Materials and Design 74 (2015) 67–75

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Mitigation of abrasive wear damage of Ti–6Al–4V by laser surface alloying

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A R T I C L E I N F O

Article history:
Received 28 July 2014
Accepted 14 February 2015
Available online 23 February 2015

Keywords:
Laser alloying
Titanium aluminides
Ti–6Al–4V alloys
Three body abrasive wear resistance

A B S T R A C T

Ti–6Al–4V alloy is lightweight, heat treatable and machinable with excellent strength characteristics. These properties favor its extensive applications in the automobile, aerospace and aeronautical industry. However, low hardenability, poor wear resistance and the tendency to gall and smear have reduced the use of Ti–6Al–4V. This study was designed to investigate the enhancement in the abrasive wear resistance of Ti–6Al–4V laser alloyed with three different premixed composition of Mo + Zr + Stellite 6 using a 4.4 kW continuous wave (CW) Rofin Sinar Nd:YAG laser processing system. Microstructural evolution in the samples was studied by optical and scanning electron microscopes. The phase evolution was studied by X-ray diffractometer. There exists metallurgical reaction and bonding between the Ti–6Al–4V substrate and the laser coatings. Scanning electron micrographs and X-ray diffraction spectra of the coatings revealed the formation of various titanium aluminides among other complex phases. The β-phase of Ti was retained owning to the presence of Mo – a β-phase stabilizer, in the powder mixture. Three-body abrasive wear resistance test indicates that the wear of the coatings was dominated by adhesive mechanism which is characterized by fine scratches. A twenty-four fold improvement in wear resistance was obtained in the coatings when compared with the native alloy.

1. Introduction

Since discovered in the early 1950s, titanium and its alloys (Ti–6Al–4V in particular), have become backbone materials for many industries such as the aeronautical, chemical, marine, power generation, sports and leisure, transportation, and biomedical industries, for manufacturing critical systems, and airframes. This is due to the unique combination of many desirable and versatile specific bulk properties of the alloy which include low density that gives rise to very attractive strength-to-weight ratio, high specific strength, low elastic modulus, superior corrosion and erosion resistance in many environments, excellent high temperature resistance and biocompatibility [1–7]. However, despite these numerous laudable properties, poor wear resistance, low hardness, high friction coefficient, low hardenability and the tendency to gall and smear have limited the engineering applications of titanium and its alloys [8–10]. The high coefficient of friction and poor tribological behavior of titanium can be traced to three fundamental factors which are: titanium's atomic structure, crystal structure and the relatively low tensile and shear strength of the titanium oxide film.

Therefore, the need to develop methods that will remove these limitations, improve and enhance the properties of titanium and its alloys while retaining the desirable bulk properties is important for industrial application. In view of the fact that the aforementioned failures of titanium and its alloys are surface dependent rather than the bulk alloy, surface modification holds a promise of improving the surface properties [11]. Surface modification processes that can be successfully applied to efficiently improve the surface dependent properties of titanium and its alloys include laser surface treatment (laser surface alloying, (LSA), laser cladding (LC)), ion implantation, physical vapor deposition (PVD), chemical vapor deposition (CVD), carburizing, nitriding, ion implantation, thermal oxidation heat treatment, shielded metal arc welding and gas tungsten arc welding [12,13].

Laser surface alloying (LSA), can rapidly provide a thick and crack-free layer in all instances with metallurgical bonds at the interface between the alloyed layer and the substrate [1]. In LSA, external alloying elements in form of powder (metal, alloy, ceramic, cermet or intermetallic) are introduced into the surface of a substrate, as pre-placed material or injected directly into the melt pool created on the substrate by a high power laser beam. The melting of the substrate occurs rapidly only at the surface, while the bulk of

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http://dx.doi.org/10.1016/j.matdes.2015.02.010
0261-3069/

the material remains cool, thus serving as an infinite heat sink. The result of this is rapid self quenching and resolidification of new alloy due to the large temperature gradients between the melted surface region and the underlying solid substrate. One consequence of this is the evolution of a wide variety of microstructures as a result of the rapid cooling from the liquid phase [14,15]. Hence, during laser alloying, the synthesis of new alloy is possible by depositing a premixed ratio of elemental powders. Powders surfaced on new or worn working surfaces of components by LSA provides specific properties such as high abrasive wear resistance, erosion resistance, corrosion resistance, heat resistance and combinations of these properties. Consequently, improvements in machinery performance and safety in aerospace, automotive, can be realized by the method [16]. According to Poulon-Quintina et al. [17], laser beams, because of specific thermal characteristics induced by laser irradiation, can generate specific microstructures including metastable phases and nano-crystalline grains.

Laser processing offers unique and significant quality and cost advantages over traditional techniques. These include high throughput speed, process compatibility, high process efficiency, low porosity and good surface uniformity. In addition, the rapid self quenching in laser alloying results in a true metallurgical bond between the composite layer and substrate, the formation of a non-equilibrium or amorphous phase as well as homogenization and refinement of the microstructure, all without affecting the bulk properties of the substrate [18,19].

