Achievement of martensite strengthening in titanium alloy thin-walled components via non-equilibrium hot stamping

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Abstract. The hot stamping using cold die technology demonstrates great advantages in improving the forming efficiency of titanium alloy thin-walled components. Martensite has been widely employed to strengthen steels, yet few applications were reported in titanium alloys. The main reason is that the martensite microstructure embrittles titanium alloys easily. In this paper, the non-equilibrium hot stamping technology is proposed for titanium alloys to solve the strength-ductility trade-off caused by martensite microstructure. Rapid heating is used to control phase transformation and grain growth during the short-time heating and obtain non-equilibrium microstructure. Non-equilibrium hot stamping experiments of the Ti-6Al-4V alloy were carried out to validate the feasibility. Results show that the rapid heating in the single β-phase region could avoid overgrowth of β grains and lead to the formation of fully fine martensite after water quenching. An Ω-shaped component with fully martensite microstructure were successfully formed by non-equilibrium hot stamping technology. The formed component has a maximum tensile strength of 1153.9 MPa, with a total elongation of 8.0% at room temperature, and the tensile strength is 13.0% higher than that of the as-received sheet.

Introduction

Thin-walled titanium alloy components are widely used in aviation, aerospace and other fields. However, due to high deformation resistance, poor plasticity and serious springback, it is challenging to form thin-walled titanium alloy components [1]. The isothermal forming process has been used for the forming of titanium alloy components, yet it results in low efficiency and high cost [2,3]. Hot stamping using cold die technology has been widely used in the forming of high-strength steel thin-walled components, which not only has a high forming efficiency, but also could improve the post-form strength [4,5].

In recent years, studies have also been carried out on hot stamping of titanium alloys. However, the martensitic transformation temperatures (M_s and M_f) of titanium alloy are much higher than those of high-strength steels [6,7]. As a result, the martensitic transformation of titanium alloy may occur in the process of hot stamping using cold die, thereby increasing the deformation resistance and reducing plasticity, resulting in forming failure [7]. In order to improve the formability of titanium alloy during hot stamping using cold die, Mu et al. proposed the using of triple-layer sheet to avoid the temperature dropping [8]. Hamedon et al. [9] and Maeno et al. [10] employed resistance heating to avoid the temperature dropping by cancelling the transfer process and improve the formability. Recently, hot stamping with rapid heating technology was put forward for titanium alloy by Wang et al. [11], in which rapid heating was used to control the microstructure evolution during the heating process, and obtain the non-equilibrium microstructure. Because rapid heating provides an insufficient time for phase transformation, grain growth and oxidation, it can improve the forming limit of titanium alloy during the hot stamping using cold die [11].

It is well-known that high-strength steels could obtain martensite microstructure to strengthen the components after hot stamping. However, few applications of martensite strengthening were reported in the forming of titanium alloy components. This is because the fully martensite microstructure obtained by solution and water-quenching in the single β-phase region normally results in a much lower ductility. In this paper, the non-equilibrium hot stamping technology is proposed for titanium alloys to solve the strength-ductility trade-off caused by martensite microstructure. A Ω-shaped Ti-6Al-4V alloy component with fully martensite microstructure was successfully formed.

Experiments

The material used in this study is a Ti-6Al-4V alloy sheet with a thickness of 2 mm. The initial microstructure of the as-received alloy sheet consists of equiaxed α phase and fine β phase. The yield strength, tensile strength and elongation of the Ti-6Al-4V alloy are 975.2 MPa, 1020.9 MPa and 13.6%, respectively. Rapid heating was performed on flat dog-bone-shaped specimens with a Gleeble-3800 thermomechanical simulator. The fully martensite microstructure can be achieved through heating to temperatures in the single β-phase region and water-quenching. Therefore, specimens were heated to 1000℃ and then water-quenched, with heating rates of 2℃·s^{-1} / 15℃·s^{-1} / 50℃·s^{-1} / 100℃·s^{-1}. An additional specimen was tested with 100℃·s^{-1} heating and 120 s soaking. Microstructure samples and tensile specimens were cut from the uniform temperature zone of the water-quenched specimens.

