Wear 322-323 (2015) 41–50

Contents lists available at ScienceDirect

Wear

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

Sliding wear and solid-particle erosion resistance of a novel high-tungsten Stellite alloy

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ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
13 October 2014
Accepted 26 October 2014
Available online 5 November 2014

Keywords:
Stellite alloy
Tungsten
Carbide
Sliding wear
Solid-particle erosion
Hardness

ABSTRACT

A high-tungsten Stellite alloy is developed for wear and erosion resistance application in this research, taking the advantage of tungsten in Stellite alloys. The microstructure of this alloy is analyzed using SEM/EDX and XRD. The sliding wear resistance of the alloy is evaluated on a pin-on-disc tribometer and the solid-particle erosion behavior is investigated using a micro-blasting jet machine at two particle impact velocities (84 and 98 m s^{-1}) and two impingement angles (30° and 90°). The experimental results of the alloy are compared with those of well-known wear-resistant Stellite 3 and Stellite 6. The worn and eroded surfaces of the specimens are studied using SEM/EDX to explore the wear and erosion mechanisms of this new alloy. The experimental results show that this novel high-tungsten Stellite alloy has superior sliding wear and solid-particle erosion resistance to Stellite 3 and Stellite 6, owing to the formation of large amounts of large-size W-rich carbides in the alloy.

1. Introduction

Stellite alloys are a group of superalloy, which are cobalt, Co, based and contain a high level (20–30 wt%) of chromium, Cr, a moderate amount (4–18 wt%) of tungsten, W, or/and molybdenum, Mo, and a small amount (0.25–3 wt%) of carbon, C [1]. They combine excellent mechanical properties with wear resistance, especially at high temperatures, with very good corrosion resistance. They are resistant to cavitation, corrosion, erosion, abrasion and galling. The lower carbon alloys are generally recommended for cavitation, sliding wear or moderate galling, while the higher carbon alloys are usually selected for abrasion, severe galling, or low angle erosion. Their exceptional wear resistance is due mainly to the unique inherent characteristics of the hard carbide phase dispersed in a tough Co solid solution matrix [1].

Chromium has a dual function in Stellite alloys; it is both the predominant carbide former, that is, most of the carbides are Cr-rich, and the most important alloying element in the matrix, where it provides added strength, as a solute, and resistance to corrosion and oxidation. Tungsten and molybdenum in Stellite alloys serve to provide additional strength to the matrix, when present in a small amount (<4 wt%). They do so by virtue of their large atomic size, that is, they impede dislocation flow when present as solute atoms. They also improve general corrosion resistance of the alloys. However, when present in large quantities, W and Mo also participate in formation of W-rich or Mo-rich carbides during alloy solidification [1–4]; Mo can form intermetallic compounds of Co_3Mo and $CoMo_6$ in low-C Stellite alloys, in addition to as a solute in the Co solid solution matrix [5,6].

One of the main applications of Stellite alloys can be wear and erosion resistance, which results from various carbides and Co solid solution [1,7]. Cobalt imparts to its alloys an unstable fcc crystal structure with a very low stacking fault energy. The instability arises from the fact that elemental Co, if cooled extremely slowly, transforms from an fcc to an hcp crystal structure at 417 °C [1,8]. Because of the sluggish nature of the transformation, the fcc structure in Co and its alloys is usually retained to room temperature, and hcp formation is triggered only by mechanical stress or time at elevated temperatures. The unstable fcc structure and its associated low stacking fault energy are believed to result in high yield strength, high work-hardening rate due to the interaction between stacking faults, limited fatigue damage under cyclic stress due to the lack of cell walls within plastically deformed material, the ability to absorb stress through transformation of the structure to hcp. The first three of these attributes are believed to be important in preventing material damage during sliding wear. The last two are believed to be responsible for the outstanding resistance to cavitation and erosion–corrosion of Stellite alloys [8].

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http://dx.doi.org/10.1016/j.wear.2014.10.012
0043-1648/

There are two main categories of Stellite alloys: CoCrW and CoCrMo systems. In the former, Stellite 6, containing 1.2 wt% C, is the most widely used of wear-resistant Stellite alloys and exhibits good all-round performance. It is regarded as the industry standard for general-purpose wear resistance applications has excellent resistance to many forms of mechanical and chemical degradation over a wide temperature range, and retains a reasonable level of hardness up to 500 °C. It also has good resistance to impact and cavitation erosion. Stellite 6 is ideally suited to a variety of hardfacing processes and can be turned with carbide tooling. Examples include valve seats and gates, pump shafts and bearings, erosion shields, and rolling couples. Because of its wide application, Stellite 6 has been extensively studied in various aspects of properties such as sliding wear on macro-, micro- and nano-scale, cavitation erosion, solid-particle erosion, high-temperature sliding wear, etc. [7,9–17]. Stellite 3, in the same category, but containing higher C (2.4 wt%) and more resistance to wear than Stellite 6 is the most commonly used for severe wear environments. Owing to the high C content thus a large volume fraction of carbides, this alloy possess excellent metal-to-metal wear resistance and resists galling when mated with other Stellite alloys [1]. The cavitation erosion study on Stellite 3, Stellite 6 and Stellite 20 demonstrated that Stellite 3 had the best resistance to erosion [11]. Similarly, the investigation of room-temperature and high-temperature sliding wear resistance of various Stellite alloys showed that Stellite 3 exhibited much better resistance to wear than Stellite 6 and Stellite 12 (CoCrW alloy containing 1.4 wt% C) at room temperature and also better wear resistance than Stellite 6 at elevated temperatures [15,16].

