Manufacture of a β-Titanium Hollow Shaft by Incremental Forming

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Abstract

Excellent mechanical properties and corrosion resistance combined with low weight qualify β-titanium materials for lightweight applications in aviation, automotive and energy engineering. Thus far, actual applications of these materials have been limited due to high material costs and limited processing knowledge. One approach for developing resource-efficient manufacturing methods is the application of incremental forming methods. This article focuses on the development of the incremental spin extrusion process, which creates hollow profiles from solid bars. This method allows hollow shape manufacturing with a much higher flexibility than other forming methods and a significantly improved material utilization in comparison to machining methods, such as deep hole drilling. Beta-titanium alloys basically have very good cold forming suitability and the resulting material properties can be controlled. The application of incremental forming methods with high hydrostatic compressive stress is a promising manufacturing approach. The β-titanium Ti10V-2Fe-3Al material has an excellent combination of the properties strength, ductility and fatigue strength. In order to utilize these properties the forming conditions and the temperature control need to be optimized. The investigations show that the Ti10V-2Fe-3Al material can be formed only in a narrow semi-hot forming temperature window. The paper describes the investigation and presents results on the design of partial forming process sequences, forming properties, microstructure formation and failure prevention. The process design objective is a very fine microstructure with a homogeneous secondary α-phase and very small grained β-phase.

Keywords

Incremental forming, spin extrusion, beta-titanium alloys (Ti-10V-2Fe-3Al), microstructure analysis

1 INTRODUCTION

The effort required to mine titanium makes it an extremely expensive material to purchase as compared to steels. Despite its excellent mechanical properties at a low weight, use of the material has remained limited due to this reason. The main motivation for using these materials comes from the aerospace industry. High strength and high fatigue strength as well as low susceptibility to corrosion at a low weight are the principal reasons for choosing titanium materials [1, 3]. Titanium alloys typically include α-, near α-, (α+β)-, β-, and near ß-alloys. While the α-phase is stronger than the β-phase, its ductility is lower due to the different lattice structure [1, 4]. Unlike the α-phase (hcp lattice structure), the β-phase comprises a bcc lattice structure that has more slide planes. The formability of alloys with a high β-portion makes these materials interesting for the application of forming processes. Processing by forming is currently limited to planar components with low weight. The most common titanium alloy is the Ti-6Al-4V (α+β)-alloy [3, 5] with a market share of 50 to 60%. It is characterized by a combination of good mechanical properties and machinability [3]. The material is suitable for operating temperatures of up to 400 °C and shows high strength in this range. Higher operating temperatures between 450 °C and 550 °C would already require alloys such as Ti-6292 and Ti-6246. The particularly temperature-resistant IMI 834 alloy has double the material costs [6]. The most versatile group is the β-titanium alloys. They have the best strength-to-mass ratio but a higher density than other titanium materials [7]. The combination of strength, ductility, and fatigue resistance is attractive. β-alloys are mostly more expensive than other comparable materials, which has severely limited their use. The materials preferably used are: Ti-10V-2Fe-3Al, Beta C, Ti-15-3, TIMETAL 21S and BT 22 for structural parts as well as Ti 17 for jet engine compressor discs [1, 7]. The properties of the β-titanium alloys are primarily determined by microstructural parameters: grain size, shape, size and percentage by volume of primary and secondary α-phase and intergranular α-phase. When homogenized by annealing, β-alloys show high ductility (plastic deformability), low deformation resistance and good formability at low temperatures [1, 10]. The β-alloy type has the greatest formability at room temperature of all alloys that are well suited for engineering applications [5]. Due to the typically excellent cold forming properties of β-titanium alloys and because of the fact that their properties can be influenced by forming, they are best suited for the application of partially cold forming methods such as spin extrusion. [1] Engineers strive for increasing material utilization due to the high price of the raw material. This is why it is imperative that alternatives to classic forming methods such as forging are found. Hollow shapes made of titanium materials are produced by cold extrusion. The method allows narrow manufacturing tolerances, good surface topographies, and increases in hardness. However, the process is limited to manufacture thin-walled tubes due to a limited length to diameter ratio. [2] Other alternative methods are extrusion and drawing. Extrusion always requires blanks produced by deep-hole drilling at a material loss of up to 40 %. There is a lack of material-saving processes for manufacturing thick-walled hollow shapes in near-net-shape quality that limits the general use of β-titanium alloys. Application of the spin extrusion process developed at IWU is to provide an innovative alternative for β-titanium processing.

