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Effect of deformation temperature on mechanical properties, microstructure, and springback of Ti-6Al-4V sheets

Rukiye Ertan[a,*], Güner Çetin[b]

[a]Department of Automotive Engineering, Engineering Faculty, Bursa Uludağ University, Görükle TR-16059 Bursa, Turkey

[b]Orhan Automotive Control Systems Industry Inc., Nilüfer TR-16159 Bursa, Turkey

(*Corresponding author: rukiye@uludag.edu.tr)

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ABSTRACT: Ti-6Al-4V titanium alloy is applied in various industrial applications such as aerospace, jet engine, and automotive industries due to its strength-to-weight ratio and excellent high-temperature properties. For these demanding applications, the formability of the material and the effect of forming parameters on the final mechanical properties are of great importance. In this study, the springback behavior of hot-formed 1 mm sheet Ti-6Al-4V alloy was investigated related to the deformation temperature ranging from 350 to 950 °C. After the hot forming, the springback angles of the U profile were examined and associated with the mechanical properties and the microstructural evolution. The microstructure changing mechanisms were mapped at each temperature of deformed sheets with the help of optical microscopy. As a result, it was observed that important microstructural changes have occurred, such as recrystallization, grain growth, and phase transformations, which themselves greatly influence the springback angle and the mechanical properties. The formability of the Ti-6Al-4V sheet material was found to be strongly dependent on the applied process temperatures and the activated microstructural deformation mechanisms. Hot forming at 850 °C leads to the lowest springback angle, but after the hot-forming, pronounced softening of the material occurs due to the recrystallization.

KEYWORDS: Hot forming; Mechanical properties; Microstructure; Springback; Titanium alloy

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RESUMEN: *Efecto de la temperatura de deformación sobre las propiedades mecánicas, la microestructura y la recuperación elástica (springback effect) en chapas de Ti-6Al-4V.* La aleación de titanio Ti-6Al-4V se utiliza en diversas aplicaciones industriales como la industria aeroespacial, de motores a reacción y automotriz debido a su buena relación entre resistencia y peso, y a sus excelentes propiedades a altas temperaturas. Para estas exigentes aplicaciones, la conformabilidad del material y el efecto de los parámetros de conformado sobre las propiedades mecánicas finales son de gran importancia. En este estudio, se investigó el comportamiento de recuperación elástica (*springback effect*) en chapas de 1 mm de espesor, conformadas en caliente, de la aleación Ti-6Al-4V, en relación con la temperatura de deformación, la cual osciló entre 350 y 950 °C. Después del conformado en caliente, se examinaron los ángulos de recuperación elástica de perfiles en U y se asociaron con las propiedades mecánicas y la evolución microestructural. Se estudiaron los mecanismos de transformación microestructural a cada temperatura de deformación con la ayuda de microscopía óptica. Se observaron importantes cambios microestructurales como recristalización, crecimiento de grano y transformaciones de fase, que influyen en gran medida en el ángulo de recuperación elástica y en las propiedades mecánicas. Se descubrió que la conformabilidad del material en chapas de Ti-6Al-4V depende, en gran medida, de las temperaturas de procesado utilizadas y de los mecanismos de deformación microestructural activados. El conformado en caliente a 850 °C produce el ángulo de recuperación elástica más baja, pero, después del conformado en caliente, se produce un ablandamiento pronunciado del material debido a la recristalización.

PALABRAS CLAVE: Aleación de titanio; Conformado en caliente; Microestructura; Propiedades mecánicas; Recuperación elástica (springback effect)

ORCID ID: Rukiye Ertan (https://orcid.org/0000-0002-9631-4607); Güner Çetin (https://orcid.org/0000-0002-7414-7756)

1. INTRODUCTION

Titanium alloys have excellent properties such as high strength at high temperatures, low density, and high corrosion resistance. They are used in biomedical, aerospace, automotive parts, defense industry, marine, and chemical industries (Leyens and Peters, 2003; Cui *et al.*, 2011). Although titanium is costly to use compared to alternative materials, it is indispensable in some applications due to these withstand properties (Beal *et al.*, 2006).

Alloy Ti-6Al-4V with α-β microstructure is the most used titanium alloy in industry, accounting for approximately 75-85% of the global titanium production (Mosleh *et al.*, 2018). This material is commonly a sheet formed by a cold or hot plastic deformation process. However, the forming of complex-shaped parts is costly and problematic due to the high yield strength and low elastic modulus. Notably, the formability of Ti-6Al-4V at room temperature is low and limited. Increasing the temperature increases the formability, reduces springback, increasing the part geometrical accuracy (Fan *et al.*, 2013; Liu *et al.*, 2017). The forming process parameters such as temperature and strain rate significantly affect flow behavior, microstructural characteristics, and mechanical properties of titanium alloys (Özturk *et al.*, 2013; Zong *et al.*, 2015; Quan *et al.*, 2015; Kopec *et al.*, 2018). Depending on the temperature, the name of the process varies, such as at low temperature it is drawing, at the intermediate temperature it is hot forming or hot stamping, and at very high temperature it is superplastic forming (SPF) (Liu *et al.*, 2002). In terms of ductility and springback behavior, it is generally preferred to form Ti-6Al-4V alloy at temperatures above 540 °C and below the β-trans temperature. In hot forming, the temperature is considered between 750 °C and 890 °C and SPF above 900 °C. Compared to SPF, the process temperatures of hot stamping are considerably lower, making it a higher potential for the forming industry. However, decreasing the forming temperature increases the springback effect (Liu *et al.*, 2002).

