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Original Research Article

A comparison of axial fatigue strength of coarse and ultrafine grain commercially pure titanium produced by ECAP

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A B S T R A C T

Commercially pure titanium (CP-Ti) has been recently used as metallic biomaterials due to excellent biocompatibility and specific strength. CP-Ti has less static and dynamic strength as compared to other metallic biomaterials. Processing by the equal channel angular pressing (ECAP) as one of the most effective severe plastic deformation (SPD) method could lead to an increase in the mechanical strength of materials, significantly. In this study, Grade 2 CP-Ti billet is inserted into Al-7075 casing, and is then deformed by ECAP, with the channel angle of 135°, through 3 passes at route B_C and room temperature. The purpose of using casing is to attain higher deformation homogeneity and more material ductility in the billet. The microstructural analysis shows that the coarse grain (CG) CP-Ti is developed to ultrafine grain (UFG) structures after ECAP. In order to investigate the static and dynamic strength of CG and UFG CP-Ti, the tensile and axial fatigue tests are conducted. The results represent that UFG CP-Ti has much more tensile and fatigue strength than CG CP-Ti, and it could be utilized as biomaterials for production of implants. Surface features of fatigue fracture are also investigated. It should be noted that the investigation of fatigue strength of UFG CP-Ti produced by ECAP at RT utilizing casing, has not been conducted so far.

1. Introduction

Nowadays, CP-Ti and its alloys are extensively used in various applications such as aerospace, automotive and biomedical, particularly as dental and orthopedic implants. This metal has lately received very much attention because of high specific strength, durability at elevated temperature, suitable weldability and castability, excellent biocompatibility and high resistance to the corrosion [1–3]. This material is a good substitute for the other metallic biomaterials, because it has a Young's modulus closer to the bone as compared to the other common metallic biomaterials like 316L stainless steel and

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Co-Cr alloys, and it also possesses better biocompatibility and high corrosion resistance [3,4]. The low mechanical strength of CP-Ti as compared to the other metallic biomaterials is one of the weaknesses of this material [1]. This defect could be removed by either adding alloying elements or applying the severe plastic deformations (SPD) processes. By the second phase and/or solid solution strengthening carried out by adding commonly toxic alloy elements such as Al and V, the ion releasing happens in the human body and causes different diseases [1,3,5,6]. The static and dynamic strength could dramatically be enhanced using SPD processes without changing the chemical elements and only via grain refinement up to the sub-micron and nano ranges, generating the high density of dislocations and the formation of the high-angle grain boundaries (HAGBs) [7,8].

The equal channel angular pressing (ECAP) is one of the most effective SPD processes to produce ultra-fine grain (UFG) or nano-crystalline (NC) bulk materials. In this process, a work-piece with a cross-section similar to the channels, is pressed through a die with two identical cross-sections channels intersecting at a channel angle of φ and an outer corner angle of ψ [7,9]. Because the work-piece cross-section does not change after applying the process, it might be exposed to the repetitive ECAP process in routes A, B_A, B_C and C in order to impose very large strains. Each applying strain in this process is called a pass [7,10].

Some alloys such as titanium (Ti) and magnesium (Mg) with HCP crystal system and also 7000 series aluminum because of age hardening, are both referred to as difficult-to-work alloys. The ductility of these alloys is actually low especially at low temperatures and particularly at the room temperature [11–14]. By applying the cold work like ECAP at the room temperature (RT) on these alloys, the unstable flow, cracking and segmentation on the surface occur [11,14,15]. The mentioned defects can be removed after imposing the ECAP on these materials, with increasing the channel angle, increasing the processing temperature, applying the back pressure, reducing the pressing speed and using the controlled annealing heat treatment [7,13,14,16,17]. The researches on the CP-Ti processed by ECAP have been carried out restrictively at room temperature [18–21], and mostly at high temperature (HT) [22–26]. In these studies, mostly the mechanical properties and microstructural analysis of UFG/NC CP-Ti have been investigated. Generally, there is a tendency to perform the ECAP processing at room temperature to avoid the grain growth at high temperature [27]. It has also been proved that inserting the billet inside the casing or capsule and processing of this biomaterial work-piece by ECAP can improve the mechanical properties of billet material, and it lead to an increase in the deformation homogeneity due to increase the uniformity of effective strain distribution [12,28,29]. Increasing the uniformity of deformation results in reducing the susceptibility to deformation localization and consequently the material ductility improves. It has been shown that increasing the deformability can enhance the static and fatigue properties of material [30], therefore it is predicted that the use of the casing could be effective in improving the static and dynamic strength of billet material.

Among the mechanical properties, the dynamic strength or fatigue properties of materials are one of the most important evaluation criteria to use a material in structural applications [31]. The analyses of the cyclic behavior of UFG/NC metals such as copper (Cu), aluminum (Al) and titanium (Ti) have been performed, considerably [32–34]. The results of the studies on the fatigue behavior of the CG/UFG materials reveal that the fatigue strength as well as the fatigue endurance limit enhance, significantly with increasing the static strength and the flow stress of material due to the grain refinement [30,32,33].

Investigation of fatigue behavior of UFG/NC of CP-Ti produced by the ECAP method has been conducted, restrictively. To evaluate the cyclic behavior of the UFG CP-Ti, the ECAP at high temperatures is mostly used and the fatigue behavior of UFG CP-Ti is investigated [22,30,35,36]. Only in one study conducted by Figueiredo et al. [21] in 2014, CP-Ti was processed by ECAP at room temperature and then the fatigue test of UFG was performed according to ISO 14801 standards for using as dental implant. According to the carried out studies, decreasing of grain size causes not only the static strength enhancement but also the fatigue properties improvement, but it increases the fatigue notch sensitivity [35]. Table 1 presents a summary of the last studies on the fatigue behavior of CG/UFG CP-Ti produced by the ECAP and ECAP-Conform.

The most researches on UFG CP-Ti have been carried out via the ECAP process at high temperatures and the fatigue properties have been studied (see Table 1). In the current

Table 1 – Summary of studies on the fatigue behavior of CG/UFG CP-Ti produced by the ECAP (The investigated items have been marked by "*").

Material (Grade 1–4)	ECAP die angle (deg.)	ECAP route	Number of passes	ECAP temperature (°C)	Type of fatigue testing	R (F_{min}/F_{max})	Frequency (Hz)	Fatigue life	Notch sensitivity	Fracture surface	Reference
2, 4	90	B_C	10	300	Axial-HCF	−1	20	*	–	–	[22]
1	120	B_C	4	Room	ISO 14801	0.1	10	*	–	*	[21]
4	–	–	–	High	ASTM F1801	0.1	30	*	–	–	[37]
4	90	–	–	400–450	Rotary-HCF	−1	50	*	–	–	[38]
2	90	B_C	4	300–500	LCF	–	10	*	–	–	[36]
2	110	B_C	4	410	HCF	−1	15	*	–	–	[39]
4	90	B_C	4, 8	450	Rotary-HCF	−1	50	*	*	–	[30,40–42]
4	90	B_C	8	450	Rotary-HCF	0.1	20	*	*	*	[43]
2	90	B_C	8	350	~HCF	–	–	*	–	–	[44]
2	110	B_C	6	410	Axial-HCF	−1	15	*	*	–	[35]
VT1	90	B_C	–	400–450	Axial-HCF	−1	10	*	–	*	[45]