1.1 Spin extrusion - an incremental forming process

Spin extrusion is a flexible rotational pressure forming process for producing long, rotationally symmetric hollow shapes, with or without a bottom, from solid circular semi-manufactures. Figure 1 shows a schematic diagram of the spin extrusion process for producing hollow shapes. The hollow in the component is created by a mandrel. This is suited for producing simple circular cross sections and tappet hole profiles such as lobed constant-diameter shapes, ellipses, polygons or axially oriented multiple-spline and gear profiles. The outer contour is obtained exclusively by the kinematics of the pressing rollers that roll off on the semi-manufacture. In this way, cylinders with axially parallel side lines, stepped contours, with or without undercut, ascending and descending cones as well as concave or convex solids of revolution can be produced. Examples of spin extrusion parts are shown in Figure 2.

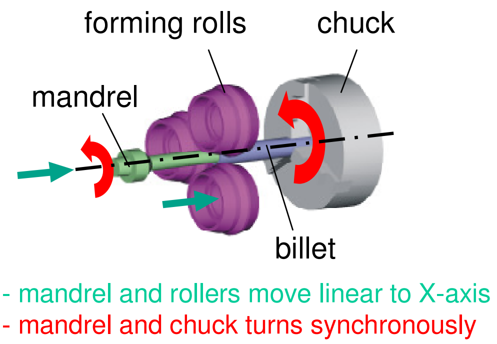


Figure 1: Schematic diagram of spin extrusion process

The spin extrusion process is particularly resource-saving. Material savings of up to 80 % for hollow shafts compared to deep-hole drilling can be achieved. Methods of partial solid material forming such as spin extrusion are characterized in that they do not plasticize the entire forming volume of the material at once but in increments that are limited in time and space [8, 9]. This allows a considerable reduction in punch force and about four times the length-diameter ratio as compared to backward cup extrusion. The process is particularly suited for high-strength materials because of the great portion of hydrostatic pressure used. Spin extrusion makes little use of die-type tools. The die that is required for backward cup extrusion has been replaced by pressing rollers. The flexibility, low tool costs, and excellent integration capacity of the process make it particularly applicable to the production of small and medium series.

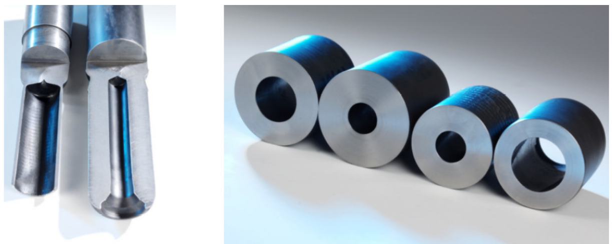


Figure 2: Spin extrusion application

1.2 Objective of the studies

So far, there is little basic knowledge about the forming conditions of β-titanium alloys.

In particular, the influence of cyclic incremental forming on phase change and grain structure, and the resulting influence on material properties from which essential improvement of utility values is expected, primarily through significant increases in strength that may even exceed the strength of steels, is completely unknown. When defining the process window, knowledge is to be gained as to the optimum dimensions of the semi-manufacture, the texture and technological process parameters (working speed and process temperature), and tool design (geometry, coating, lubricant). To make these materials optimally suitable for process chains, it is intended to obtain such material properties that allow cost-efficient finishing by metal-cutting. For this purpose, a controlled thermomechanical material treatment during the forming process must be found.

2 STATE OF DEVELOPMENT

2.1 Temperature control

During the first stage of the study, the task was to establish the temperature control for the process and to determine a suitable forming temperature. Since ß-titanium alloys have excellent cold forming properties and their properties can be controlled by adequate forming parameter design, the use of cold forming processes with high hydrostatic compressive stress was a promising approach. However, first tests showed that the required forming forces were considerable larger than the maximum forces permitable.

A semi-hot forming approach has been developed. A major problem of temperature control is the changing temperature distribution during the processing and the resulting considerable local temperature differences within the specimen.