The W content in Stellite alloys is normally less than 20 wt%. As mentioned above, W exists in the CoCr solution matrix as a solute when its content is low (<4 wt%), while it promotes formation of W-rich carbides when present in large quantities. To take this advantage of W, the present research was aimed to increase W content of Stellite alloy in an excessive amount ($\sim$32 wt%) to create a new high-W Stellite alloy. The focus of the research was on the microstructure, sliding wear and solid-particle erosion resistance of this alloy, compared to conventional wear-resistant Stellite 3 and Stellite 6. The worn and eroded surfaces of these alloys were examined using SEM/EDX to assist the analysis and understanding of the wear and erosion test results.

2. Materials and methods

2.1. Microstructural analysis

The chemical composition (wt%) of new alloy is shown in Table 1, together with those of Stellite 3 and Stellite 6 for comparison. These chemical compositions were provided by the supplier (Kennametal Stellite Inc.) of the alloy specimens. The W content in the new alloy is increased to 32 wt% from the normal 4–18 wt% in Stellite alloys, in the meanwhile, the Cr content is reduced to 22 wt% in order to keep the required Co amount in Stellite alloys. The C content in this alloy is selected to be 1.5 wt%, which is considered as high for Stellite alloys and intended to promote W-rich carbide formation.

Table 1
Chemical compositions (wt%, Co in balance) of tested Stellite alloys.

Alloy	Element							
	Cr	W	Mo	Ni	Fe	C	Si	Mn
Stellite 3	30.5	12.5	0	3.5	5	2.4	2	2
Stellite 6	29	4.5	1.5	3	3	1.2	0.75	0.5
New alloy	22	32	0	0	0	1.5	0	0

The alloy specimens were fabricated with a centrifugal casting process. The cast specimens were cut to approximately 45–60 mm in length and 5 mm in thickness and then mounted by encapsulating into a compression mounting compound. For microstructural analysis, the specimen surface was ground with grit papers from course ♯180 to fine ♯600 and polished with abrasive cloth plus 1 μm alumina powders. The polished surface was etched electrolytically using an aluminum cathode at a voltage of 3 V for about 10 s. The etchant was a mixed solution containing 9 g CrO_3, 15 ml HCl and 150 ml H_2O. The microstructures of the alloys and the chemical compositions of each phase in the microstructures were analyzed using SEM/EDX and XRD.

The obtained SEM images of microstructure are presented in Fig. 1. Stellite alloys have a microstructure typically consisting of complex wear-resistant carbides dispersed in a tougher and more ductile Co solid solution matrix. There are two types of carbides in the microstructures. The EDX spectra in Fig. 2 reveal that the black phase is Cr-rich, shown in Fig. 2(a), which implies that it is Cr-rich carbides, while the white phase is W-rich, shown in Fig. 2(b), which is W-rich carbides. For the elemental content tables associated with the EDX spectra, since the SEM/EDX instrument used in this research has a limitation in detection of C, it cannot provide an accurate content of C. Thus the element content tables contain only the metallic elements. The phase in gray for the three alloys is Co solid solution, as shown in Fig. 2(c), Co and Cr dominate the phase.

For Stellite 3 in Fig. 1(a), the microstructure consists of major Cr-rich carbide (black) and minor W-rich carbide (white) dispersed in Co solid solution matrix (gray). The XRD spectrum in Fig. 3 further confirms that the Cr-rich carbide is Cr_7C_3 and the W-rich carbide is $(W,Co)_6C$. The microstructure of Stellite 6 in Fig. 1 (b) shows nearly entire Cr-rich carbides embedded in Co solid solution matrix and little white phase is observed, which means that W-rich carbides are trivial in this alloy. This is due to the less W content in Stellite 6. The XRD pattern in Fig. 3 indicates that there are two types of Cr-rich carbides in Stellite 6: Cr_7C_3 and Cr_3C_2.

As concerns the new alloy, it differs from Stellite 3 and Stellite 6 in microstructure significantly. First, there is a very large volume fraction of W-rich carbides in this alloy. Second, these carbides have large size. Third, Cr-rich carbide also exists in this alloy but the amount is less than that in Stellite 3 and Stellite 6. The XRD pattern in Fig. 3 shows that there are two types of W-rich carbides in this alloy: $(W,Co)_6C$ and Co_4W_2C, and the Cr-rich carbide is Cr_7C_3. Referring to Table 1, according to the C contents of three alloys, Stellite 3 is hypereutectic and Stellite 6 is hypoeutectic. As a result, the carbide volume fraction of the former is larger than that of the latter. For the new alloy, although its C content is not very high, due to the excessive W content, this alloy also has a hypereutectic microstructure with the W-rich carbides being the primary phase. As shown in the XRD spectra in Fig. 3, the peaks of W-rich carbides are much stronger than those of Co solid solution for the new alloy, while the peaks of Co solid solution are stronger for Stellite 3 and Stellite 6. Furthermore, the volume fractions of carbides in these alloys were estimated using SEM and the system software; the results are presented in Table 2.

2.2. Sliding wear test

The wear resistance of new alloy together with Stellite 3 and Stellite 6 was investigated at room temperature using a pin-on-disc tribometer, which consists of a stationary “pin” under an applied load in contact with a rotating disc. The pin used in this research was a spherical tip having a radius of 2.5 mm and was