An Ω-shaped component as shown in Fig. 1(a) was used as the demonstrator to validate the non-equilibrium hot stamping process. Rectangular-shaped initial sheets with a size of 200 mm × 120 mm were machined from the as-received Ti-6Al-4V alloy sheet, with its rolling direction along the longitudinal direction. The principle of the non-equilibrium hot stamping process is schematically illustrated in Fig. 1(b). The process routine includes rapid heating, transfer, forming and in-die quenching. The rapid heating was achieved through the contact heating method. In the contact heating, titanium alloy sheets were heated between the high-temperature heating plates within 60 s. The sheet was quickly transferred into the forming dies after heating within 1~2 s, and then formed with in-die quenching simultaneously.

Microstructure samples and tensile specimens were cut from the Ω-shaped components near different measuring points, as shown in Fig. 2. Microstructure observations were performed through a Zeiss Scanning electron microscopy (SEM). The room temperature tensile tests with a strain rate of 0.001 s^{-1} were performed on a Shimadzu AGS-X electronic universal testing machine.

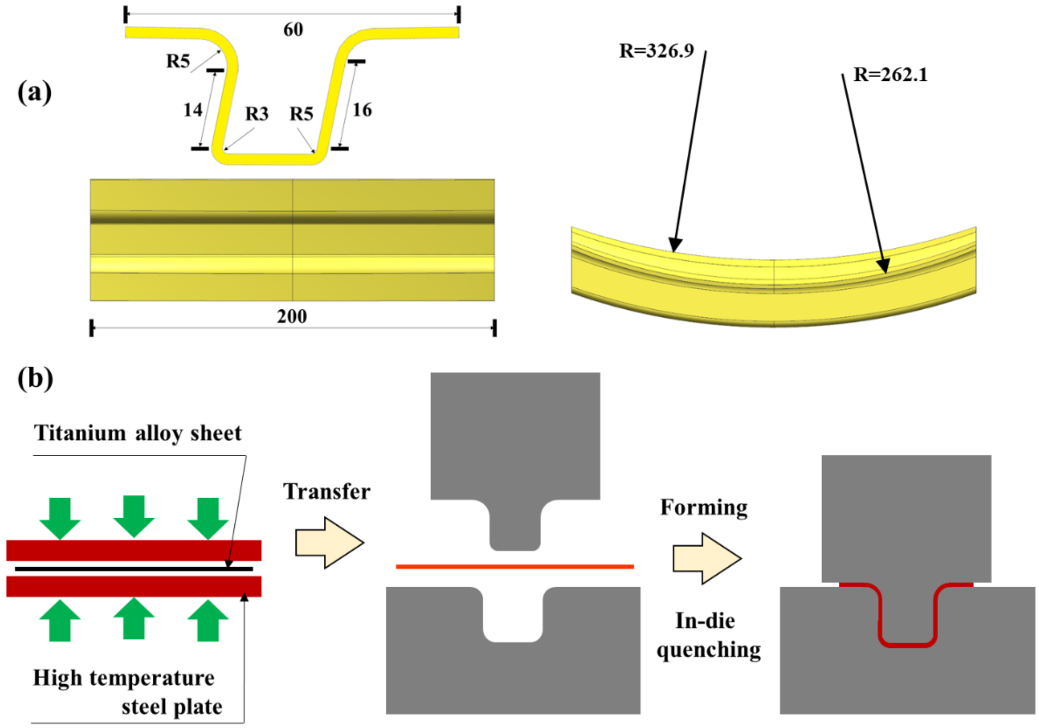

Fig. 1. (a) The dimensional information of the Ω-shaped component and (b) the principle of non-equilibrium hot stamping process (All dimensions are given in mm).

