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An evaluative approach to correlate machinability, microstructures, and material properties of gamma titanium aluminides

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ABSTRACT

Several generations of gamma titanium aluminides have been developed over time, and they are nowadays commercially available. The differences in chemical composition, as well as the thermal treatments, greatly influence the properties of the alloys. This implies considerable effects on the production process performances. Benchmark trials were performed on three γ-TiAl alloys: Ti–48Al–2Cr–2Nb, Ti–43.5Al–4Nb–1Mo–0.1B, and Ti–45Al–2Nb–2Mn + 0.8 vol.% TiB_2 XD, focusing on machinability and material characterization. The extremely dissimilar results obtained when turning and milling can be traced back to the different microstructures, as well as to the alloying elements, factors both affecting the mechanical and thermal material properties.

1. Introduction

Gamma titanium aluminides (γ-TiAl) are heat-resistant intermetallic alloys designed for advanced structural applications in aerospace and automotive engines, mainly by virtue of the valuable performance-to-weight ratio [1]. Different alloys, developed in the last few decades, can be counted in this material group. Microstructures typically show a combination of the Ti_3Al (α_2) and TiAl (γ) phases, which exists between 40 and 48 at.% of aluminium content. The chemical composition and the thermal treatments mainly influence the microstructures and the material properties of the alloys, as well as the appropriate selection of alloying elements. Chromium and Manganese are added to increase ductility. Molybdenum and Niobium in small amount (<5 at.%) improve oxidation and creep resistance, whilst Boron is used as grain refiner [2]. The main weakness that limits the widespread use of γ-TiAl alloys is the difficult machinability, leading to poor surface quality and limited tool life [3]. In literature, evidences of surface damage including fracture/pullout were noticed [4,5]. According to Hood et al., these defects are randomly distributed across the workpiece, and vary in size from 20 to 500 μm. Moreover, higher levels of cutting speed and flank wear lead to a machined surface with largest level of cracks. Marginally less fracture/pullout has to be expected as a consequence of the smaller grain size of the alloys [6]. On the other hand side, accelerated tool wear occurs due to the high hardness and brittleness of γ-TiAl alloys. In combination with hardening tendency and low thermal conductivity, a high chemical reactivity with cutting tool materials was described [4]. Moreover, the presence of abrasives in the microstructure is another factor adversely affecting tool wear. Vargas Pérez evidenced abrasive wear due to the action of TiB_2 ceramic particles when end milling [7]. The reduction of tool life due to the presence of TiB_2 particles was also mentioned in [6].

Aim of this investigation is to identify a correlation between the material properties and the machinability in turning and milling for three different γ-TiAl alloys produced by investment casting, and HIPed afterwards. Microstructural analyses were performed, and the mechanical properties were obtained by means of tensile and hardness tests. The temperature behaviour of the linear coefficient of thermal expansion, of the thermal conductivity and of the density was acquired. Milling and turning experimental trials were carried out under conventional flood cooling, by using coated and uncoated cutting tools. The polar diagram method was applied to compare the machinability of the different workpiece materials [8,9].

2. Experimental approach

In order to investigate the influence of the workpiece material on machinability, benchmark trials were executed on three alloys with different chemical compositions: (1) Ti–48Al–2Cr–2Nb, (2) Ti–45Al–2Nb–2Mn + 0.8 vol.% TiB_2 XD, and (3) Ti–43.5Al–4Nb–1Mo–0.1B. Investigated specimens were produced by Access GmbH (Germany) via an investment casting process, using a centrifugal casting machine ALD-Leicomelt 5 TP, which is an industrial-scale equipment certified for producing TiAl aircraft components. For each alloy, all the samples (rods and blocks) were cast in the same batch. Then, the samples were HIPed for 6 h at 1185 °C, at a pressure of 172 MPa, in a pure Argon atmosphere. The heat/cool rate was less than 10 K/min. The cast skin was removed

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from blocks (15 mm × 30 mm × 120 mm) and rods (∅ 16 mm × 160 mm length), prior to the cutting tests.

2.1. Material characterization

For the characterization of the alloys, different methods were applied. Samples for microstructural analysis were cut from the workpieces, then ground, polished and etched by Kroll's reagent. The observation of the microstructures was performed by means of an optical microscope. Characteristic images at 100× and 200× magnification were taken. Tensile tests were carried out in accordance with the NF EN 10002-1 and NF EN 2002-001 standards, by means of an Instron 8033 testing machine. The ascertainment of the elongation was carried out with a laser extensometer type KS-L-100-4019-AN. The tests were performed in stroke control, and conducted to bring the samples up to failure in tension. The section of the specimens was 4 mm in diameter, and the test speed was 0.27 mm/min. The workpiece hardness was measured prior to the cutting tests, by means of an Emcotest M4U 025 universal hardness tester, according to the HV_{100} test conditions. For the determination of the thermal conductivity, a Flashline system 4010 was used, and the changes of the density over the temperature were measured by means of a TMA 402 F1/F3 Hyperion machine.

2.2. Machinability analysis in turning and milling tests

Longitudinal external turning tests were executed on an Index GU 800 CNC lathe, adopting finishing process parameters. Cutting speed was v_c = 80 m/min, feed was f = 0.1 mm, and depth of cut was a_p = 0.25 mm. Cutting operations were performed with uncoated cemented carbide ISO K10 grade CNMA 120424 inserts clamped in a PCMN 2525 M12 tool holder. Milling experimental trials were carried out on a 5-axis CNC milling machine Chiron FZ 15S. Carbide toroidal-end mills, 8-mm in diameter, TiAlN coated, have been used. Cutting speed v_c = 90 m/min, feed f = 0.1 mm/tooth, axial and radial depth of cut $d_z = d_r$ = 0.3 mm were selected as fixed finishing cutting conditions. The workpiece tilt angle was $\lambda = 45°$ (Fig. 1). The process parameters and the tool geometries were chosen according to previous research studies [4,10]. A 6% emulsion of Fuchs Ecocool TN 2525-HP oil in water, supplied at a pressure of 6 bar, was applied as lubrication condition, both for turning and milling. The tools were provided by Febametal S.p.A. (Italy). Tool wear was monitored with a Keyence digital microscope. Surface roughness profiles were acquired by a Mahr Perthometer PGK120. Cutting forces were measured in turning by using a 3-component Kistler dynamometer. Machined surfaces and worn tools were analyzed by means of a scanning electron microscope (SEM).