Many studies have been carried out on the deformation behavior at high temperatures of Ti-6Al-4V alloy (Brooks, 1982; Welsch *et al.*, 1993; Semiatin *et al.*, 1999; Picu and Majorell, 2002; Fan *et al.*, 2017; Wang *et al.*, 2017). Quan *et al.* (2015) performed a series of Ti–6Al–4V alloy compressions with a height reduction of 60% in a temperature range of 750 – 1050 °C and a strain rate range of 0.01–10 s^{-1} on a Gleeble-3500 thermo-mechanical simulator. They found that the formability of titanium alloys could increase by increasing the temperature and could decrease by increasing the strain rate in the lower temperature region. The strain required for the same amount of dynamic recrystallization (DRX) volume fraction in a constant strain rate increased with decreasing temperature, in contrast, for a constant temperature, it increased with increasing strain rate. However, they found that the elongation to failure more strongly depends on the strain rate than does the deformation temperature for the Ti6Al4V alloy. Mosleh *et al.* (2018) investigated the effect of temperature and strain rate on the superplastic deformation behavior of Ti-based alloys in the (α+β) temperature field alloys. They found that 850 °C and 0.001 s^{-1} are the optimum superplastic temperature and strain rate for maximum elongation for the Ti6Al4V alloy. Typically, an increase of the tensile strength value was observed as the strain rate increased and the temperature decreased. Increasing temperature further led to a decrease in the elongation to failure, due to the β-phase fraction increase. Kopec *et al.* (2018) studied the formability of the Ti-6Al-4V alloy on a novel hot stamping process. They found the elongation ranging from 30% to 60% could be achieved at temperatures ranging from 750 to 900 °C, respectively, and qualified parts can be formed successfully at 750- 850 °C. The hardness of the material after deformation first decreased with the temperature due to recovery and subsequently increased mainly due to the phase transformation. Öztürk *et al.* (2013) used the electric resistance heating method to investigate the effect of temperature on the mechanical properties of the Ti-6Al-4V sheets. The yield stress and tensile stresses decrease with an increase in the temperature considerably, and the total elongation is raised significantly above 500 °C.

However, few references can be found focusing on the springback behavior of the hot-stamped Ti-6Al-4V alloy. In terms of production time and cost, keeping the springback phenomenon to a minimum and achieving the required mechanical performance is vital. Zamzuri *et al.* (2013) have applied the resistance heating to the hot hat-shaped bending of Ti–6Al–4V alloy sheets. They found that using resistance heating above 370 °C is effective in preventing the springback and oxidation of the titanium alloy sheet. The bending load at a heating temperature of 880 °C reduced from 6.5 kN at room temperature to 1.8 kN. Zong *et al.* (2015) investigated the springback behavior of Ti-6Al-4V alloy via the V-bending process, and they found that the rising temperature effectively softens and facilitates the flow behavior. The springback angle was eliminated when Ti-6Al-4V was treated at around 750 °C and held for 8–10 min.

Therefore, the paper aims to evaluate the springback behavior of the Ti-6Al-4V alloy deformed on the U-bending process at room temperature and temperature ranges between 350-950 °C. The springback angles of the deformed sheets were measured. Tensile and hardness tests were performed on the specimens taken from the upper and side-wall surfaces of the deformed sheets. Microstructural analysis was also conducted on upper and side-wall specimens. The effect of the deformation temperature on the springback behavior and mechanical properties of the Ti-6Al-4V alloy is then critically examined related to the microstructural modifications.

2. MATERIALS AND METHODS

In this study, Ti-6Al-4V alloy sheets with 1 mm thickness were investigated. The chemical composition of the sheet is given in Table 1.

TABLE 1. Chemical composition of Ti-6Al-4V (wt.-%)

Composition	Al	V	Fe	O	N	H	C	Ti
Content	5.9	4	0.09	0.14	0.01	0.002	0.01	Bal.

In the as-received condition, Ti-6Al-4V alloy microstructure with slightly elongated grains of h.c.p. α (light) and intergranular b.c.c. β (dark) two-phase structure was observed under an optical microscope (Fig. 1).