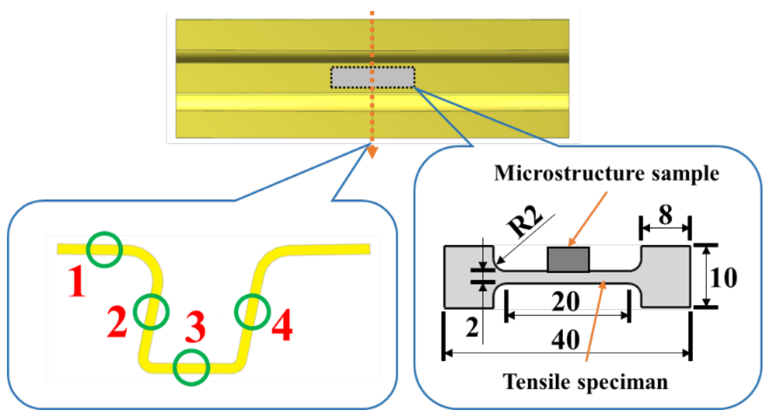

Fig. 2. Diagram of measuring points on the Ω-shaped component, and the dimensional information of tensile specimen and microstructure sample cut from the component around the measuring point (All dimensions are given in mm).

Results and discussion

Fig. 3 shows the fully martensite microstructure after heated to 1000°C through different heating rates then water-quenched. It can be seen that the average size of prior β grains decreases as the heating rate rises, as well as the average width of lamellar α. With soaking for 120 s after rapid heating, the average size of prior β grains and the average width of lamellar α rise apparently. The average size of prior β grains and the average lamellar α width in different microstructures are shown in Fig. 4(a). When the heating rate rises from 2°C to 100°C/s at temperature of 1000°C, the average size of prior β grains decreases from 58.3 μm to 19.5 μm, and the average width of lamellar α decreases from 679.1 nm to 352.0 nm. With soaking for 120 s after heating, the average size of prior β grains rises from 19.5 μm to 94.9 μm in the microstructure heated at 100 °C/s, and the average width of lamellar α increases from 352.0 nm to 719.7 nm.

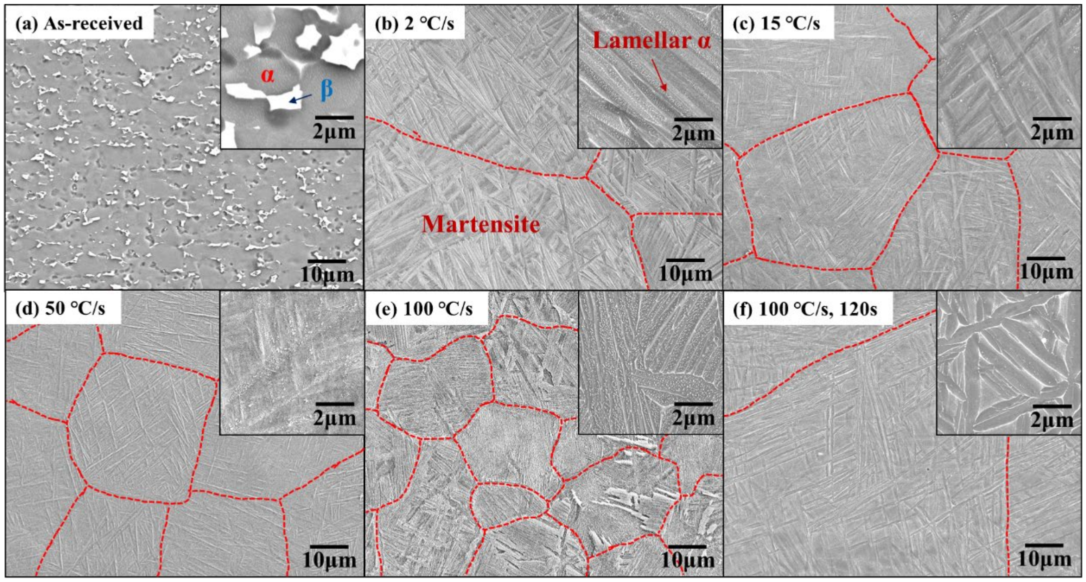

Fig. 3. Microstructures of (a) the as-received Ti-6Al-4V alloy and the Ti-6Al-4V alloy heated to 1000℃ with a heating rate of (b) 2℃/s, (c) 15℃/s, (d) 50℃/s, (e) 100℃/s and (f) 100℃/s with 120 s soaking.

