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Effect of tungsten carbide addition on the tribological behavior of Astaloy 85Mo powder consolidated via spark plasma sintering

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ABSTRACT

Hard particle addition in ferrous powders allows the production of sintered materials with higher toughness, hardness and wear resistance, with potential use in different technological applications. This combination of properties is attained following correct mixture and sintering procedures that result in the formation of composites with low porosity and adequate particle distribution. In this work, Astaloy 85Mo ferrous powders were mixed with different tungsten carbide (WC) additions (2, 5, 7 and 10 wt%) by mechanical alloying (MA) and consolidated by spark plasma sintering (SPS), providing samples with higher real density, and without an increase in porosity (or apparent volume). SPS enhanced sinterability using low sintering time that reduces carbon diffusion from WC to the ferrous matrix. Tribological evaluation was conducted by means of ball-on-disk tests with different loads (5, 10, 15 and 20 N). Specimens were in contact with an AISI 52100 ball with a diameter equal to 10 mm and the friction and wear coefficient of both bodies in contact were reported. Results indicated that WC addition contributed to load support and decrease of matrix plastic deformation. Additions higher than 7 wt% of WC, in conditions of high normal load, resulted in the detachment of WC particles and abrasive wear of the counterpart.

1. Introduction

The production of components using powder metallurgy (PM) can offer advantages compared with conventional casting process, such as lower cost, fabrication of complex geometries and requirement of reduced or no additional machining [1,2]. Another important advantage of this process is the possibility of mixing different powders, which allows obtaining a broad variety of materials with different properties and functionalities. This wide material combination has contributed to the increase in manufacturing of sintered components for different application fields, including automotive and aerospace industries, as well as cutting and forming tools [3,4]. Nevertheless, for some applications, conventional sintering process is not effective, since a mixture of powders with different particle sizes and melting points cannot reach high density and mechanical strength [5,6]. Alternative processing techniques, such as powder injection molding and spark plasma sintering (SPS) allowed the production of nearly full dense parts [7]. Mechanical milling (MM) can also be successfully used, before sintering, to obtain highly dense materials due to particle size reduction and an improvement in the mixture homogenization [8,9].

The MM process is basically characterized by cycles of deformation, cold welding and fragmentation of a mixture of powder particles [10]. This process is highly-energetic by the effect of ball impingement and attrition against jar and powders, which results in mechanically hardened particles that, in some cases, can be difficult to compaction. Hence, the formulation of a milling route, particularly for mixtures with metallic powders, requires a selection of adequate parameters to obtain a more efficient reduction in particle size. Mechanical alloying (MA), which can be obtained during MM, is useful to produce powder mixtures with low particle size and a more homogenous particle distribution, which can inhibit particle segregation during sintering. Thus, in this work we hypothesize that a deliberated combination of more efficient mixing and sintering methods may produce sintered materials with enhanced density and mechanical properties.

SPS is an efficient PM process that has been widely used to sinter ceramic and metallic materials. Its extensive use is justified by its unique operating conditions, favored by the Joule effect that induces high heating rates [11] as compared with conventional PM methods. The SPS offers a series of advantages, including accurate control of sintering energy, shorter processing time, high reproducibility and reliability [12,13].

The use of both MM and SPS methods can enable the manufacturing

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of alloyed or composite materials with superior physical and mechanical properties, from mixtures of two or more different powder particles. Among the wide possibilities of material combinations, the production of particle-reinforced metal-matrix composites (MMCs) is of great interest, due to the possibility of obtaining a good combination of a tough matrix reinforced with hard particles (i.e oxides, carbides and borides) that increase the mechanical strength and the wear resistance [14]. The beneficial effect of ceramic reinforcements in the wear resistance is related to the capability to restraint nucleation and propagation of cracks and to the increase in load carrying capacity of the softer matrix. As reported in previous works, ceramic particles (TiC, VC, Cr_3C_2, TiCN) increase hardness as well as wear and oxidation resistance of high-speed steel (HSS) matrix composites processed by powder metallurgy [15–19]. Tungsten carbide (WC) is widely used in cemented carbides and mechanical components, since it meets the requirements of high hardness, high wear resistance, low thermal expansion coefficient and good wettability with molten metal [20,21]. WC particles reinforced MMC components manufactured by PM exhibit an attractive combination of mechanical and thermal properties with low manufacturing cost [22]. The efficiency of particle reinforcement depends on the volume fraction and carbide distribution in the microstructure of the composite material [23].

In addition to carbide powder particles, primary carbides that precipitate in the HSS martensitic matrix during solidification provide further improvement in hardness and wear resistance of these materials. In this case, the improved microstructure can be attributed to the formation of a carbide layer around the reinforcement particles, acting as a stronger interfacial bonding between the carbide network and the metallic matrix that, consequently, enhance wear resistance of the MMC material [19,24].

In terms of wear behavior, researches have verified the positive effect of reinforcement particles (TiB_2, TiC) in the reduction of wear rate of the stainless steel matrix composites. More detailed analyses of wear behavior of these materials indicated a strong dependence of wear rate on the volume fraction of the ceramic particles [25]. For Fe-based matrix composites with high WC additions (30% vol.) a homogenously dispersed microstructure with a strong matrix-reinforce bonding was obtained, which resulted in an improved abrasive wear resistance from 6 up to 9 times compared with a conventional martensitic steel [22].

