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Effect of severe plastic deformation realized by hydrostatic extrusion and rotary swaging on the properties of CP Ti grade 2

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ABSTRACT

The study is concerned with the influence of severe plastic deformation induced in CP Ti grade 2 by cold hydrostatic extrusion combined with rotary swaging on the process parameters, surface quality, tolerances, material microstructure, grain refinement, mechanical properties, thermal stability and mechanical homogeneity. The nano-size refinement to <90 nm achieved in CP Ti grade 2 by this method resulted in the increase of its strength to above 1000 MPa, with moderate ductility of ∼13%, and good thermal stability up to 500 °C. The rotary swaging which followed cold hydrostatic extrusion improved the surface quality and increased the grain refinement. The applicative potential of nano-titanium CP Ti grade 2 is discussed and illustrated using three examples, namely the medical implants intended for surgical osteosynthesis, high strength fixing components, and net-shape complex profiles for structural components. The major advantage of nano CP Ti grade 2 over the alternative materials lies in its high purity and the absence of toxic components whereas the high strength of titanium is preserved during its refinement to the nanosize. The properties of nano CP Ti grade 2 are compared with those of the Ti–6Al–4V Ti grade 5 alloy and CP Ti grade 4, commonly used at the present.

1. Introduction

Titanium is an ideal structural material e.g. for the manufacture of medical implants since it has very good biocompatibility with human tissue and does not react with body fluids. Since the mechanical strength of pure titanium is not high enough, the Ti–6Al–4V titanium alloy grade 5 is commonly used but, as presented by Alvarez and Nakajima (2009), it contains toxic additives such as vanadium and aluminium. One of the effective methods of improving the strength of titanium is to subject it to severe plastic deformation (SPD). Investigations aimed at improving the strength of titanium are extensively conducted so that it can be used as the substitute for Ti–6Al–4V grade 5 alloy. The most popular methods are equal channel angular pressing (ECAP) (Stolyarov et al., 1999), and high pressure torsion (HPT) (Valiev et al., 2002). The other methods include multiple forging (MF) (Salishchev et al., 1999), accumulative roll bonding (ARB) (Milner et al., 2013), and twist extrusion (TE) (Stolyarov et al., 2005).

Besides the high strength, the prefabricates of the final structural components and implants must meet other demands, such as the appropriate surface quality and geometrical tolerances. Because most of the SPD techniques do not allow reworking large material volumes, some modification based on the combination of several processes have been proposed. Most often the ECAP process is combined with cold rolling, Stolyarov et al. (2003), conventional extrusion, Kang and Kim (2010), drawing, Raab et al. (2008) or a special thermo-mechanical treatment, Latysh et al. (2006). Asymmetric and symmetric, Li et al. (2012), and multipass caliber rolling, Inoue et al. (2007), have also been applied. The shortcomings of the above-mentioned techniques lie in that the deformation proceeds at elevated temperatures which decreases the final strength of the material and deteriorates the surface finish quality. The present study was undertaken with the aim to obviate these shortcomings by introducing high pressure which allows applying higher strains during the cold deformation (hydrostatic extrusion) combined with rotary swaging which decreases the final surface roughness.

In the present work, the authors propose to combine hydrostatic extrusion (HE) with rotary swaging (RS) in order to fabricate prefabricates from CP Ti grade 2 at room temperature, with a

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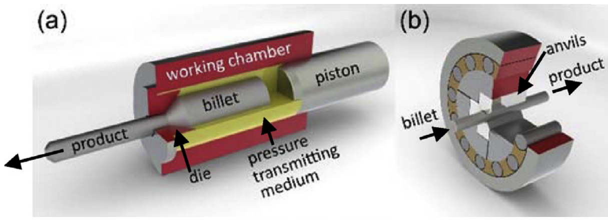

Fig. 1. Schematic representation of (a) the hydrostatic extrusion, and (b) the rotary swaging processes.

highly refined structure and high strength intended for various components used in the machine, structural, and medical fields. Lewandowska and Kurzydlowski (2008) reported that, in pure aluminium, the grain refinement achieved by hydrostatic extrusion is more effective than that achieved by other SPD methods, because, among other factors, of the higher strain rates applied. The efficiency of the grain refinement by hydrostatic extrusion was already demonstrated in titanium (Pachla et al., 2008). This has motivated the present authors to combine the strong grain refinement technique such as the hydrostatic extrusion with rotary swaging as the tool for improving the surface finish quality in the extruded products.

The present research is concerned with the influence of the cold severe plastic deformation realized by high pressure processing combined with rotary swaging on the properties of the CP Ti grade 2. The hydrostatic extrusion process is characterized in details. The evolutions of the structure of CP Ti grade 2 (grain refinement), its mechanical properties, their spatial distribution and thermal stability, surface quality, longitudinal mechanical homogeneity and reproducibility of the results are discussed. The as-processed titanium was used as the prefabricates for fabricating final products. The prospective fields of application are suggested.