The strength and elongation of water-quenched Ti-6Al-4V alloy tensile specimens after heating to 1000℃ with different heating rates are shown in Fig. 4(b). The yield strength of the alloy increases from 922.4 MPa to 1032.0 MPa when the heating rate rises from 2℃/s to 50℃/s, then decreases to 991.1 MPa when the rate reaches 100℃/s, compared to 982.7 MPa after 120s soaking. The tensile strength increases from 1116.6 MPa to 1263.0 MPa when the rate rises from 2℃/s to 50℃/s, then decreases to 1209.4 MPa when the rate reaches 100℃/s, compared to 1165.9 MPa after 120 s soaking. The yield strength of the specimen heated at 1000℃ is higher than that of the as-received alloy when the heating rate reaches 15℃/s or higher, and the tensile strength is higher than that of the as-received alloy. The elongation increases from 5.2 % to 13.0 % when the heating rate rise from 2℃/s to 100℃/s, and decreases to 4.5 % after 120 s soaking. The water-quenched Ti-6Al-4V alloy heated to 1000℃ has the highest yield strength and tensile strength at a heating rate of 50℃/s, with an elongation of 9.6%. Results above indicate that rapid-heated Ti-6Al-4V alloy can achieve better strength and ductility with fully martensite microstructure after heating to a temperature in the single β-phase region, due to finer prior β grains when the alloy is heated at a higher rate.

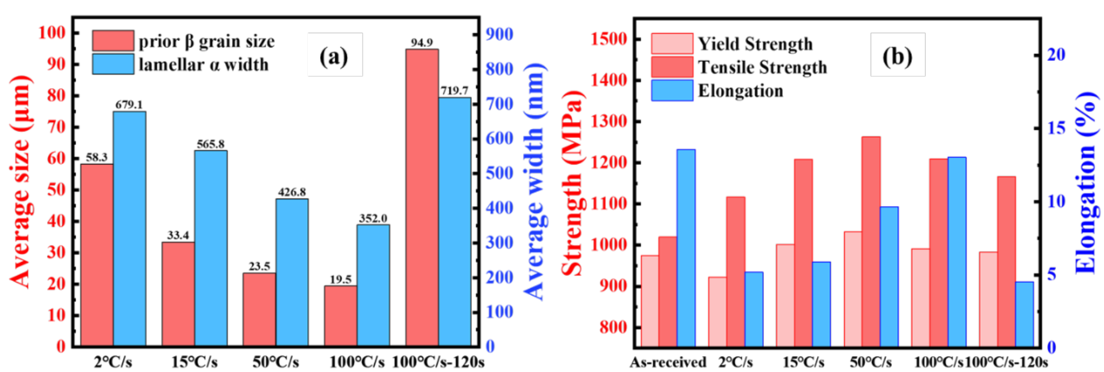

Fig. 4. Effects of heating rate on (a) the average prior β grain size and the average lamellar α width, along with (b) the strength and elongation of the Ti-6Al-4V alloy with fully martensite microstructure.

Considering both post-form property and heating device requirements, heating rates ranging from 10 to 50℃/s are recommended for the non-equilibrium hot stamping. Fig. 5 shows a qualified result of the Ti-6Al-4V alloy Ω-shaped component formed by the novel process. The sheet was heated to 1050℃ within 60s, with an average heating rate of 17.5℃/s. It can be seen that no cracks appear on the component surface and the geometry features were also accurately formed. This proves that titanium alloys thin-walled components can be successfully formed by hot stamping using rapid heating to the temperature in the single β-phase region.