Temperature simulations were used to analyze temperature distributions and to determine feasible temperature ranges for the forming process. Figure 3 shows an example. The influence of temperature due to tool contact is clearly visible. The specimen surface cools down by up to 300 K within ten seconds. This also considerably increases the punch strain in the process.

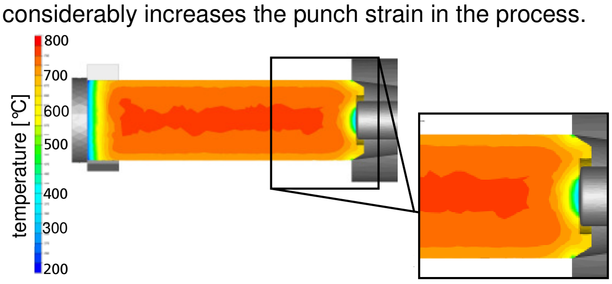
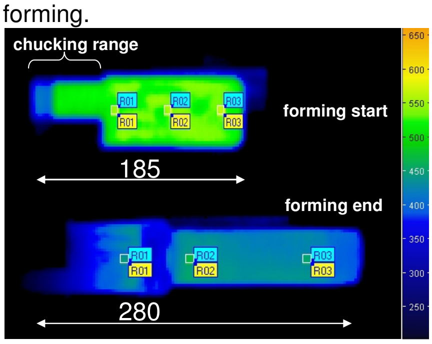


Figure 3: Simulation of the cooling process on a spin extrusion specimen with cold tools after 10sec

A test program with variations of many process parameters was carried out, to determine a feasible forming process set-up.

In conclusion, forming of the Ti10V-2Fe-3Al test material by spin extrusion only becomes reliable in a narrow temperature distribution window between approx. 500 °C and 600 °C. If the temperature is below 500 °C, the forming completely fails or the resulting workpieces contain defects, such as cracks. On the other hand, if the specimens are formed at higher temperatures, especially above 750 °C, the material strength is reduced to such an extent that the forming also fails. The material flow occurs not only in the forming area, but also at the section directly at the chucking.

In a main test series of 26 specimens, the specimens were heated in an oven for 60 minutes at a temperature of 650 °C under inert argon gas atmosphere. Due to handling time the forming temperature at the beginning of the process is approx. 100 °C lower. The thermographic recording (Figure 4) shows the temperature distribution at the start of the forming process and the temperature after forming.



measured values		
Def	T [°C]	eps
R01	547	0.86
R02	555	
R03	562	

measured values		
Def	T [°C]	eps
R01	439	0.86
R02	468	
R03	451	

Figure 4: Thermographic measurement of a Ti specimen before and after spin extrusion

After heating the billet in the oven, the surface temperature in the machine at the beginning of the trial is approx. 550 °C. When the forming process has ended, i.e. after approx. 180 seconds, the Ti specimen has cooled down to 450 °C.

Figure 5 shows a typical punch force curve for the spin extrusion process at a specimen temperature at the start of forming of approx. 550 °C. For the used titanium alloy, the maximum punch force required for forming is 680 kN. Compared to lower specimen temperatures, the forming force increases significantly at approx. 350 °C. The reason for this is that the compressive yield point $\sigma_{0,2} = 500$ MPa at 500 °C rises to $\sigma_{0,2}$ = 650 MPa at 350 °C.