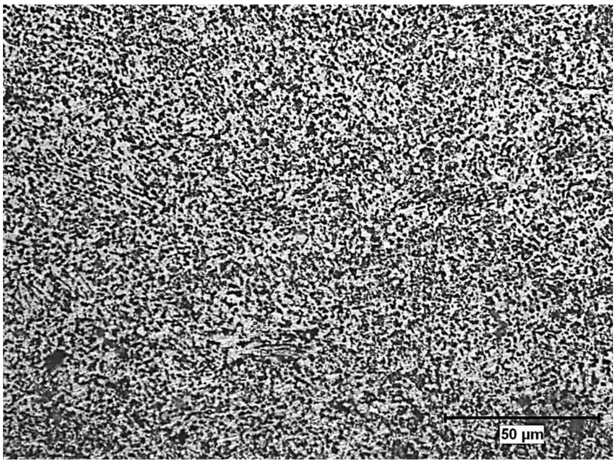

FIGURE 1. The microstructure of Ti-6Al-4V alloy as received.

Ti-6Al-4V sheets were primarily cut into blanks with a size of 500×400×1 mm^3 in the specimen preparation process, and the blanks' length direction was along the rolling direction. Then the blanks were heated to temperatures of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C for 10 min in a conventional furnace. At the end of this process, the heated blanks were directly transferred to the press and subsequently formed. The transfer time from the furnace to the cold die was 5 s, and the temperature drop was around 50 °C. The hot-forming process was carried out on a 200 ton hydraulic press with 10 mm/s punch speed. The blanks were formed and held for 1 min in the dies. The experimental setup is shown in Fig. 2a, in which the punch and die were made by a tool steel.

The test specimens, as shown in Fig. 2b, were taken from the bottom and the side-wall of the formed U blank. The microstructure evolution of the samples was observed through optical microscopy. The samples were prepared by conventional metallographic procedures for microstructural characterization of titanium, including hot mounting, grinding, and polishing. The samples were polished using 600, 800, 1200, 2000, and 2500 SiC papers, and the final polishing was carried out using a 3 µm diamond polishing solution and water-based lubricant. The samples were etched in Kroll etchant for 15–20 s, wiped with a cotton ball, and thoroughly washed and dried. Microstructure images were captured using a Nikon Eclipse MA100 optical microscope.

The tensile and hardness tests were performed at room temperature. The dimensions of tensile test specimens according to the ASTM E8 standards were given in Fig. 2b. Tensile tests were performed at 10 mm/min constant strain rate on UTEST 25 tons universal tensile testing machine. The Vickers hardness values of the specimens after the hot-forming were measured through a Metkon Duroline-M brand hardness tester at room temperature with six measurements per specimen. Measurements were performed using a 0.5 kg load for 10 s dwelling time.

The images of the U-profiles were taken with an Olympus digital camera white light scanning system to determine the springback behavior. A wireframe model was generated from the digital images, and texture mapping was done using the RapidForm software. The scanned data was registered into the

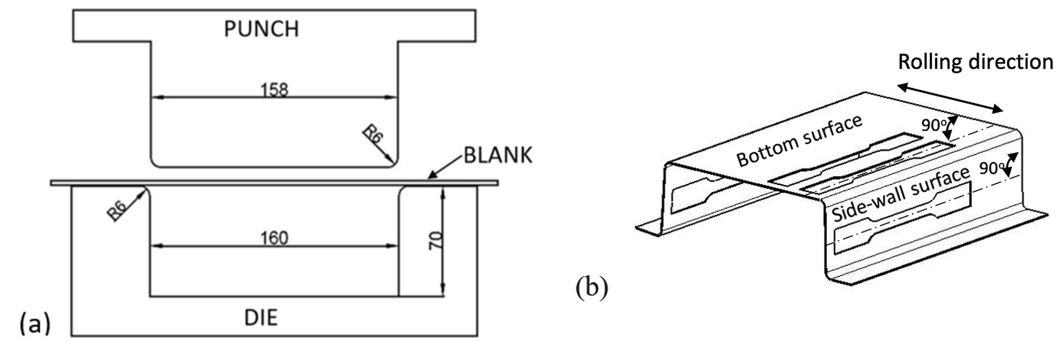

FIGURE 2. Experimental setup of (a) hydraulic press and (b) die and punch used for hot forming.

CAD data to display the data sets by using the software. The springback behavior of the U-profiles was defined by the side-wall angle, having the most critical effect on dimensional accuracy and thus affecting the subsequent assemblies (Zong *et al.*, 2015). The springback amount was measured by the angle (θ) between the deformed shape of the blank without and after springback (Fig. 3).