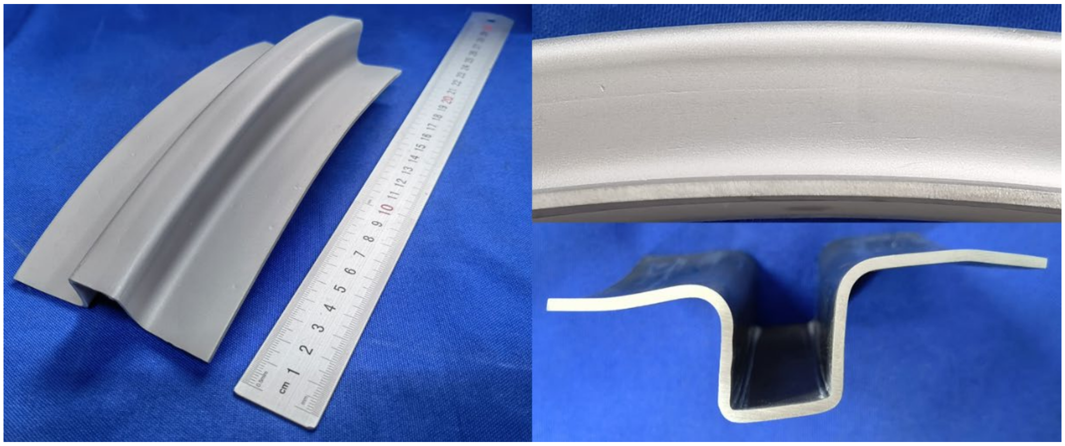

Fig. 5. A qualified result of Ω-shaped component formed at a sheet temperature of 1050℃.

Microstructures of the Ω-shaped component with a sheet temperature of 1050℃ are shown in Fig. 6. It can be seen that the Ω-shaped component can achieve fully martensite microstructure after hot stamping with a sheet temperature of 1050 ℃. The average sizes of prior β grains in the fully martensite microstructure near the measuring point 1 to 4 are 76.5μm / 65.0μm / 81.3μm / 60.4μm, respectively. Prior β grains in the microstructures near the measuring point 2 and 4 are finer than those in the microstructures near the measuring point 1 and 3.

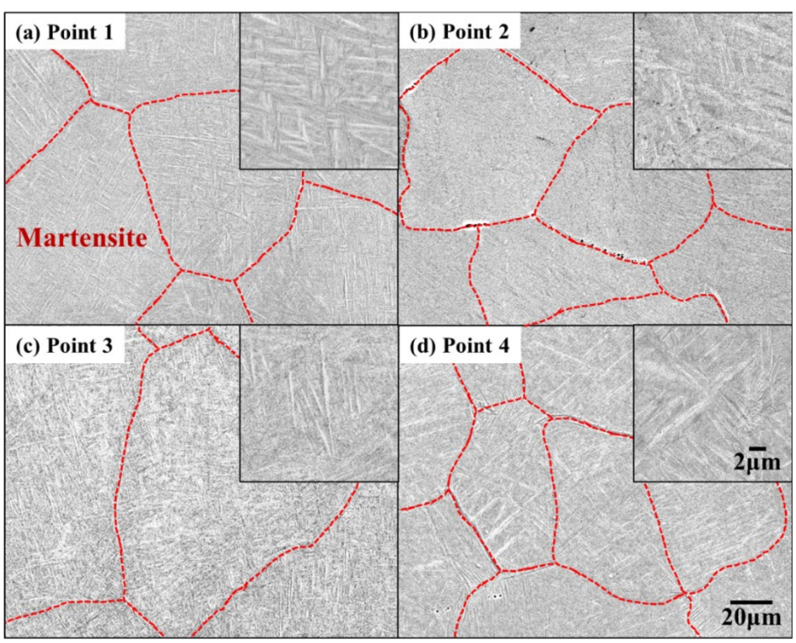

Fig. 6. The fully martensite microstructure in the Ω-shaped component near the (a) measuring point 1, (b) measuring point 2, (c) measuring point 3 and (d) measuring point 4.

The mechanical properties of the Ω-shaped component near different measuring points are shown in Fig. 7. It can be seen that the yield strength and the tensile strength of the component are higher than those of the as-received sheet. The yield strength of the component remains at a range of 1011.2 MPa ~ 1060.6 MPa, 3.7% ~ 8.8% higher than that of the as-received sheet. The tensile strength remains at a range of 1106.3 MPa ~ 1153.9 MPa, 8.4% ~ 13.0% higher than that of the as-received sheet. Furthermore, the elongation of the component exceeds a range of 7.7% ~ 8.5%. The distribution of the overall mechanical properties is relatively uniform.