A number of investigations have been carried out on the alloying of Ti substrate with a mixture of powders. Fallah et al. [20] used a fiber laser to modify the surface composition of a Ti–6Al–4V plate through deposition of the blown powder mixture of Ti–45 wt%Nb. The authors reported that continuous beads were formed with pore-free sections and a homogeneous composition corresponding to that of β (Ti, Nb) solid solution phase. Three kinds of laser boronizing composite coatings were in situ synthesized on Ti substrate by using powders of B, BN and B_4C as starting materials [19]. Results show the coating has higher microhardness and better wear resistance than pure Ti substrate and the composition, microstructure, microhardness, and wear resistance of the resulting laser boronized composite coatings vary with the composition of the starting materials [21].

Popoola et al. [22] investigated laser coating of commercial titanium alloy with combination of Zr and TiC and reported an increase in the hardness of the substrate. Fogagnolo et al. [1] introduced niobium into the surface layer of titanium by laser surface alloying and reported that the resulting microstructure led to reduction of approximately 30% in Young's modulus and a more than 100% increase in hardness. Ochonogor et al. [23] developed titanium metal matrix composite on titanium alloy and reported that the wear resistance of the alloy improved significantly, indicating a fifteen fold wear rate reduction due to the proper distribution of the ceramic particles. Lin et al. [12] investigated in situ formed TiNx reinforcing phase within the clad layer of Ti–6Al–4V by gas tungsten arc welding (GTAW) and reported that the hardness of the TiN clad layer is two times better, whilst the wear resistance is ten times more than that of the Ti–6Al–4V substrate. Chikarakara et al. [24] reported that high speed laser surface modification of Ti–6Al–4V led to a microhardness increased up to 760 $HV_{0.05}$ which represented a 67% increase compared to the bulk material. Chun et al. [25] fabricated intermetallic compound composite coating on pure Ti substrate by laser and reported that the intermetallic compound coating contributes to greatly increase the microhardness of the pure Ti substrate yielding a high-average hardness which is about four times higher than that of pure Ti substrate. Therefore, the values of wear rate for intermetallic coated samples are nearly two orders of magnitude lower than that of pure Ti substrate.

Molybdenum (Mo) and its alloys have outstanding combination of high temperature properties (such as high melting point, low vapor pressure and high temperature strength), while zirconium (Zr) has a tendency to promote chemical homogenization. Laser alloying with zirconium is suitable to control fretting wear damage [26]. Molybdenum coatings can increase the fretting fatigue strength and prevent material loss during fretting at room and high temperatures. Molybdenum coatings exhibit good corrosion resistance, which is beneficial for fretting resistance [27,28]. Molybdenum is a beta phase stabilizer in titanium while zirconium behaves more as neutral solute and has little effect on the transformation temperature, acting instead as strengthener of the alpha phase [26]. Stellite 6 powder has a unique inherent characteristics of the hard carbide phase dispersed in a CoCr alloy matrix giving it exceptional resistance to wear and many forms of mechanical and chemical degradation over a wide temperature range. In addition, stellite 6 retains a reasonable level of hardness up to 500 °C and resists oxidation up to 1095 °C. It is usually used for alloying due to its high hardness and good bonding strength with the substrate [29,30]. Consequently, a composite coating of premixed ratio of powders of Zr, Mo and stellite 6 formed on titanium is expected to evolve complex microstructure of a stabilized beta phase in the matrix of the titanium, which will enhance the surface properties of the alloy.

Literature exploiting laser to alloy Ti with different premixed powder ratio in order to tailor the predominant phase in the matrix of Ti and evolve complex microstructures that will improve Ti properties is rare. Moreover, there are limited publications that discuss laser alloying of Ti–6Al–4V with pre-mixed ratio of Mo, Zr and stellite 6 powders in order to take advantage of the unique properties of these powders that were discussed above. Hence the process had not been fully understood. Therefore, this research work investigates the abrasive wear damage of titanium alloy by using laser to incorporate different premixed composition of Zr + Mo + stellite 6 on Ti–6Al–4V. Detail and systematic study of the phase evolution and transformation, resultant microstructure, microhardness and abrasive wear resistance behavior of the composite coatings were carried out.

2. Experiments

2.1. Materials and methods

Test pieces cut from as-received (AR) Ti–6Al–4V alloy were used in this investigation. The nominal chemical composition of the alloy is 6.01 wt% Al, 3.84 wt% V, 0.30 wt% Fe, 0.15 wt% Si, 0.10 wt% C, 0.15 wt% O, 0.15 wt% N, Ti, balance. Samples were machined to specimen plates of dimensions $(100 \times 100 \times 6)\ mm^3$. The plates were sandblasted to clean the surface, minimize reflection of radiation during laser processing and accelerate the absorption of laser energy by the metal. The alloying powder was made up of different compositions of Molybdenum (Mo), Zirconium (Zr) and stellite 6 (S_6) powders. The chemical composition of the stellite 6 powder is 2.26 wt% Fe, 0.28 wt% Mn, 26.48 wt% Cr, 3.26 wt% Ni, 0.068 wt% Nb, 8.095 wt% W, balance Co. The grain size of all the powders used is <45 μm. The powders were weighed separately and then mixed in a vial into three different compositions as shown in Table 1.

Table 1
Composition of the alloying powder.

Sample no	Powder composition
T-M-Zr-S_6 1	50 wt% Mo + 30 wt% Zr + 20 wt% S_6
T-M-Zr-S_6 2	30 wt% Mo + 20 wt% Zr + 50 wt% S_6
T-M-Zr-S_6 3	20 wt% Mo + 50 wt% Zr + 30 wt% S_6