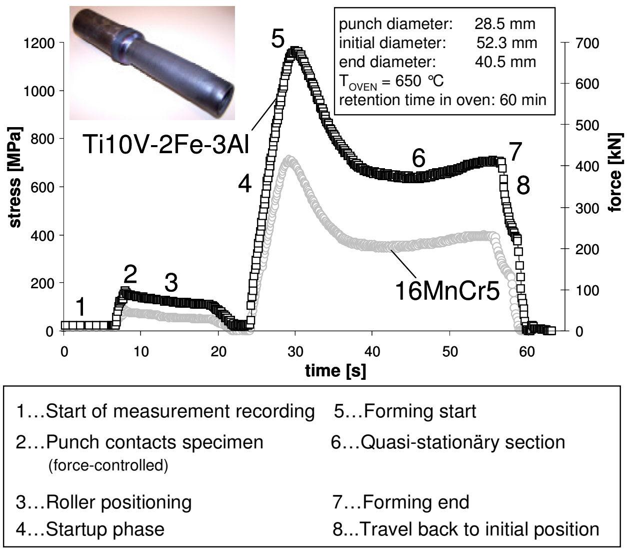


Figure 5: Typical punch force curve for the spin extrusion process

Lowering the process temperature to 350 °C results in significantly increased process forces of approx. 870 kN, causing the punch to buckle. When the specimen temperature is above 650 °C, the specimen material is severely upended around the chucking area. The material softens tremendously. The compressive yield point is at $\sigma_{0,2}$ = 430 MPa. The material does not flow as desired in the forming zone but is just upended by the punch and the pressing rollers. Thus, there is only a narrow temperature window (550 °C to 650 °C) for a guaranteed spin extrusion process of the used titanium alloy, and many factors influence the way in which the material is formed and defined microstructures are produced.

2.2 Material characterization

The material used was supplied in solution annealed condition, reaches an upper yield point of approx. 620 MPa and an ultimate tensile strength of approx. 815 MPa. This corresponds to a specific strength of approx. 175 Nm/kg, a 75 % higher specific strength than conventionally used case-hardened steel 16MnCr5. Due to its longer uniform elongation and ultimate elongation (A_g = 32 %, A_5 = 35 %), this β-titanium alloy provides a good basis for shaping processes such as spin extrusion. The ISO-V notched bar impact work of solution annealed Ti-10V-2Fe-3Al is $A_v \approx 47$ J at room temperature and provides sufficient reserves against crack propagation.

A characteristic of this alloy (solution treated condition) is the very large β grain. The mean diameter is approximately 300 µm and is visible in Figure 6.

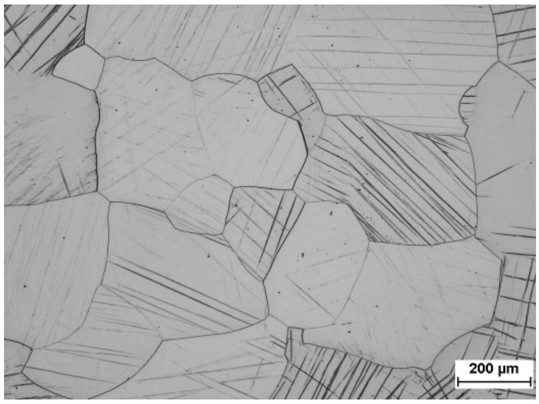
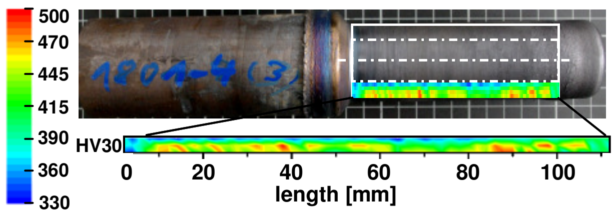


Figure 6: Image of the grain structure of Ti-10V-2Fe-3Al in solution annealed condition

After spin extrusion, the mechanical properties of the hollow shaft produced (initial diameter D = 52.3 mm and punch diameter d_i = 28.5 mm) were characterized and compared with the properties of the solution annealed material. The produced profile was subjected to extensive hardness and pressure testing. Figure 7 shows an example of a hollow shaft consisting of the β-titanium alloy used and the variation of Vickers hardness over the wall thickness.



7: Spin extruded shaft made of Ti-10V-2Fe-3Al with hardness variation in the forming zone

A hardness gradient of a 100 HV30 can be seen from the inner to the outer side of the wall. The mean hardness at the inner wall is approx. 350 HV30, that of the outer wall 450 HV30. The running-in section of the shaft was neglected in the hardness measurement because this section has a different initial geometry and thus different mechanical properties.