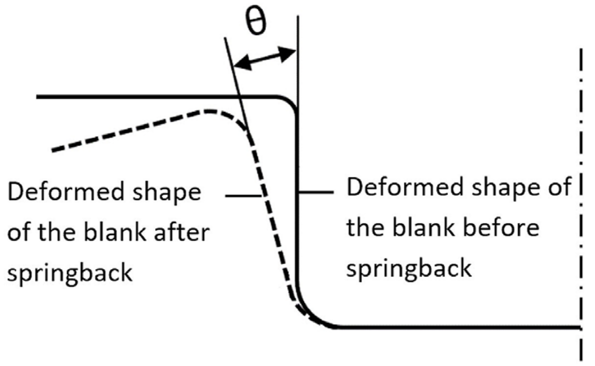

FIGURE 3. The location of specimens taken from formed part.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

The room temperature tensile properties and microhardness of the test specimens, which were cut from the bottom and the side-wall surface of the formed parts, produced through the hot-forming process at different temperatures, are presented in Fig. 4. The trend of curves shows that the forming start temperature has a significant influence on the tensile strength and hardness of the formed parts. Increasing the forming temperature leads to a reduction of the tensile strength and hardness in the exact parallel. As it can be seen, there are differences in the tensile strength between the side-wall and the bottom surface specimens after 450 °C. Because of the gap between the die, punch, and sheet, the contact time of the side-wall surface is delayed compared with the bottom surface of the formed component, leading to a reduced heat transfer. The bottom surface of the punch contacts the sheet earlier than the side-wall surfaces of the sheet during hot forming and rapid cooling starts from higher temperatures primarily at the bottom surface. Besides, deformation hardening occurs due to compression by punch and die increase at the bottom surface of the blank. Furthermore, the actual contact area is smaller on the side-wall surface than the bottom surface, pressed between die and punch. For these reasons, a decrease in the tensile strength and hardness related to the temperature was realized more prominently in the side-wall surface above 450 °C.

The material, which gradually softens up to 750 °C, the tensile strengths of the bottom and the side-wall specimens were slightly decreased about 7% with increasing forming temperature from 450 °C to 750 °C. A similar change occurred in the microhardness. After 750 °C, undergoes a phase change above this temperature, producing an increase in the tensile strength and microhardness. Tensile strength, which reached a minimum value of around 1010 MPa at 750 °C, increased about 4% in the bottom specimens and 3% in the side-wall specimens until 950 °C. Beyond 750 °C, the microhardness increased more slightly compared to the strength in all specimens.

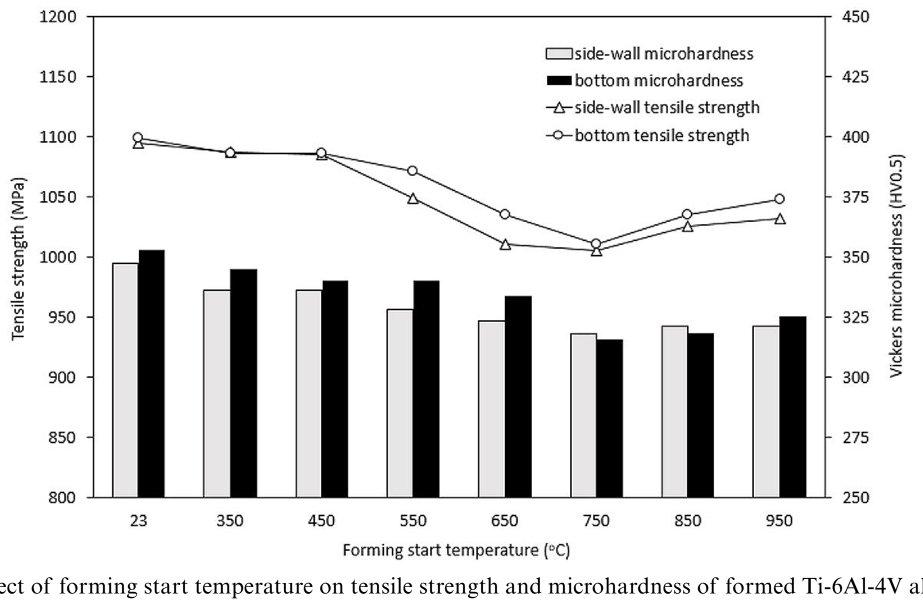

FIGURE 4. The effect of forming start temperature on tensile strength and microhardness of formed Ti-6Al-4V alloy parts in the bottom and side-wall surfaces.

3.2. Microstructure evaluation

The effect of the forming start temperatures on the microstructural changes is investigated in this study. The microstructure of the samples with forming start temperatures ranging between 350 to 550 °C are given in Fig. 5. The microstructure images of bottom and side-wall samples are very similar, and no significant difference is noticed regarding the phases found or their grain sizes. The microstructure of the room temperature formed part consisted of primary α phase and β phase, and the average length of the lamellar α phase was about 3-7 μm (Fig. 5a). The microstructure of the samples with 350 °C and 450 °C forming start temperatures did not differ noticeably from the starting structure due to the small amount of β phase that exists at this temperature. Fig. 5a-c show the uniform duplex microstructure composed of lamellar α phase together with the β phase. It can be observed that the lamellar structure (Fig. 5a-c) has transformed into an equiaxed structure (Fig. 5d) with the increase in temperature. However, a decrease in the tensile strength and microhardness was also observed at 550 °C (Fig. 4).

