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Effect of Incremental Forming Parameters on Titanium Alloys Properties

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Abstract**—**Shear spinning is closely related to the asymmetric incremental sheet forming (AISF) that could significantly reduce costs incurred by the fabrication of complex aeronautical components with a minimal environmental impact. The spinning experiments were carried out on commercially pure titanium (Ti-Gr2) and Ti-6Al-4V (Ti-Gr5) alloy. Three forming modes were used to characterize the titanium alloys properties from the point of view of different spinning parameters. The structure and properties of the materials were assessed by means of metallographic analyses and microhardness measurements. The highest value wall angle failure limit was achieved using spinning parameters mode for both materials. The feed rate effect was observed only in the samples from the Ti-Gr2 material, when a refinement of the grain microstructure with lower feed rate and higher tangential speed occurred. Ti-Gr5 alloy exhibited a decrease of the microhardness at higher straining due to recovery processes.

Keywords**—**Incremental forming, metallography, shear spinning, titanium alloys.

I. Introduction

TITANIUM and its alloys are industrially of great importance due to their excellent properties such as high strength, hot workability, corrosion resistance, strength-weight ratio, toughness, etc. in high performance applications (i.e., aerospace, automotive, and bio-medical materials) [1]–[4]. However, exhaustive application of the products made from titanium and its alloy counterparts into the commercial sector has been limited by the high cost of the metal and its heat treatment [1]. This limitation has engineered a considerable amount of scientific and technological interest in developing potentially viable and economically affordable manufacturing methods that aid in reducing the cost of the product.

One of these methods is an asymmetric incremental sheet forming (AISF), based on the localized plastic deformation of the blank under the action of a punch tool which follows a continuous and numerically controlled path [5]–[8]. Main advantages of this method are no die, or only a simple and cheap die is required, and the process can be carried out on cheap machines that are often already available; this makes the process particularly suitable for low-series production.

In spite of the huge amount of papers containing the description and results of incremental sheet forming of various types of materials [9]–[11], there is a lack of information on AISF of titanium alloys, especiallyTi-6Al-4V alloy.

Ti-6Al-4V (Grade 5) titanium alloy is known as the "workhorse" of the titanium industry because it is by far the most common Ti alloy, accounting for more than 50% of total titanium usage [1], [2]. It is $\alpha+\beta$ alloy that is heat treatable to achieve moderate increases in strength.

There is an incremental technology closely related to AISF, but it is applied on symmetrical parts – shear spinning process. Spinning is a well-developed forming technology where higher wall angles are achieved and is more easily feasible as compared to AISF. Therefore, the shear spinning could be chosen for preliminary description and characterization of not overly tested materials behavior.

This paper presents results of the spinning experiments carried out on two titanium alloys – commercially pure (CP) titanium (Grade 2) and Ti-6Al-4V (Grade 5) alloy.

In order to evaluate if some spinning conditions could be exported to AISF operations, a set of spinning trials were performed – regular spinning parameters, AISF parameters (constant rpm and high tangential speed are analogue to the traverse speed in AISF; and low feed rate that is analogue to a tool step down in AISF) and AISF at a feed rate value typical for spinning.

The main goal of this paper was to describe the properties and microstructure of the titanium alloys chosen from the point of view of the effect of the revolutions and the feed rate. Trials made using AISF parameters are compared to those made using AISF parameters at spinning feed rate.

II. Experimental

A. Materials

Unalloyed commercial purity titanium (Grade 2) and Ti-6Al-4V (Grade 5) titanium alloy sheets (Table I) of 1.0 and 1.6mm in thickness, respectively, were used for the experiments. The as-received sheets were in annealed condition (700°C/1h for the Grade 2 sheet and 790°C/50min for the Grade 5 sheet, both air cooled).

TABLE I
Composition of the Experimental Materials (wt.%).

Material	Al	V	Fe	C	N	H	O+N	Ti
Ti-Gr 2	-	-	max. 0.3	max. 0.1	max. 0.03	max. 0.015	max. 0.25	bal.
Ti-Gr 5	6.52	4.02	0.20	0.006	0.003	0.001	0.174	bal.

B. Forming Experiments

The forming experiments were performed using ZENN-100 CNC Spinning Lathe machine (DENN manufacturer) with main spindle power 30.5kW (0 – 3000rpm) and slides

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maximum forces (X, Z axis) of 40kN. Tungsten Carbide roller (radius of 2.5mm) and standard drawing lubricant (600 cSt) were used during the forming of the titanium alloys.