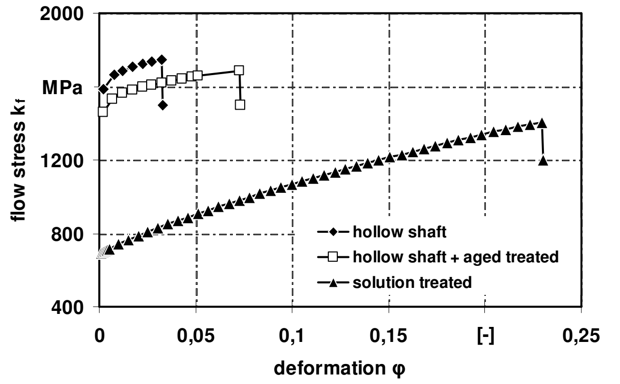


Figure 8: True stress-strain behavior of Ti-10V-2Fe-3Al under quasistatic compression load

In addition, static pressure tests were performed on cylindrical specimens, dimensions Ø 6 x 6 mm. The stress-strain behavior of the supplied, only solution treated material was used as a reference value. Figure 8 shows the average value of three specimen.

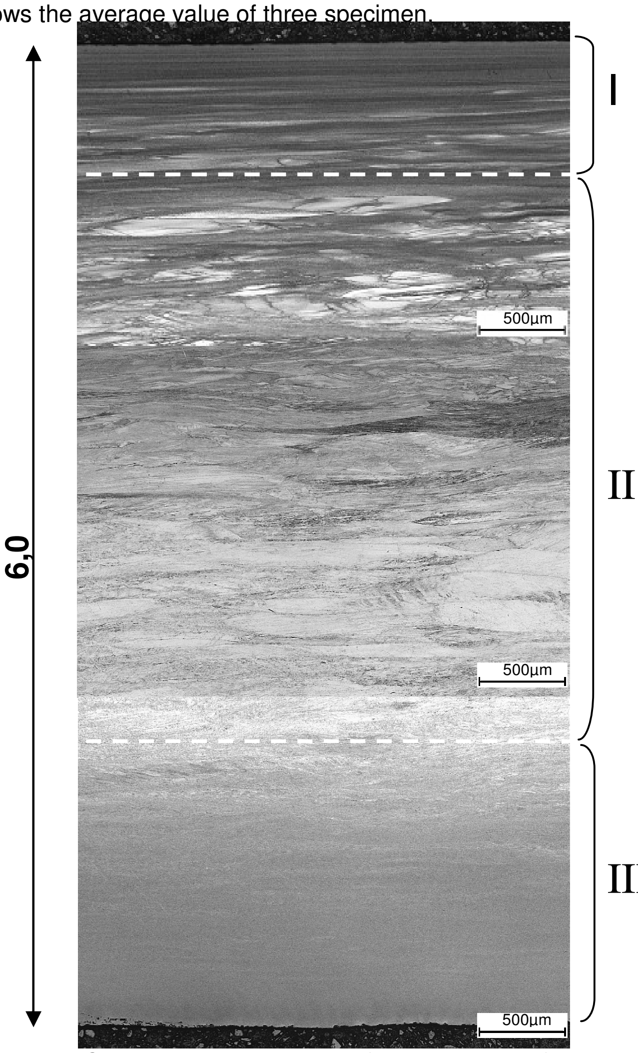


Figure 9: Characteristic structure of the sections: fine-grain inner side (I); coarse-grain central region (II); fine-grain and homogeneous outer side (III)

The yield point of the formed material is 1460 MPa, more than 100 % higher than that of solution annealed Ti-10V-Fe-3Al. But the deformability of the material drops considerably due to the forming process. A heat treatment was added after the spin extrusion process to increase deformability. A typical procedure of making this alloy more deformable and ductile is shown by Kiese and Wagner [10]. The last step of this treatment is tempering the material at 540 °C for 8 h. The result is higher strength and increased deformability. This was also performed successfully for the spin extruded shaft under investigation here. Its deformability was almost doubled while its strength diminished only slightly. Photomicrographs were made for further characterization of the formed hollow shaft. The survey photomicrographs taken were typical for forming (Figure 9). The margins show dynamic recrystallization of the coarse β grains due to the high local degree of forming and the forming temperatures used. The outcome is a very fine-grained and homogeneous structure in these regions (Figure 10). The β grain size is approx. 10 µm after the forming process, which explains the high strength obtained. Subsequent age-hardening at 540 °C results in precipitation of very small (< 2 µm) finely distributed α-phases that determine the increase in ductility of the heat treated specimen (Figure 11).