On the other hand, the microstructure evolution of Ti-6Al-4V alloy during forming processes at elevated temperatures includes three mechanisms: recovery, recrystallization, and phase transformation. Consequently, the micro constituents and microstructures varied in several types, and two types of α, primary and secondary (or transformed β), are present. The primary α is present during prior hot working, and the secondary α is produced by transformation from β (Brooks, 1982). The α phase in these conditions has different appearances and maybe acicular or lamellar, platelike, serrated, martensitic, basket weave or Widmanstätten. In this study, the microstructure samples of the bottom surface of hot-formed blanks at 650 °C, 750 °C, 850 °C, and 950 °C are given in Fig. 6, and the samples of the side-wall surface in Fig. 7. The microstructure images and mechanical tests (Fig. 4) clearly show that most of these mechanisms and micro constituents took place when the temperature was higher than 650 °C. The microstructural changes show that different mechanisms occur in the bottom and side-wall surfaces of the formed part. The microstructure of the samples taken from the formed part at 650 °C consists of elongated α grains (light) in a matrix with transformed β grains (dark) for the

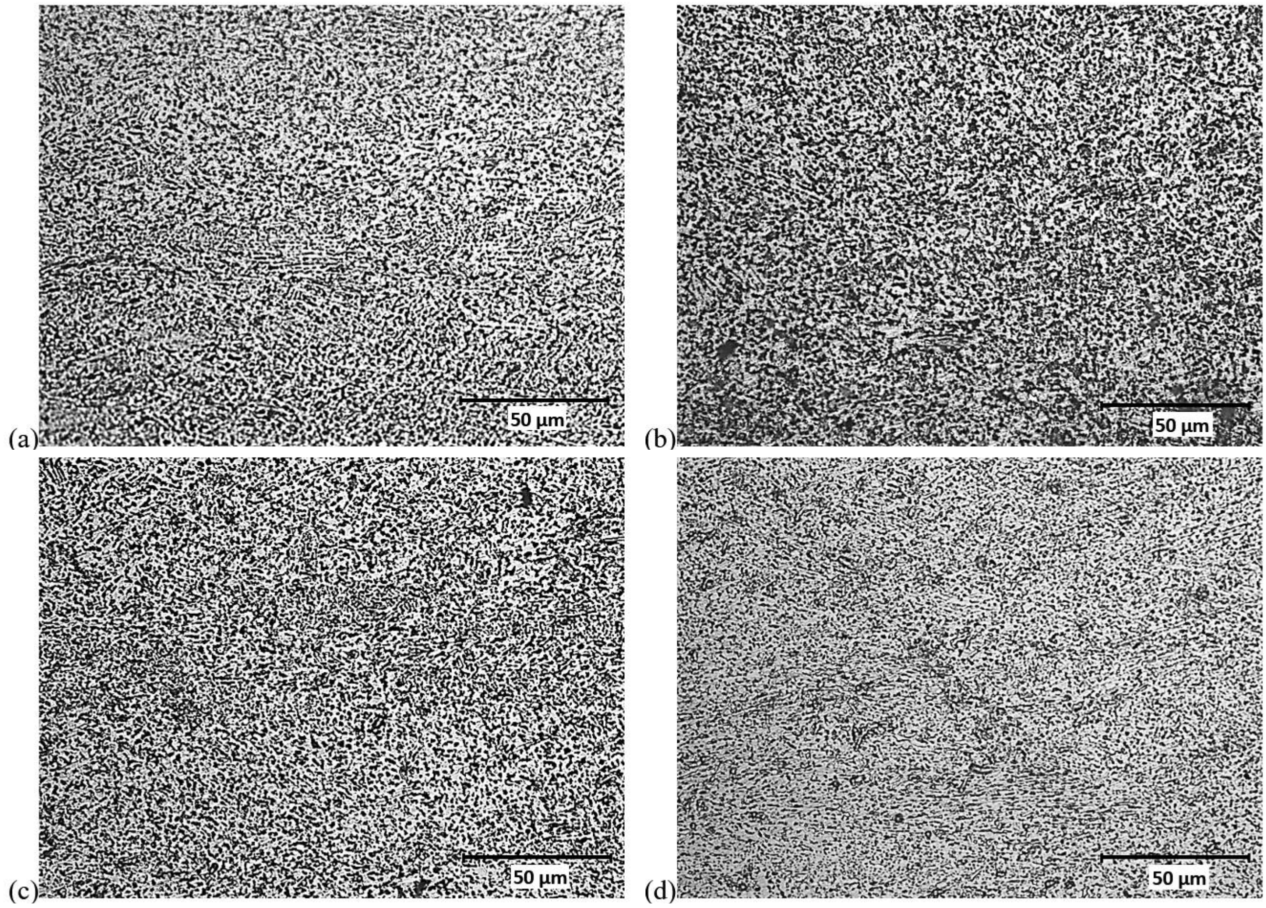

FIGURE 5. Microstructure images of the samples with (a) room temperature, (b) 350 °C, (c) 450 °C, and (d) 550 °C forming start temperatures.