In order to evaluate a wall angle limit, a specific design of the formed parts was chosen (see Fig. 1). A progressive mandrel with 60° to 10° wall angle (30° - 80° in AISF convention) was used to obtain this specific shape of the parts. The forming experiments arrangement in the CNC machine is shown in Fig. 2.

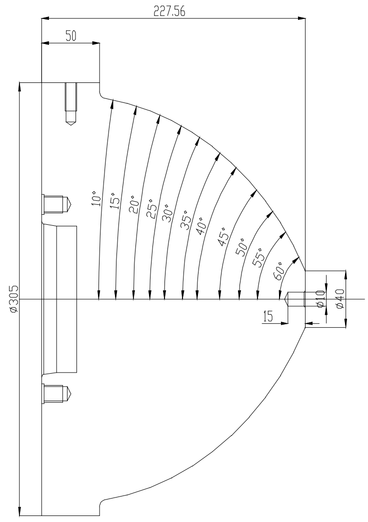

Fig. 1 Design of the formed parts used

For both experimental materials, three sets of experiments were arranged, including:

- regular spinning mode (constant 400rpm, feed rate of 0.25 mm/rev),
- AISF parameters forming (constant tangential speed of 4 m/min, 0.56 mm/rev), and
- AISF parameters forming at spinning rates (constant tangential speed of 256 m/min, 0.56 mm/rev).

All experiments were performed at ambient temperature.

C. Experimental Methods

The sectioning of formed parts for metallographic analyses was performed by means of linear precision saw IsoMet 4000 using a blade speed of 3000 rpm and cutting rate of 4 mm/min. The microstructure and surface microcracks of the cut specimens was investigated by means of light microscopy.

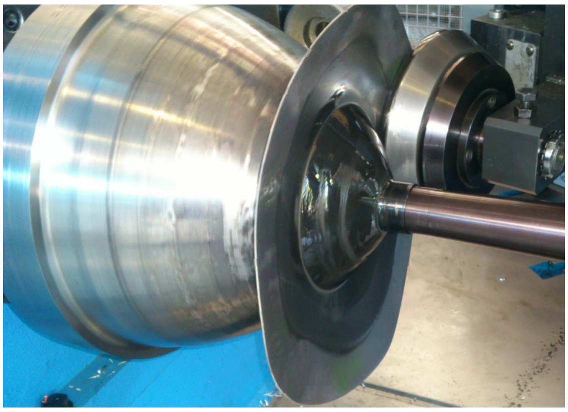

Fig. 2 The arrangement during the forming experiments

The metallographic analyses were assessed using Olympus GX51 light optical microscope. Microstructure of the specimens was revealed by etching using solution of either the Kroll's reagent (1.5ml HF, 4ml HNO_3, and 94ml H_2O) or the Weck's reagent (2g NH_4HF_2, 25ml ethanol, and 100ml H_2O). The average grain sizes were measured by chord intercept method.

The surface quality of the formed materials was inspected using the Vega3 SB scanning electron microscope (SEM) with tungsten heated cathode.

Vickers microhardness measurements HV1 were performed on the polished cross-section surfaces of the metallographic samples after metallographic analyses. Microhardness of the samples was evaluated using the Wolpert Wilson 402MVD microhardness tester.

III. Results and Discussion

A. Wall Angle Failure Limit

The forming operation starts from the lower wall angle value (the highest in the spinning convention, see Fig. 1). As the wall angle increases during the forming operation the sheet gets thinner until a fracture occurs. The fracture location provides the wall angle limit value.

The forming parameters together with the maximum load and wall angle failure limit for both materials and all three forming modes are presented in Table II.

TABLE II
FORMING PARAMETERS AND RESULTING VALUES OF THE MAXIMUM LOAD AND FAILURE WALL ANGLE FOR ALL FORMING MODES

Mode	Revolutions (rpm)	Tangential speed (m/min)	Feed rate (mm/rev)	Material	Maximum load (kN)	Wall angle failure limit Spinning convention	Wall angle failure limit ISF convention
Spinning	400	63 – 364	0.25	Ti-Gr2	12	20°-15°	70°-75°
				Ti-Gr5	17	25°	65°
AISF	4.8 - 28	4	0.56	Ti-Gr2	5.5	40°	50°
				Ti-Gr5	24	40°-30°	50°-60°
AISF + Spinning	274 - 1590	256	0.56	Ti-Gr2	15	30°-20°	60°-70°
				Ti-Gr5	17.5	25°	65°

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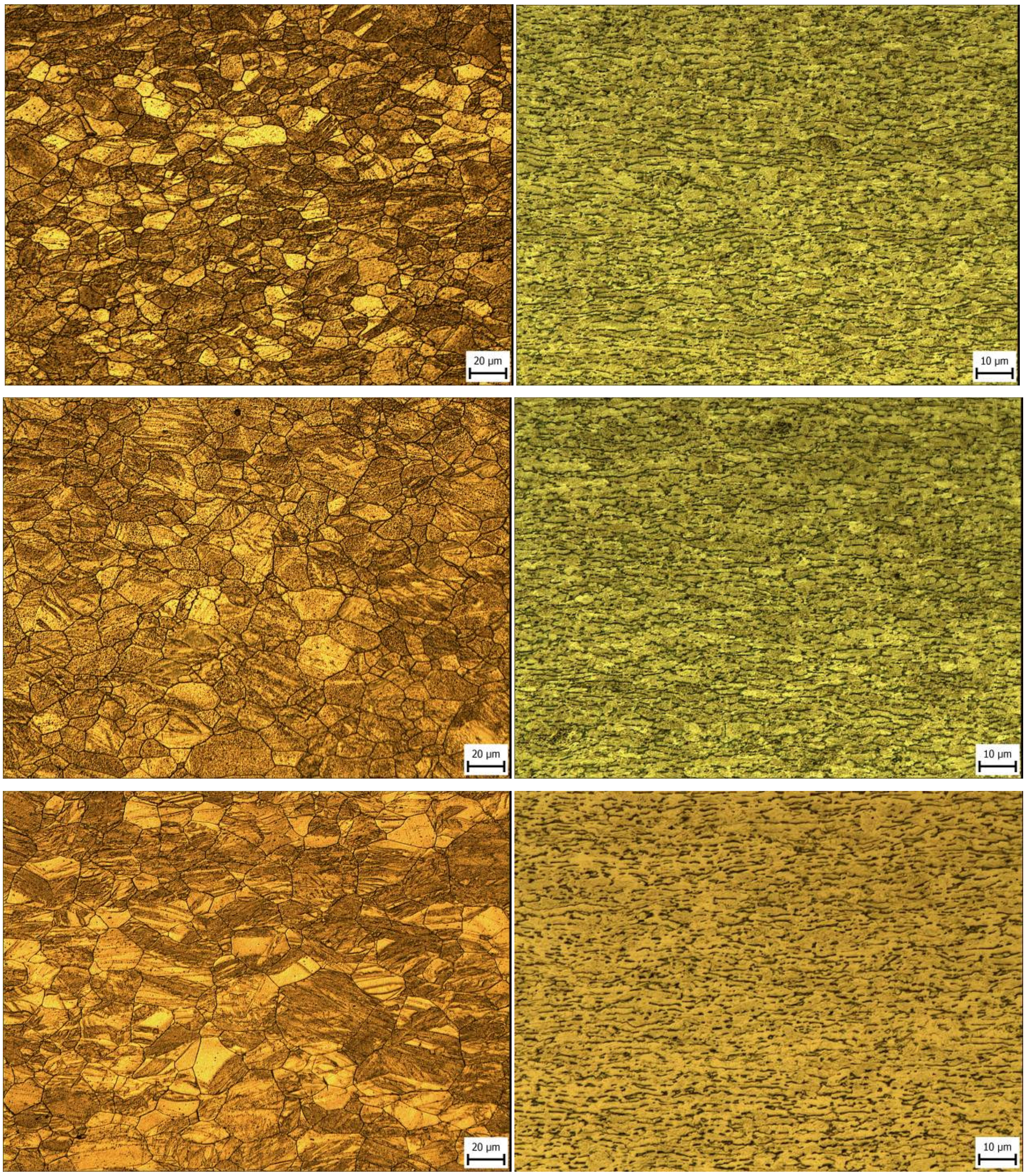

Fig. 3 Microstructure of the specimens taken from the CP titanium (left)and Ti-Gr5 alloy (right) deformed parts at wall angle of 45° – spinning mode (top), AISF mode (middle) and AISF parameters forming at spinning rates (bottom). Etched by the Kroll's and/or Weck's reagent. Magnification of 500× (left) and 1000× (right)

It is evident that the highest value wall angle failure limit (in the AISF convention) was achieved using spinning parameters mode for both materials. It means that higher revolutions together with lower feed rate imply higher limit forming properties of titanium alloys. Moreover, as expected, higher loads had to be applied to Ti-Gr5 sheets to get corresponding wall angle as compared to the commercial purity titanium.

B. Microstructure Characterization

Several microstructure comparisons were assessed within the scope of each material. Effect of forming mode on the CP titanium and Ti-Gr5 alloy microstructure at wall angle of 45° is presented in Fig. 3. Graphical presentation of the grain size measurement results is shown in Fig. 4. The average grain size in the initial state before forming experiments was 14.5µm and 2.4µm for Ti-Gr2 and Ti-Gr5, respectively.

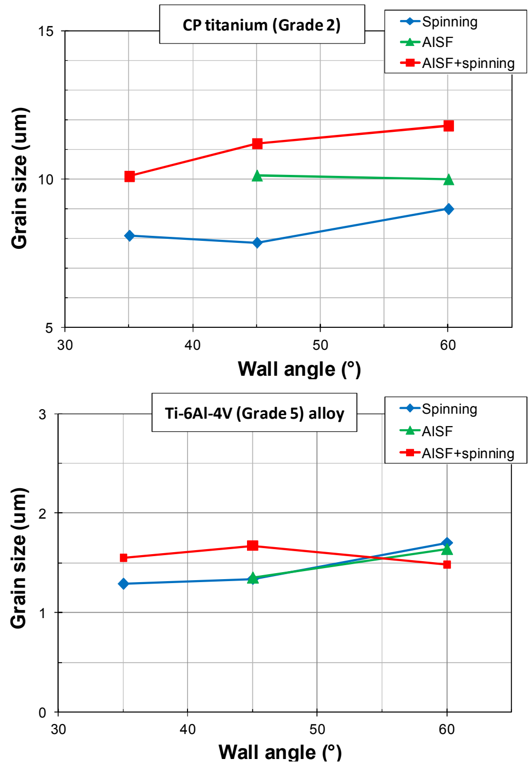

Fig. 4 Graphical presentation of the grain size measurement results (the spinning convention) – Ti-Gr2 (top) and Ti-Gr5 (bottom)

As a typical α-type titanium alloy, Ti-Gr2 exhibits twins in deformed sheet areas, due to hexagonal close packed (hcp) crystal structure and the lack of sufficient slip systems to accommodate the imposed strain. There is evident trend of a refinement of the grain microstructure with lower feed rate and higher tangential speed, i.e., sheets deformed using the regular spinning parameters exhibited finer microstructure as compared to the AISF or their combination (Fig. 3). This is also in good agreement with the results of the grain size measurements presented in Fig. 4.

In the case of Ti-Gr5 alloy, microstructure with α-phase and intergranular β-phase slightly elongated in the direction of forming is observed. The boundaries of α-α grains type are not completely defined. They are only outlined by β-phase due to α- and β-phase interface contrast. There is no significant difference in microstructure and grain size in the samples taken at different wall angle levels (Figs. 3 and 4).

C. Microhardness Measurement

The results of the microhardness measurements are graphically summarized in Fig. 5.The average microhardness in the initial state before forming experiments was 153 and 320units of HV1for Ti-Gr2 and Ti-Gr5, respectively.

The dependence of the microhardness HV1 values on the wall angle differs for Ti-Gr2 and Ti-Gr5 materials. In the case of Ti-Gr2, the microhardness increases with deformation extent, i.e., with the wall angle decrease (in the spinning convention) or increase (in AISF convention). And on the contrary, the microhardness decreases with straining in the case of Ti-Gr5 alloy.

From the results, it is evident that AISF mode of forming exhibits the lowest strain hardening, and contrarily, the highest hardening is observed for the combined mode.

The decrease of the microhardness at higher straining (lower wall angle in the spinning convention) observed in Ti-Gr5 alloy specimens is caused by recovery processes occurring due to a high stored deformation energy in the formed material and increased temperature during forming due to a friction. This is connected with the stacking fault energy value which is higher in the cubic crystal structure materials (Ti-Gr5) and low in the hcp materials (Ti-Gr2) [12]. The recovery processes also allowed achieving a quite high value of the wall angle failure limit during the spinning mode of forming (Table I).

D. Surface Quality

A higher number of surface cracks was observed in the case of the spinning mode forming of Ti-Gr2 sheets as compared to other two forming modes. It follows that the higher feed rate results in better surface quality.

Similar behavior was observed also for the Ti-Gr5 alloy, but in comparison with the commercial purity material, more pronounced surface cracking occurred in the alloy. Moreover, the whole surface was cracked in some areas of the samples taken from the Ti-Gr5 alloy. Examples of the microcracks occurring in the Ti-Gr5 alloy surface are shown in Fig. 6.

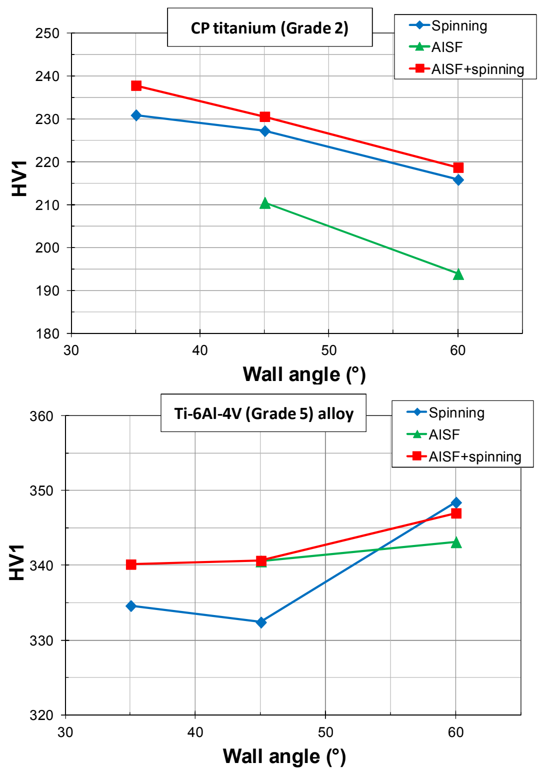

Fig. 5 Dependence of the microhardnesson the wall angle level (the spinning convention) – Ti-Gr2 (top) and Ti-Gr5 (bottom)

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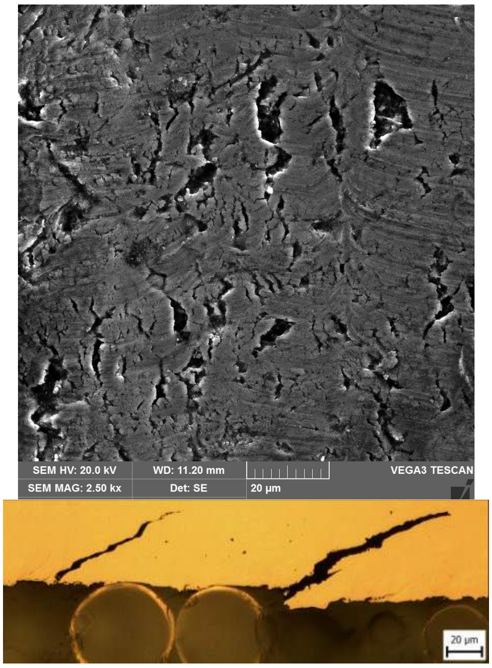

Fig. 6 Examples of the microcracks occurring in the surface of the sheet after forming using regular spinning parameters (Ti-Gr5 alloy) – SEM micrograph (top) and light microscopy (cross-section, unetched, 500× magn.)

Generally, the microcracks were mostly observed at the outside surface (in a contact with the tool) of the formed sheets. The length of the microcracks observed was up to 120µm.

IV. Conclusion

Two titanium materials, commercial purity (Grade 2) and Ti-6Al-4V (Grade 5) alloys were successfully formed at ambient temperature using different forming parameters of shear spinning and AISF modes.

The results of this investigation could be summarized as follows:

- Higher revolutions together with lower feed rate imply higher limit forming properties of titanium alloys.
- The grain microstructure of Ti-Gr2 refines with lower feed rate and higher tangential speed, i.e., sheets deformed using the regular spinning parameters exhibited finer microstructure as compared to the AISF or their combination.
- In the case of Ti-Gr5 alloy, there is no significant difference in microstructure and grain size with different wall angle levels.
- The microhardness of Ti-Gr2 sheets increases with deformation extent, whilst it decreases with straining in the case of Ti-Gr5 alloy, whereby the AISF mode of forming exhibits the lowest strain hardening, and contrarily, the highest hardening is observed for the combined mode.
- Higher feed rate results in better surface quality.
- More pronounced surface cracking was observed in Ti-Gr5 alloy in comparison with Ti-Gr2.

It could be summarized that regular spinning forming mode results in higher limit forming properties and strain hardening. AISF parameters lead to better surface quality and lower hardening of the material.

The results of the experiments and analyses carried out will be adopted by AISF for its further development.

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