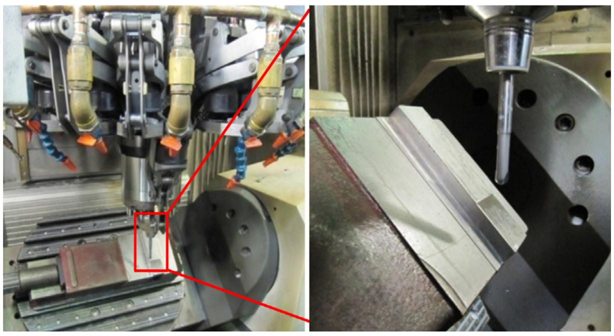

Fig. 1. Experimental setup for milling tests.

3. Results and discussion

3.1. Material properties

Microstructural analyses of as-cast and HIPed materials (Fig. 2) reveal that the differences in chemical composition reflect on the

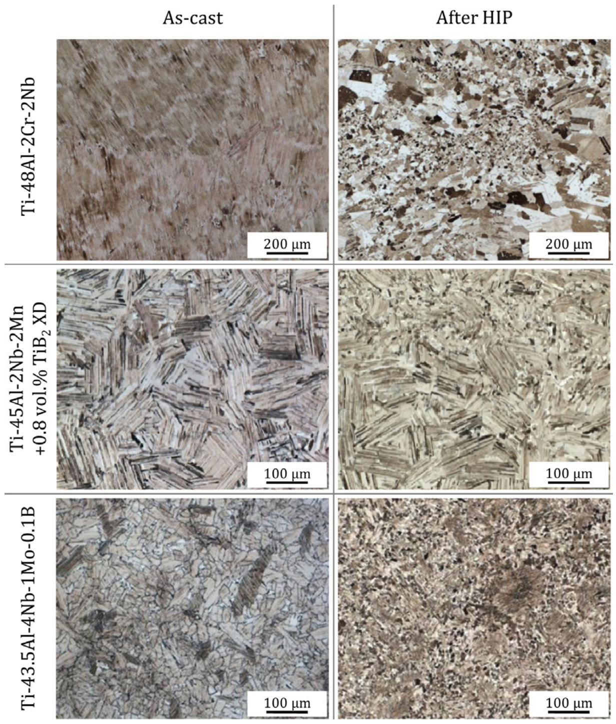

Fig. 2. Microstructures of gamma titanium aluminides.

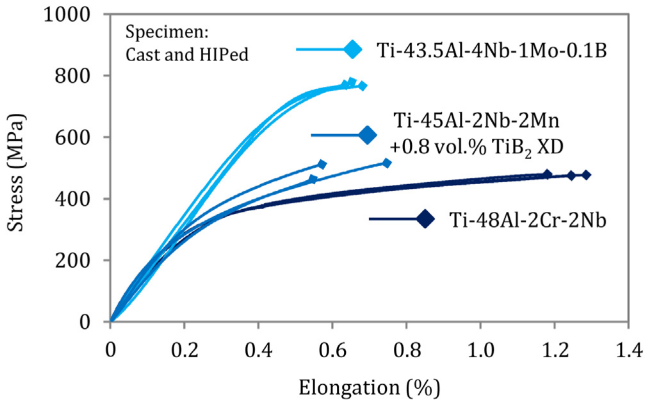

Fig. 3. Typical stress-elongation curves for the three TiAl alloys.

formation of the grain structure, that is further modified by the HIP treatment. Microstructures reveal mainly the two phases α_2 (Ti_3Al) and γ (TiAl), and the Boron addition leads to the presence of borides. The analyses were repeated in randomly selected areas of the workpieces and prove the microstructure to be homogeneous. Few casting defects, not being located near the machined surface, did not affect the cutting process. Fig. 3 reports the stress-elongation curves for the three cast and HIPed gamma titanium aluminides. The Ti–48Al–2Cr–2Nb alloy has the highest elongation at break, therefore its ductility is higher in comparison to that of the other alloys. The Ti–43.5Al–4Nb–1Mo–0.1B alloy has the highest tensile strength and elastic modulus, resulting in a higher mechanical resistance and stiffness. The toughness, which is proportional to the area enclosed below the curves, is higher for the Ti–48Al–2Cr–2Nb and the Ti–43.5Al–4Nb–1Mo–0.1B alloys, in comparison to that of the Ti–45Al–2Nb–2Mn + 0.8 vol.% TiB_2 XD alloy.

The surface hardness was measured on the blocks, after the cast skin removal. Average values resulted to be 295 HV_{100} for the Ti–48Al–2Cr–2Nb alloy, 372 HV_{100} for the Ti–45Al–2Nb–2Mn + 0.8 vol.% TiB_2 XD alloy, and 394 HV_{100} for the Ti–43.5Al–4Nb–1Mo–0.1B alloy. The standard deviation of the 30 measurements acquired for each alloy was less than 4% of the average values. The linear coefficient of thermal expansion, the thermal conductivity, and the density are presented as a function of the temperature in Fig. 4. The thermal expansion coefficient and the

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