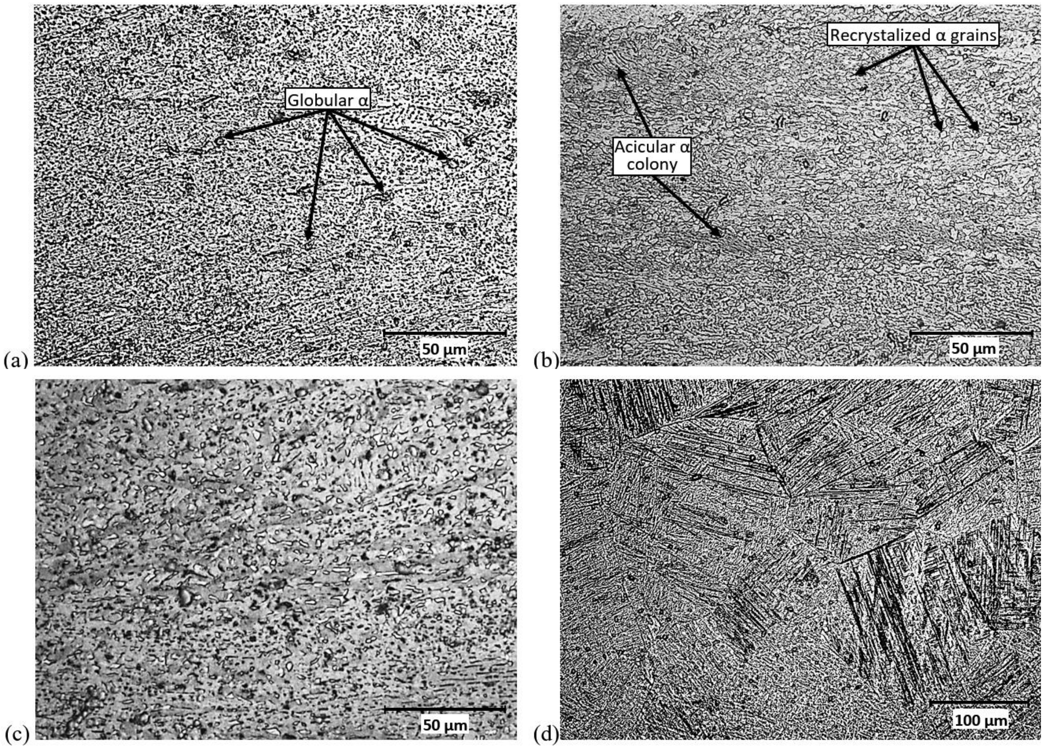

FIGURE 6. Microstructure images of the bottom surface samples with (a) 650 °C, (b) 750 °C, (c) 850 °C, and (d) 950 °C forming start temperature.