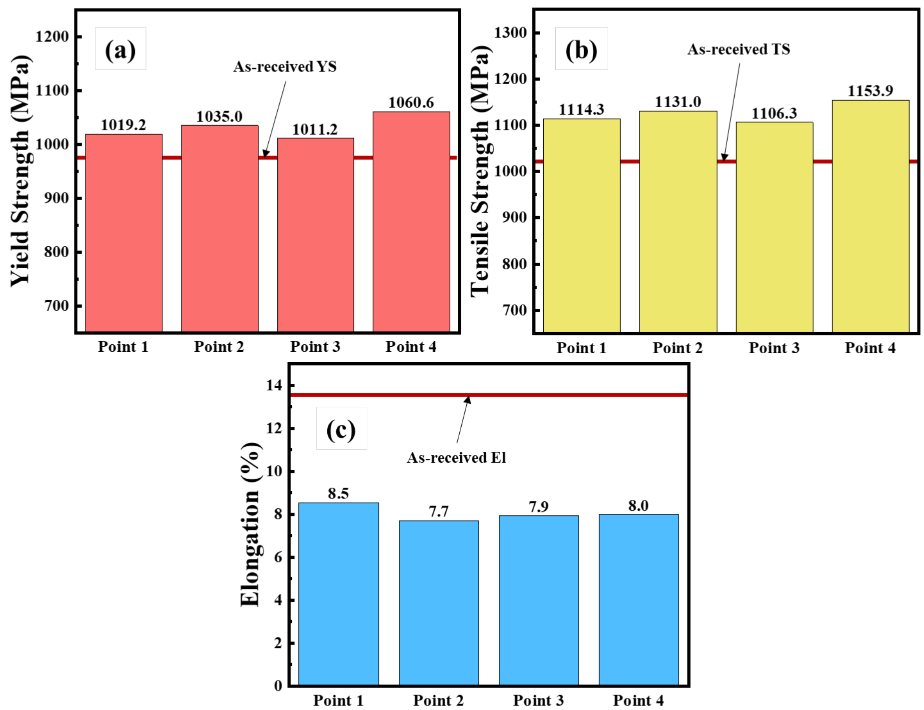

Fig. 7. The (a) yield strength, (b) tensile strength and (c) elongation of the Ti-6Al-4V alloy near different measuring points in the Ω-shaped component.

The above results demonstrates that one could use martensite microstructure to strengthen titanium alloy component and meanwhile avoid the crack failure by non-equilibrium hot stamping process. This is because when the heating temperature is in the single β-phase region, a higher heating rate leads to finer prior β grains, along with finer internal lamellar α after water-quenching [12]. The refined martensite microstructure could strengthen titanium alloys and reserve most plasticity at the same time [13].

Conclusion

In this study, the effects of rapid heating in the single β-phase region on the Ti-6Al-4V alloy microstructure evolution and mechanical properties was investigated. The Ti-6Al-4V alloy Ω-shaped component with fully martensite microstructure was formed via non-equilibrium hot stamping process. The distribution of microstructure and mechanical properties was summarized. The main conclusions are as follows:

(1) The martensite microstructure after rapid heating affects the mechanical properties of Ti-6Al-4V alloy significantly. The average size of prior β grains and the average width of internal lamellar α decrease as heating rate rises. A higher heating rate in the single β-phase region tends to increase both strength and elongation. The tensile strength of Ti-6Al-4V alloy increases from 1116.6 to 1263.0 MPa and the elongation increases from 5.2 % to 9.6 %, when the heating rate rises from 2℃/s to 50℃/s.

(2) The titanium alloy thin-walled components could be strengthened by fully martensite microstructure, which could be obtained by non-equilibrium hot stamping with rapid heating process. With heating temperature of 1050℃ and average heating rate of 17.5℃/s, a Ti-6Al-4V alloy thin-walled component with fully martensite microstructure was successfully formed. A maximum tensile strength of the formed component could reach up to 1153.9 MPa, which is 13.0% higher than that of the as-received sheet. And a total elongation of 8.0% was remained at room temperature.

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