2. Material and experimental methods

The material examined was CP Ti grade 2 according to American Standard ASTM (2005) with a purity of 99.74 wt.% in the form of round rods 50 mm in diameter and mean equivalent grain diameter $d_{eq} \sim 30\,\mu m$, where d_{eq} is defined as the diameter of a circle which has the surface area equal to the surface area of a given grain. The mechanical properties of initial CP Ti grade 2 were: the ultimate tensile fracture strength UTS = 550 MPa, yield stress YS = 440 MPa, elongation to fracture $\varepsilon_f = 24\%$, and Vicker's microhardness of 205 HV0.2. The rods were subjected to cold severe plastic deformation by a combination of cumulative hydrostatic extrusion (HE) followed by rotary swaging (RS), Fig. 1. One of the main differences between these two processes is the difference in the homogeneity of the plastic deformation, Fig. 2. In HE the relative uniformity of deformation is mainly due to the small die angles and the improved lubrication at the billet-die interface. This results in the absence of heavy shearing at the surface of the extruded products, and enables extruding, without cracking, Pugh (1970), many materials difficult to deform, such as magnesium alloys, Pachla et al. (2012a) or cast irons, Pachla et al. (2011). In rotary swaging, the processing of brittle materials become possible thanks to the low stress induced in one forming pass and the very homogeneous manner in which the workpiece is formed. The incremental die kinematics largely eliminates the friction effect between the die and the workpiece resulting in the deformation distortion being even slighter than that occurring in hydrostatic extrusion as illustrated by HMP.

Both processes involve 2-axial compression and uniaxial tension stress state induced during forming, but HE introduces much greater distortion of the grid patterns since the strain ratios per pass are here higher by up to one order of magnitude compared to those achieved in RS. The rotary swaging was only applied as the finishing operation with the aim to improve the surface quality and straightness of the prefabricated titanium rods.

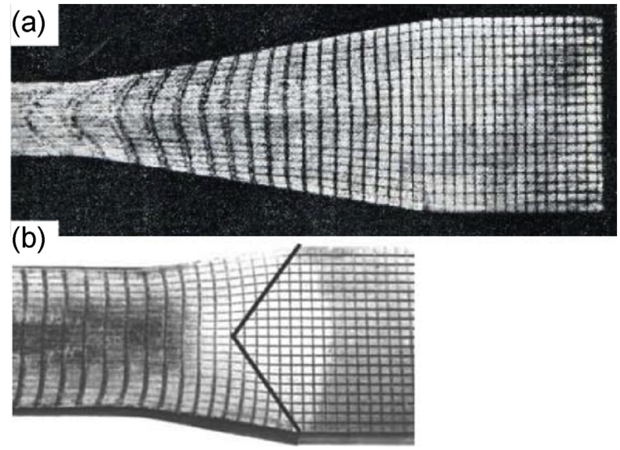

Fig. 2. Comparison of distorted grid patterns in (a) the hydrostatic extrusion, Pugh (1970), and (b) the rotary swaging, HMP GmbH.

The hydrostatic extrusion was run at room temperature in hydrostatic extrusion presses with the available pressure range up to 2000 MPa, designed and constructed at the Institute of High Pressure Physics, Polish Academy of Sciences Unipress. The available cumulated extrusion reductions were $21 < R_{cum} < 52$, where R_{cum} is the ratio of the cross section surface area of the initial material before and after extrusion, which corresponds to the cumulated true strain $3 < \varepsilon_{cum} < 4$ with the true strain being defined as the natural logarithm of R_{cum}. The cumulative hydrostatic extrusion allowed severe plastic deformation to be induced in the final CP Ti grade 2 products, which was thanks to the repeated one-pass deformation conducted with the high extrusion ratios $1.6 < R < 5.2$, i.e. the true strains $0.47 < \varepsilon < 1.65$. Each extruded product was cooled with cold running water immediately after it left the extrusion die. The pressure transmitting medium compressed to very high pressure improves the lubrication effectiveness thereby reducing the friction forces to a minimum. In this way, almost entire work done in compression of the medium (generating pressure) is converted into the work of deformation. The lubricants employed were a paste based on 60% MoS_2 and refined oil, copper, PTFE and an aluminium layer deposited by physical vapour deposition. The die angle was $2\alpha = 45^\circ$ and the true strain rate ranged between 2.5 and 15.8 s^{-1}.

The extruded rods were subjected to rotary swaging at room temperature in a four-anvil swager R3-4 manufactured by HMP GmbH with a stroke frequency of 3730 per minute. The swaging was also run in the cumulative way with the cumulative reduction R_{cum} between 1.2 and 1.4 which corresponds to the cumulative true strain $\varepsilon_{cum} = 0.16$–0.32. After each pass the product was immediately cooled with the cold water. Both the HE and RS processes were conducted without intermediate annealing. The combination of these two processes allowed achieving the cumulative true strain $3.2 < \varepsilon_{cum} < 4.26$, i.e. the reduction ratio within the $25 < R_{cum} < 71$ range.

The surface quality of the CP Ti grade 2 rods was investigated in a Hommel-Werke T8000 profilometer and a Hitachi TM-3000 scanning electron microscope (SEM). The microstructure was examined on transverse cross-sections of the rods using transmission electron microscopy TEM (JEOL JEM 1200EX) and optical microscopy (Nikon Eclipse LV150). The mechanical investigations included the static tensile test conducted at room temperature with the sample length-to-diameter ratio equal to 5 and a constant strain rate of 0.008 s^{-1}, using a Zwick/Roell Z250 kN machine. The microhardness was measured on transverse sections of the extruded rods in an