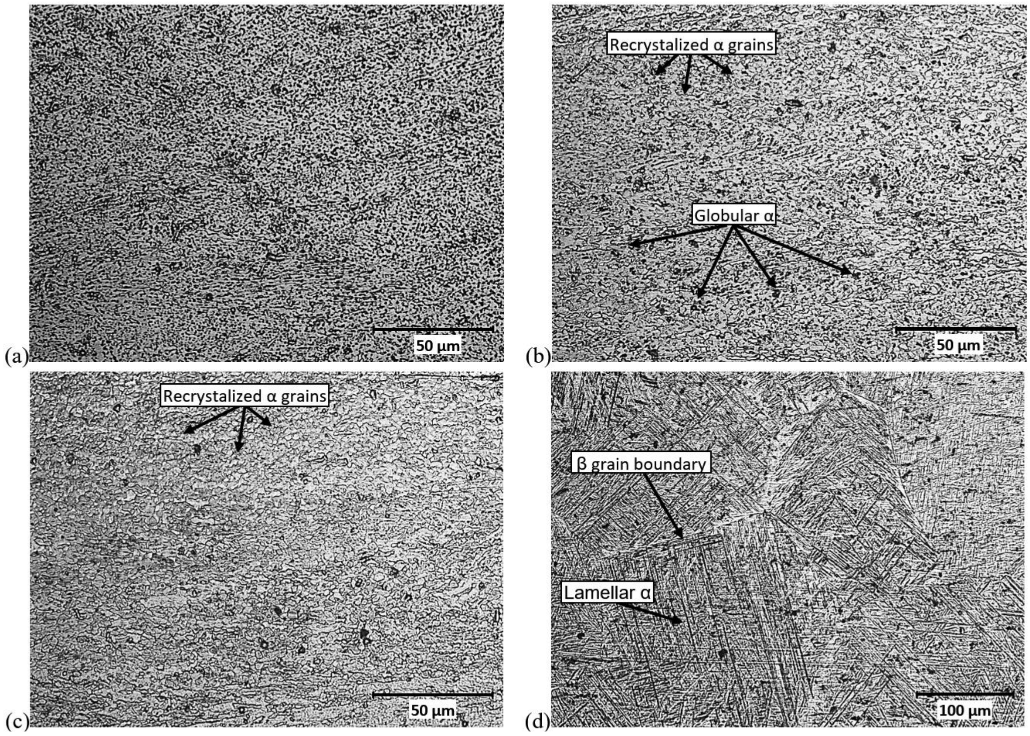

FIGURE 7. Microstructure images of the side-wall surface samples with (a) 650 °C, (b) 750 °C, (c) 850 °C and (d) 950 °C forming start temperature.

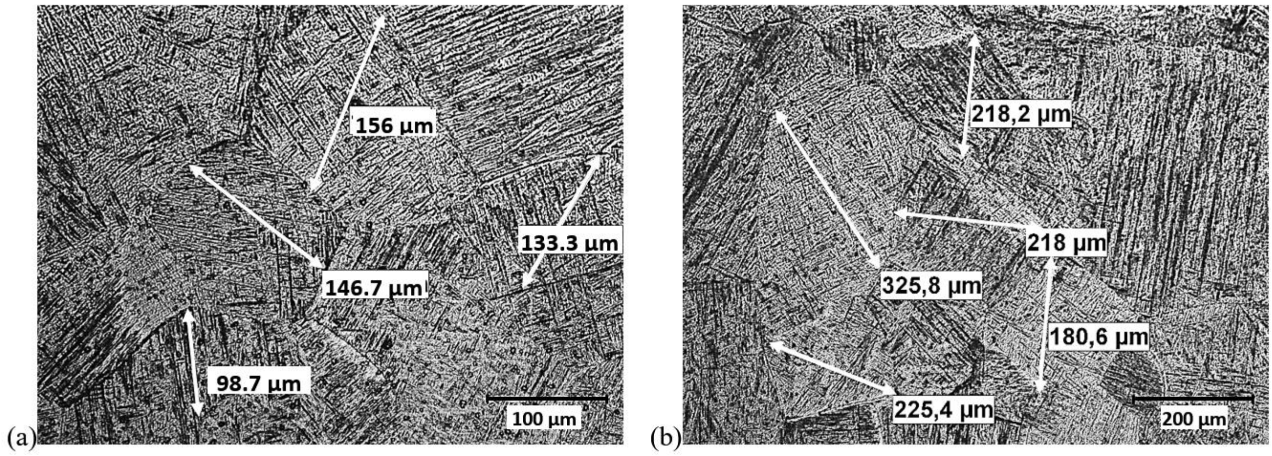

FIGURE 8. Microstructure images with grain size measurements of (a) the bottom and (b) the side-wall surface samples formed at 950 °C temperature.

bottom and side-wall surfaces (Fig. 6a and 7a). Also, the grain size of primary α increased in some places, and a coarse-grained equiaxed structure called globular was formed within an intergranular phase. Globularization is deformation-induced and occurred at kinks in the lamellae and some of the prior-beta grain boundaries with the loss of coherency of α/β interfaces (Fan *et al.*, 2017). A critical strain is required for the initiation, and increasing temperature increases the globularization rate (Semiatin *et al.*, 1999). The critical strain rate was exceeded in this study, and globular α has slightly occurred above 650 °C.

It can be observed that increasing the forming temperature increased the transformed β containing acicular α (Fig. 6b). Acicular α is the most common transformation product, a result of nucleation and growth on crystallographic planes of the prior β matrix (Welsch *et al.*, 1993). It is possible to see that acicular α occurred in colonies at the bottom surface samples of blanks formed at 750 °C (Fig. 6b). This formation slightly took place in the side-wall surface samples at a higher temperature of 850 °C (Fig. 7c). It is thought that this difference occurs because the bottom surface of the punch contacts the blank earlier than the side-wall surfaces during forming, and the rapid cooling starts from higher β rates in the bottom surface samples. Fig. 6b also shows the homogeneously distributed dynamic recrystallized (DRX) equixial α grains with 2-5 µm in size in the sample deformed at 750 °C forming start temperature. DRX was mostly occurred in the α phase due to the low content of the β phase in microstructure at 750 °C (Wang *et al.*, 2017). The tensile strength and microhardness results also support this, showing the lowest value at 750°C, due to the softening effect of recrystallization.