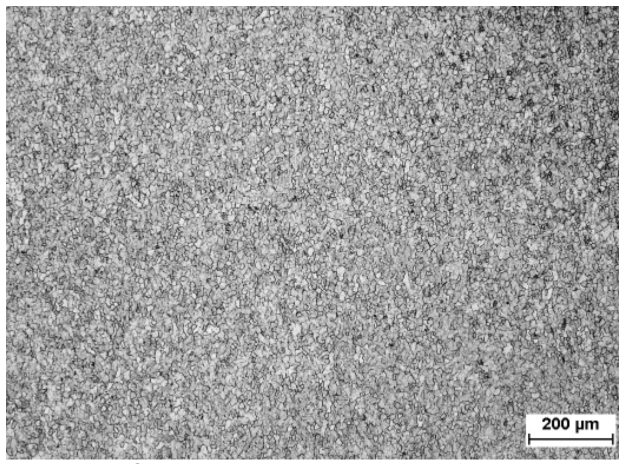


Figure 10: Characteristic structure of the formed marginal regions of the hollow shaft produced

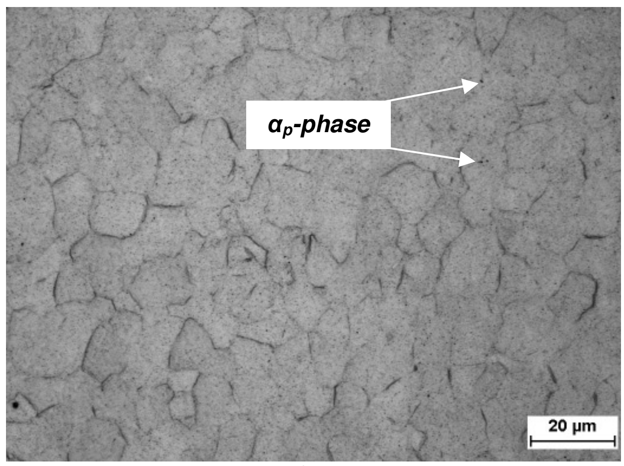


Figure 11: Precipitation of globular and homogeneous distributed *α_p-phase*

Further studies will seek to adapt forming temperatures, speeds and forming degrees to make this forming process even more efficient. Another focus of research is an optimized heat treatment step after the spin extrusion process to increase deformability. Currently just 50 % of the crack initiation energy of the deformed material is reached as compared to the solution annealed condition (Figure 12). To reach complete recovery of the crack initiation energy, the subsequent heat treatment would have to have a forming degree of φ ≈ 0.16 at the same strength. First tests have already improved crack initiation energy by approx. 100 % (Figure 12: hollow shaft and aged treated).

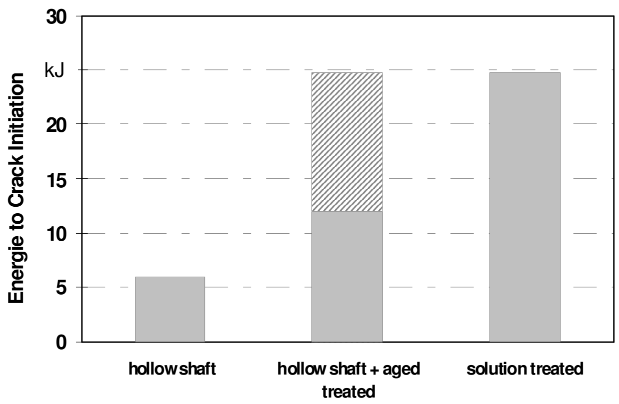


Figure 12: Energy required for crack initiation

Summary and outlook

After putting a considerable effort into preliminary studies of the temperature regime, it succeeded in determining a temperature window for manufacturing a hollow shaft made of Ti-10V-3Al-2Fe using spin extrusion and to produce this shaft by forming. The high deformations occurring during this process result in extreme grain refinement that contributes to a massive increase in strength. However, the material loses considerable deformation capacity due to the forming process. The deformation capacity could be increased by a heat treatment subsequently after the spin extrusion process.

It is the objective of further studies to recover the crack initiation energy while retaining strength. For this purpose, the forming parameters will be further adjusted and improved using thermomechanical treatments.

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