Under mild sliding conditions, oxidational wear can be a predominant mechanism for TiC− or Al_2O_3-reinforced HSS steel matrix composites. The effect of ceramic particles protect the metallic matrix against oxidational wear depends on the ratio of the particle size to the thickness of the oxide tribolayer, as well as on the strength of particle-matrix bonding [19].

For low-alloy steel powders and low contents of carbide-forming elements, such as Astaloy, the improvement in strength and wear resistance is usually achieved by quenching and tempering and surface treatments of the compacts [26–28]. These materials are ferrous-based pre-alloyed powders with Ni, Cu, Mo and Mn elements and are advantageous over high-alloy steels regarding the low cost, good compaction and hardenability [29–31]. For some applications heat treatments are not effective, since higher strength and wear resistance levels are required. An alternative method of enhancing mechanical and tribological properties of these materials is the change in microstructure by the incorporation of hard reinforcement particles into the low-alloy steel powders.

Few studies have reported the addition of carbide reinforcements into the low-alloy steel matrix to improve mechanical strength or wear resistance of the base material [32]. The effect of both powders mixing and sintering techniques on microstructure, mechanical properties, wear rate and wear mechanisms of carbide-reinforced low alloy steel are also issues to be understood.

The aim of this research is to investigate the effect of WC additions on the tribological performance of Astaloy 85Mo low-alloy steel. A route with MA and SPS steps is proposed to obtain Astaloy + WC composites with minimal porosity and enhanced mechanical properties. Ball-on-disk tests were conducted to study the wear and friction response of each mixture. After the tests, the wear mechanisms were identified for the different normal loads. The effect of WC on the load carrying capability and plasticity-dominated wear mechanism was also investigated by means of Focus Ion Beam (FIB) and indentation analysis.

Table 1
Chemical composition of powders (wt.%).

Element	C	Mo	Cr	Ni	O	Fe	W
Astaloy 85Mo	0.3	0.85	0.029	0.10	0.07	Balance	< 0.006
WC	6.11	0.02	0.001	0.001	< 0.003	0.09	Balance

2. Experimental procedure

Astaloy 85Mo (Fe, 0.3 wt% C 0.85 wt% Mo; Höganäs, Inc.) and tungsten carbide powders were the raw materials. The nominal chemical composition of the powders is shown in Table 1. The complete route used to produce the sintered samples from different mixtures of Astaloy and WC powders is summarized in Fig. 1. The test configuration for tribological characterization of the consolidated materials is also presented.

For the PM preparation of the WC-containing Astaloy 85Mo samples, raw powders with different morphologies and particle size were selected. Mixtures of Astaloy powder with additions of (2, 5, 7 and 10) wt.% of WC were produced. To enhance homogenization and particles packing, steel-ceramic mixtures were obtained using a planetary ball mill (Fritsch Pulverissete 4) at a maximum rotational speed of 200 rpm for 10 h under argon atmosphere. Milling balls made of AISI 52100 steel (62 HRC), with 10 mm-diameter, were set using a ball-to-powder weight ratio of 10:1 in a jar mill with counterclockwise rotation, i.e., in the opposite direction to main disk, with a transmission ratio of 1:-2. To avoid powder overheating, the total milling time of 600 min (60 cycles) consisted of a 10-min milling stage (ON) and 20-min pause stage (OFF).

To verify the efficiency of the milling process, particle size distribution was measured using a laser diffraction analyzer (Horiba LA-960). X-ray diffraction (XRD) analyses of powders were also conducted to identify crystalline phases including oxides that might have formed during mechanical alloying. For that purpose, the following XRD parameters were used: Cu-KÎ ± radiation ($\lambda = 0.15418$ nm), Bragg Brentano configuration (θ-2θ), at 40 kV, 30 mA, 2θ range from 20° to 100°, step size of 0.05° and 2 s of integration time. The indexing of XRD powder patterns were conducted with the aid of the XPert HighScore Plus software.

The mixtures were consolidated by spark plasma sintering (SPS) using a DR. SINTER® SPS1050 (Sumitomo Coal Mining Co. Ltd., Japan) apparatus. Disks with 20 mm of diameter and 5 mm of thickness were produced in a high-density graphite die. Samples were heated up to a sintering temperature of 1000 °C at a heating rate of 100 $°C.min^{-1}$, applying a compressive pressure of 70 MPa simultaneously during both the heating and the 5 min of isothermal holding at the sintering temperature. Finally, the samples were free -cooled to room temperature at a cooling rate of approximately 10 $°C\,s^{-1}$ in the SPS chamber. The complete SPS cycle was conducted in vacuum.

The apparent density of the sintered samples was measured using the Archimedes principle, according to the ASTM B962-17 standard, and their absolute density was obtained according to the linear rule of mixtures, considering the theoretical density value of the individual materials (7.85 $g\,cm^{-3}$ for Astaloy 85Mo and 15.70 $g\,cm^{-3}$ for tungsten carbide) [33,34]. The relative density of the sintered samples was determined by comparison of the experimental value with the absolute one. For the microstructural analysis of the sintered materials, metallographic samples were prepared through the following sequence of