The samples formed at 850 °C forming start temperature exhibited both equiaxed and elongated α structures, the amount of globular α increased in the intergranular β phase. As the temperature increases, β phase transformation increases, and the volume fraction and grain size of DRX grains also increase (Fig. 6c). Individual grains elongated in the direction of the metal flow or plastic deformation.

The microstructure of the formed part at 950 °C forming start temperature indicates a coarse transformed β structure (Fig. 6d and Fig. 7d). At high temperature and low strain rate, a long time exposure can result in dynamic grain growth. At 950 °C, the structure consists of stable α and β phases in the shape of colonies of parallel α-phase lamellae in primary β-phase grains (Fig. 6d and Fig. 7d). This characteristic microstructure is called "basket weave" or Widmanstätten. The Widmanstätten structure often nucleates at the α-allotromorphous and includes lamellar α+β colonies surrounded by untransformed thin β phase. The width of the α plates increased drastically compared with room temperature formed part grain width, from about 3-7 µm to 55-120 µm in the bottom surface samples (Fig. 8a) and 120-350 µm in the side-wall surface samples (Fig. 8b). Due to the later contact with the blank and tools, slower cooling (cooling in the air) of the side-wall surface samples takes place and significant grain coarsening occurred compared to the bottom surface samples.

3.3. Springback behavior

The springback angles of Ti-6Al-4V alloy formed parts at different forming start temperatures are given in Fig. 9. By comparing the profile of U-bending parts formed at different temperatures, it is found that the springback angle was reduced significantly with the increase in the forming start temperature. The angle decreased from 24° to 15° between the

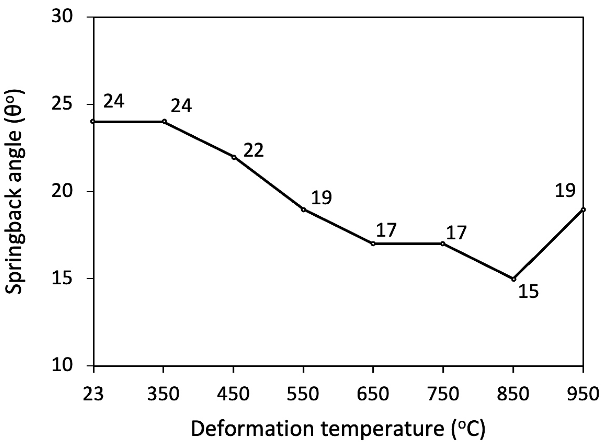

FIGURE 9. The effect of forming start temperature on springback angles of formed Ti-6Al-4V alloy parts.

room temperature and 850 °C forming start temperature. Zong *et al.* (2015) and Kopec *et al.* (2018) reported that the Ti-6Al-4V exhibits good ductility and material softening during the hot deformation process at temperatures between 700-850 °C and the springback angle was reduced between these temperatures. The phase transformation of Ti-6Al-4V alloy between these temperatures is dominated by the fact that there is two-phase change as the temperature is increased: dynamic recrystallization and β phase transformation. Picu and Majorell (2002) have described that the rise in temperature causes the increase in the rate of β phase transformation and causes flow stress drop. So, the deformation at high temperatures lowers the mechanical strength and reduces the amount of springback for the formed sheet because of their lower yield strength to elastic modulus ratio (Welsch *et al.*, 1993). However, with the increase in forming start temperature from 850 °C to 950 °C, the springback angle increased to 19° because of the formation of the Widmanstatten microstructure as stated above.

4. CONCLUSIONS

In this study, the effect of the forming start temperature on mechanical properties, microstructure, and springback behavior of the bottom and side-wall surface specimens of the U-profile formed parts were investigated. Based on the test results and microstructural analyzes, the following conclusions were derived:

- There is no significant difference noticed in the microstructure evolution and mechanical properties until 550 °C forming start temperature between the bottom and side-wall surfaces. However, the springback angle decreased by 24%.
- Increasing the forming start temperature increased the transformed β and globular α within the intergranular phase. In addition, dynamic recrystallization was found to appear during forming of Ti-6Al-4V alloy at 750 °C forming start temperature. By increasing the forming start temperature from 550 °C to 750 °C, the hardness of the bottom surface specimens decreased by 7.4%, and the side-wall samples decreased by 3%. The tensile strength of the formed parts decreased by 60 MPa in the bottom surface specimens and 40 MPa in the side-wall specimens, and the springback angle decreased by 11% between these temperatures.
- After heating to 950 °C temperature, significant phase transformation and grain coarsening occurred. The microstructure of the bottom and side-wall surface samples was fully transformed into a Widmanstätten structure. The tensile strength and hardness distribution demonstrated the same tendency and indicated an increase of about 3%, and the springback angle was also increased by 26.7% due to the phase transformation between the 850 °C and 950 °C deformation temperatures.

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