfully formed from TC4 titanium alloy by FAST with high efficiency.

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L. Wang: Supervision

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: