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Effect of Structure on Properties of Incrementally Formed Titanium Alloy Sheets

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***Abstract*—**Asymmetric incremental sheet forming (AISF) could significantly reduce costs incurred by the fabrication of complex industrial components with a minimal environmental impact. The AISF experiments were carried out on commercially pure titanium (Ti-Gr2), Timetal (15-3-3-3) alloy, and Ti-6Al-4V (Ti-Gr5) alloy. A special testing geometry was used to characterize the titanium alloys properties from the point of view of the forming zone and titanium structure effect. The structure and properties of the materials were assessed by means of metallographic analyses and microhardness measurements. The highest differences in the parameters assessed as a function of the sampling zone were observed in the case of alpha-phase Ti-Gr2 at the expense of the most substantial sheet thinning occurrence. A springback causes a smaller stored deformation in Timetal (β alloy) resulting in less pronounced microstructure refinement and microhardness increase. Ti-6Al-4V alloy exhibited early failure due to its poor formability at ambient temperature.

***Keywords*—**Incremental forming, metallography, hardness, titanium alloys.

I. Introduction

NOWADAYS, titanium and its alloys are widely used in various industrial sectors (e.g., aerospace, automotive, and bio-medical materials) due to their excellent properties such as high strength, hot workability, corrosion resistance, strength-weight ratio, toughness, etc. [1]–[5]. However, the high costs of the titanium products, as a result of demanding forming and heat treatment processes [1], limit their use also in other less sophisticated applications. This leads to extensive scientific and technological interest in developing potentially viable and economically affordable manufacturing methods that aid in reducing the cost of the products.

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 [6]–[9]. 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 [10]–[12], there is a lack of information on AISF of titanium alloys, especially from the microstructure and mechanical properties point of view.

Titanium is allotropic metal with a hexagonal close packed (hcp) crystal structure at lower temperatures and a body-centred cubic (bcc) structure at temperatures above 882°C. Generally, the titanium alloys could be classified into four categories – alpha (α), near-alpha, alpha plus beta (α+β), and beta (β) phase alloys [1]. The alpha-phase and near-alpha alloys exhibit lower strength but the best corrosion and creep resistance and weldability. The alpha plus beta alloys have an excellent combination of strength and ductility. The beta alloys (metastable) offer good formability and increased fracture toughness.

This paper presents results of AISF experiments carried out on three different titanium alloys – commercially pure (CP) titanium (Grade 2), Timetal (Ti-15-3-3-3) alloy and Ti-6Al-4V (Grade 5) alloy. In order to evaluate and compare behaviour of different structure titanium alloys during AISF at ambient temperatures, forming experiments were performed using a special testing geometry of the parts.

The main goal of this paper was to describe the properties and structure of the titanium alloys chosen from the point of view of the forming zone and titanium structure effect.

II. Experimental

A. Materials

Unalloyed commercial purity titanium (Grade 2), Timetal (Ti-15-3-3-3), and Ti-6Al-4V (Grade 5) titanium alloy sheets (Table I) of 1.0mm in thickness were used for the experiments. The as-received sheets were in annealed condition (700°C/1h for the Grade 2 sheet 816°C/5min for the Timetal alloy and 790°C/50min for the Grade 5 sheet, all air cooled).

B. Forming Experiments

Two-point AISF processing was performed in a robotic machine (1000 kg capacity) with a blank holder of dimensions of 870×770mm using a ceramic wheel of 100mm in diameter.

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-15-3*	3.29	14.55	0.10	0.012	0.006	0.004	0.010	bal.
Ti-Gr 5	6.52	4.02	0.20	0.006	0.003	0.001	0.174	bal.

*Moreover, Ti-15-3 alloy contains 3.01 wt.% Cr and 3.03 wt.% Sn

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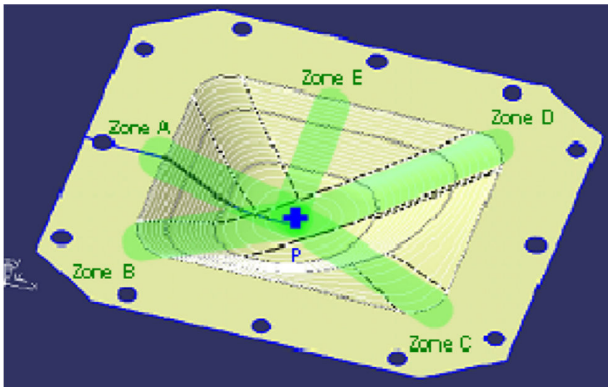


Fig. 1 Design of the formed parts used

A negative forming configuration and feed rate of 1 m/min were used. A commercial mineral oil was used as a lubricant during the processing. The AISF forming tests were made using special test geometry (a bench shape, see Fig. 2) with varying wall angles (max. 35°). All experiments were performed at ambient temperature.

C. Experimental Methods

The samples for the metallographic analyses and hardness measurements were taken from the significant areas/zones of the formed sheet shown in Fig. 1. Two specimens were taken from the formed flat zones (A and E zones), three from the corner zones (B, C, and D), one from the formed bottom zone (P), and one from the unformed part (1) of the sheet.

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 metallographic analyses were assessed using Olympus GX51 optical microscope. Specimen microstructure 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.

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.



Fig. 2 The arrangement during the forming experiments

III. Results and Discussion

A. Forming Trials

From the point of view of formability, Ti Grade 2 (Ti-40) material shape has been produced successfully without any problems or defects (e.g., bulge, wrinkle or tear). Similarly, Timetal (15-3-3-3) alloy has been easily formed; however, a much higher springback occurred after releasing of the sheet clamping [13]. This behavior is caused by high yield strength and low Young's modulus of this β alloy.

In the case of Ti-6Al-4V (Grade 5) alloy, even the material was in the annealed condition, the sheet has shown early failure due to poor formability of this material at room temperature [14].

B. Microstructure Characterization

The microstructure comparison from selected zones of each material is shown in Figs. 3 to 5. The deformed microstructure of the corner zone (B) and flat zones (A and E) were compared with the unformed initial state of the sheet.

As a typical α-type titanium alloy, CP titanium exhibits twins in deformed sheet areas (Fig. 3), due to hexagonal close packed (hcp) crystal structure and the lack of sufficient slip systems to accommodate the imposed strain. Therefore, twinning is preferable deformation mechanism for the hcp metals. The formed bottom zone P contains almost undeformed grains and the microstructure is similar to the microstructure of the initial unformed zone (Fig. 3 (a)). The most deformed zones of the AISF sheet are the flat zones A and E (with high slope of the test geometry design) accompanied by the formed corner zones B (Figs. 3 (b)-(d)).

In the case of Ti-15-3-3-3 titanium alloy, the deformation mechanism is different as compared to the CP Ti. Ti-15-3-3-3 alloy is a kind of metastable β-titanium alloy with the body-centered cubic (bcc) crystal structure and deform by a slip. From Fig. 4, a grain subdivision and fragmentation could be seen, but no deformation or shear bands and slip lines are visible by reason of etching reagent used (Kroll's reagent). The extension of the microstructure changes as a function of the zone area in the AISF Ti-15-3-3-3 alloy is similar to the CP titanium sheet microstructure. The most deformed zones of the sheet are the flat zones A and E (Figs. 4 (b), (d)), and the least deformed area is the formed bottom zone P containing almost undeformed grains.

As the α+β phase Ti-6Al-4V alloy exhibited early failure, differences of the microstructure change in various zones of the AISF sheet are quite small. The unformed zone shows a typical annealed recrystallized microstructure with equiaxed α-phase and intergranular β-phase (Fig. 5 (a)). The α-α grains boundaries are not completely defined. They are only outlined by the β-phase due to a α- and β-phase interface contrast. The other zones, except the bottom zone P that was not reached due to early failure, contain a deformed microstructure with a slightly smaller spacing of β-phase grains as compared to the unformed zone. The early failure occurred in the zone E, i.e. in the zone with the mostly deformed microstructure and, hence, with the minimum grain size.

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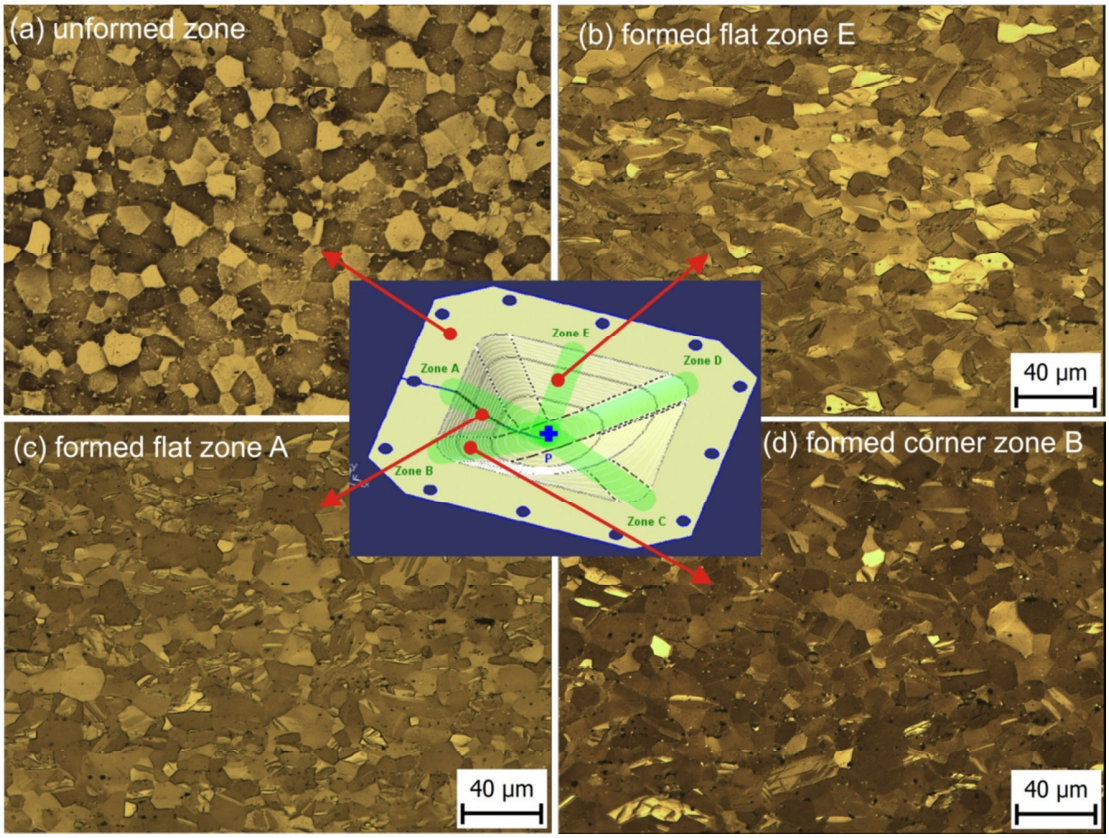


Fig. 3 Microstructure of the CP titanium in different zones AISF formed part. Etched by the Weck's reagent (magn. 500×)

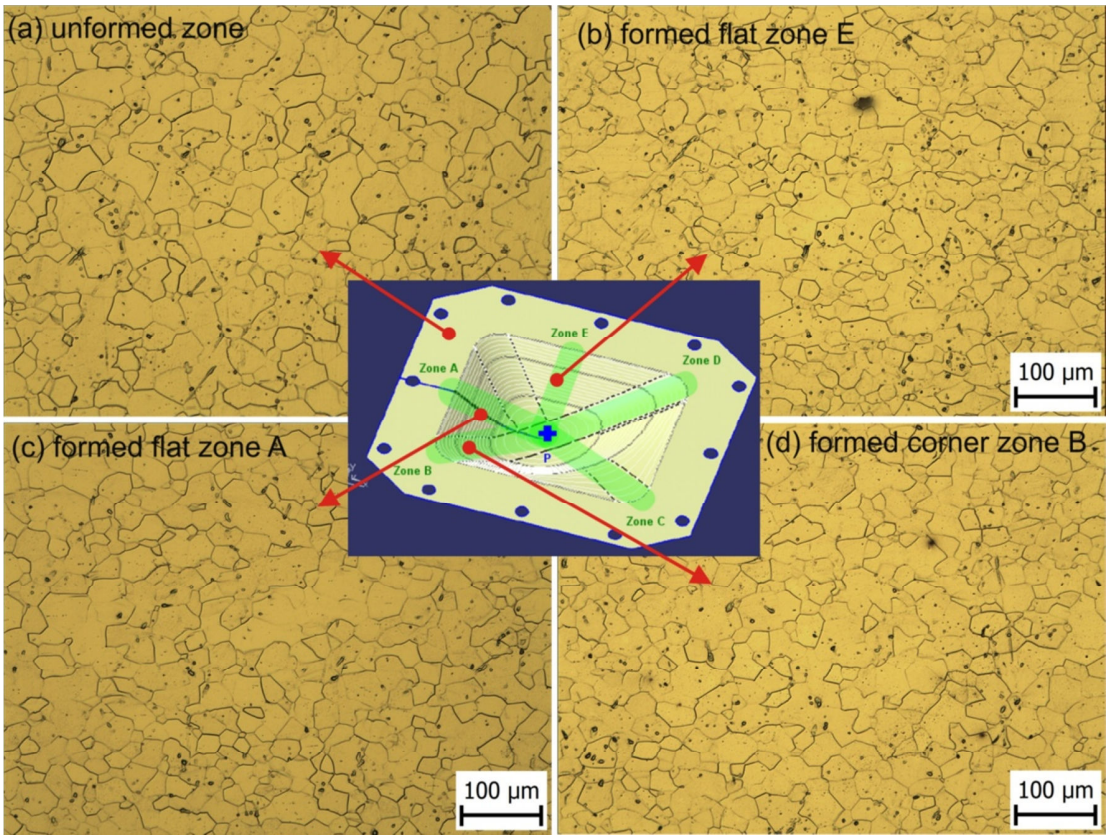


Fig. 4 Microstructure of the Timetal (Ti-15-3) alloy in different zones AISF formed part. Etched by the Kroll's reagent (magn. 200×)

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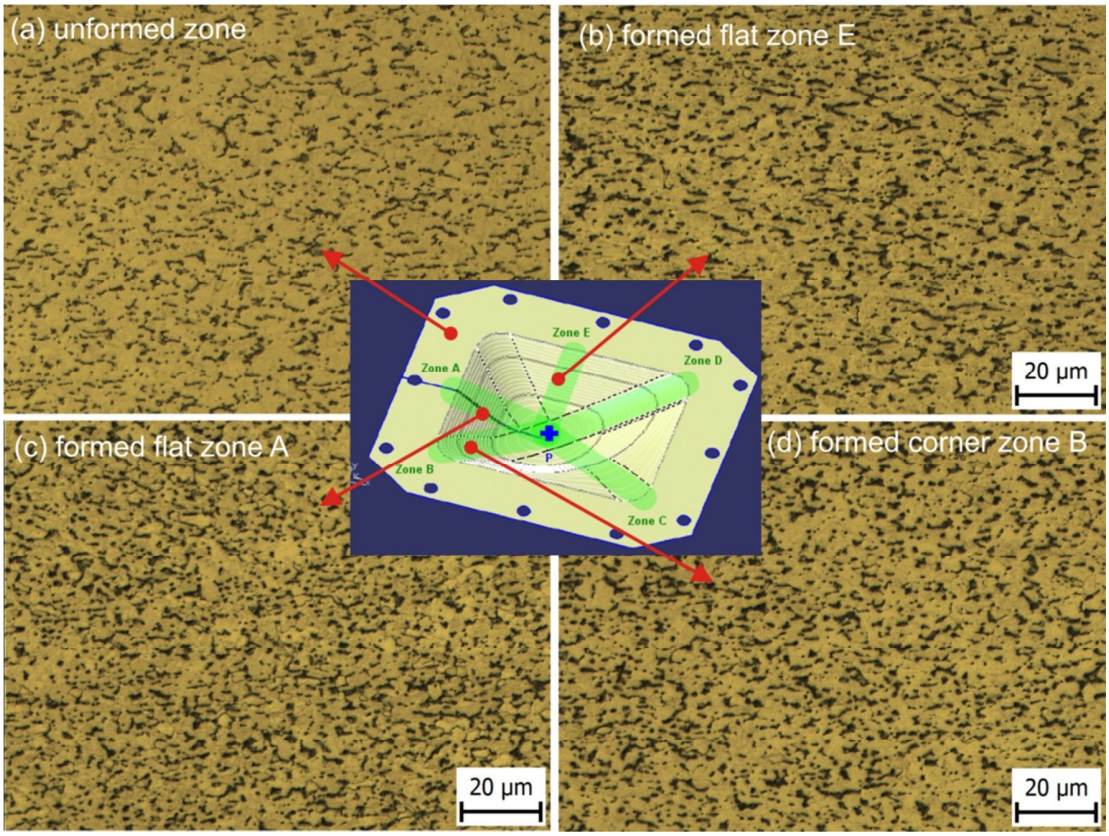


Fig. 5 Microstructure of the Ti-6Al-4V alloy in different zones AISF formed part. Etched by the Kroll's reagent (magn. 1000×)

It could be summarized that the most deformed zone with the finest grain microstructure corresponds to the flat zone E with high slope of the test geometry design. This was also confirmed by grain size and thickness measurements.

The results of the grain size measurement (measured in the direction of thickness) are summarized in Fig. 6. From this graph it is obvious that the finest grain microstructure could be observed in the formed flat zones A and E for all examined materials.

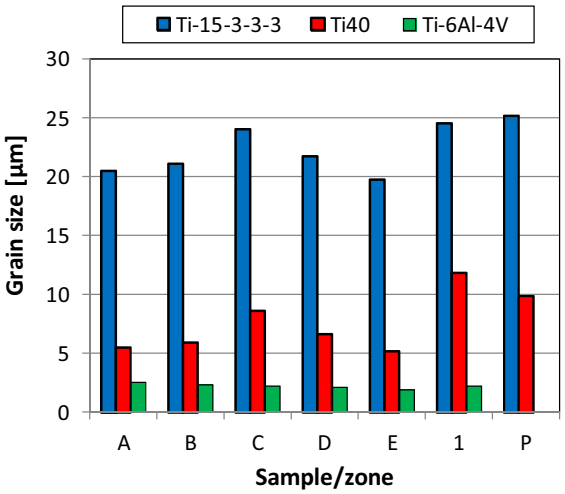


Fig. 6 Grain size measurement results for all three materials in different AISF deformation zones

On the contrary, the zones with the most coarse grain microstructure are the unformed zone and the formed bottom zone P. This corresponds well with the microstructures shown in Figs. 3 to 5.

C. Thickness Measurement

When the grain size is compared to the thickness measurement results (relative thickness value) in the individual zones (Fig. 7), it is obvious that the grain size decreases with the decreasing thickness of the sheet. Only in the case of the Grade 5 alloy, the thickness of the sheet is almost the same for whole piece due to its early failure.

The maximum thinning occurs in the most deformed zones of the part, i.e., the zones A and E. In these zones of the CP titanium part the sheet thickness decreases about 20 % with regard to the initial sheet thickness. Similarly to the microhardness results (Fig. 8), the thickness of the sheet in the zone C remains unchanged as compared to the initial thickness value. These facts also prove that no considerable deformation occurs in the zone C.

From the graphs in Fig. 7, it is clear that the highest differences in the thickness of the processed sheet as a function of the sampling zone were observed in the case of alpha-phase CP titanium (55% grain size change as compared to the initial sheet thickness). The smaller stored deformation in the Ti-15-3-3-3 alloy, resulting in less pronounced microstructure refinement (25% for grain size), is probably given by the significant springback occurring in this alloy.

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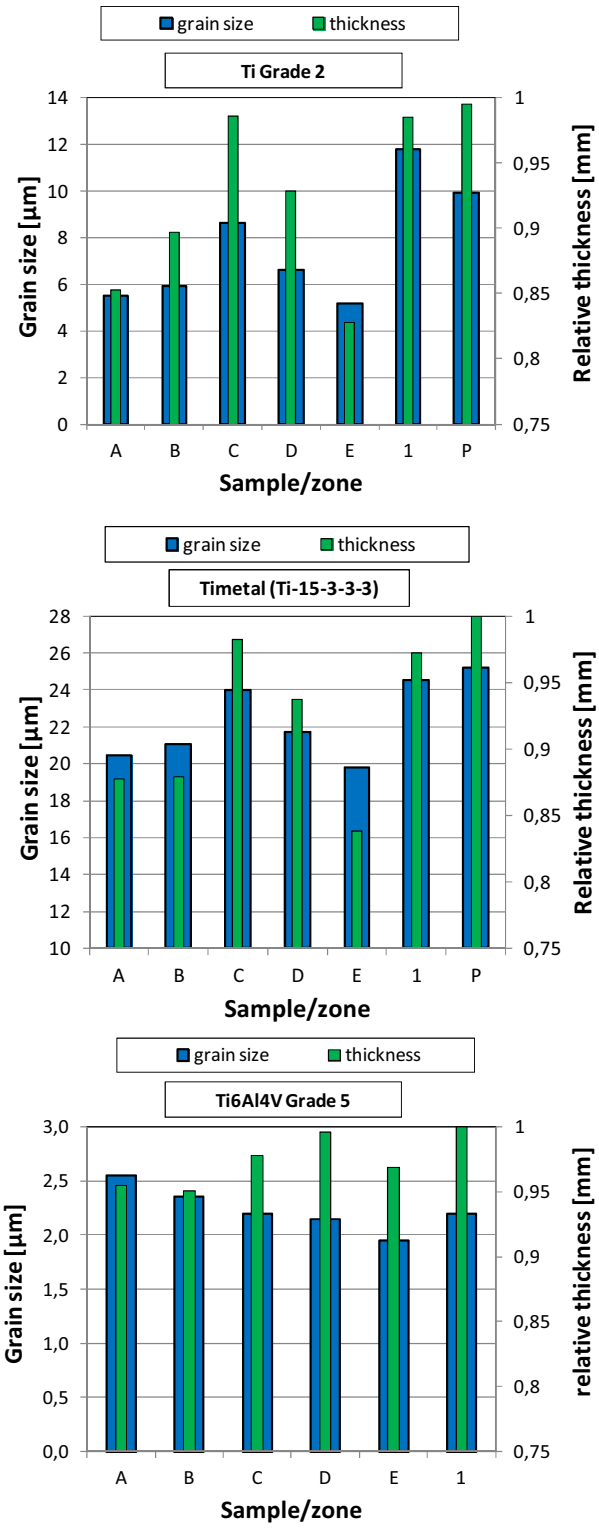


Fig. 7 Grain size and thickness comparison in different zones of CP Ti (top), Timetal (middle) and Ti-6Al-4V (bottom) AISF parts

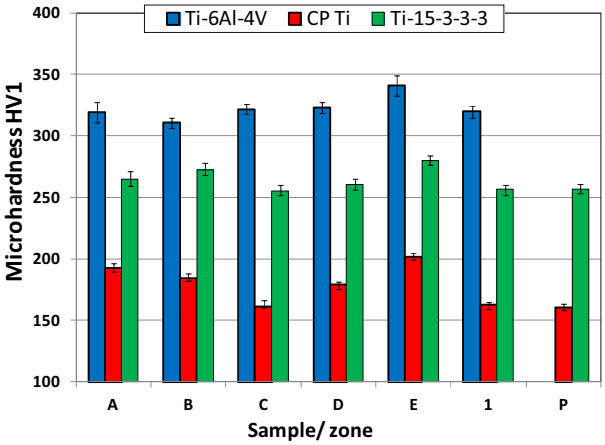


Fig. 8 Comparison of the microhardness of all three materials in different AISF deformation zones

D. Microhardness Measurement

The microhardness measurement results (Fig. 8) are in good agreement with the grain size and sheet thickness measurements – the highest microhardness value corresponds to the lowest grain size and the sheet thickness values measured, and vice versa. Also, the highest differences in the microhardness of the processed sheet as a function of the sampling zone were observed in the case of CP titanium. As could be expected, the least differences in microhardness were obtained in the early failed Ti-6Al-4V alloy.

From the comparison plot in Fig. 8, it is obvious that Ti-6Al-4V (Grade 5) alloy exhibits the highest microhardness values and, conversely, the lowest microhardness values were measured in CP Ti (Grade 2) samples.

IV. Conclusion

Three titanium materials, commercial purity (Grade 2), Timetal (Ti-15-3-3-3) and Ti-6Al-4V (Grade 5) alloy sheets were incrementally formed using special testing geometry at ambient temperature.

The results of this investigation could be summarized as follows:

- The parameter values evaluated (such as grain size, sheet thickness and hardness) are dependent on the sampling zone of the AISF part.
- From the point of view of the metallographic analyses, the most deformed zone with the finest grain microstructure corresponds to the flat zones A and E with the highest slope of the test geometry design.
- The highest differences in the parameters assessed as a function of the sampling zone were observed in the case of alpha-phase CP titanium. However, the most substantial sheet thinning occurs in the alpha-phase material.
- A smaller stored deformation in Timetal (β alloy) resulting in less pronounced microstructure refinement and microhardness increase, is probably given by the significant springback occurring in this alloy.
- In the case of Ti-6Al-4V (Grade 5) alloy, even the

material was in the annealed condition, the sheet has shown early failure due to poor formability of this material at room temperature.

It could be summarized that regular AISF parameters are suitable only for the alpha-phase titanium alloys. The beta-phase and α+β alloys need to be deformed at higher temperatures in order to prevent the springback and cracking occurrence, respectively.

The results of the experiments and analyses carried out will be used for further AISF development and finite element analyses.

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