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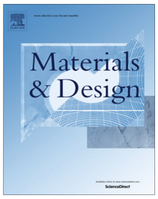

The influence of surface modification techniques on fretting wear of Al–Si alloy prepared by gravity die casting

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ABSTRACT

In this study, the fretting wear resistance of Al–Si alloy subjected to ultrasonic nanocrystalline surface modification (UNSM) and high-frequency ultrasonic peening (HFUP) techniques was investigated. The objective of this study is to mitigate the fretting damage that occurs between the cylinder block and bed-plate, and the bed-plate and cylinder head of engines. The fretting wear resistance of the untreated and treated specimens was investigated using a ball-on-disk fretting machine under dry and oil-lubricated conditions. The results showed that both treated specimens led to a higher resistance to fretting wear compared to those of the untreated specimens, which may be attributed to the increase in surface hardness and roughness, and homogeneously distributed Si particles over the surface. Moreover, microstructure of Al grains and Si particles was studied using a transmission electron microscopy (TEM). The results of this study are expected to make these surface modification techniques more attractive for Al–Si alloy due to the mitigation in fretting.

1. Introduction

Al–Si alloys have been widely used in the automotive industry, especially for engine applications to meet the continuous demand for better fuel efficiency, lower thermal-expansion coefficient and cleaner exhaust [1]. The suppliers of engine cylinder blocks are constantly striving to manufacture better, lighter and durable blocks in order to improve and enhance the efficiency of automobile engines since the cylinder blocks are the largest and most intricate single piece of metal used in an internal combustion engine (ICE) on to which other important engine parts are mounted. Si is probably one of the most expensive alloying additions to Al, which improves castability, formability and weldability, and increases strength to weight ratio and resistance to wear as well. These improvements are significant not only when the Si phase undergoes structural modifications, but also when the Si particles are finely distributed in the matrix phase. However, in spite of the attractive mechanical properties, engine vibration cause a relative slip between the bolted contact surface of cylinder blocks, resulting in the occurrence of fretting wear, which can accelerate fretting and fatigue failures by creating crack initiation sites. The locations where fretting may occur are bolted joints. Fretting is a type of wear generally associated with vibration and is one of the major causes of failure in many mechanical components and may occur on a small scale but it can initiate other types of wear leading to severe damage of the engine blocks [2–4]. High operating temperature of an engine can also accelerate the wear mechanism resulting in a different fretting wear behavior. It is therefore very important to increase the wear resistance, particularly under fretting conditions by modifying microstructure and improving the mechanical properties of Al–Si alloys. When cylinder blocks cast of hypoeutectic like AA319 or AA356 are used, cylinder liners made of cast iron or in some cases metal matrix composite must be added. However, their overall manufacturing costs remain high due to casting and machining costs [5] that requires the development of new Al–Si alloys with the required combination of good casting and improved surface properties that could mitigate the fretting wear and reduce the vibration in engines. An alternative is the use of specific surface modification and coating techniques that provide higher resistance to fretting wear during engine operation [6–8]. It has been well known that surface plastic deformation processes have become widely used to generate nanostructured materials in order to enhance fretting wear by increasing the strength of materials [9–12]. Basavakumar et al. have studied the influence of grain refinement on the wear behavior of Al–Si alloy [13]. They have reported that the wear

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behavior of Al–Si alloy mainly depends on the grain refinement and Si particles in the matrix. It has also been reported earlier that grain refinement can improve the wear behavior of Al–Si alloy under dry sliding conditions [14].

Ultrasonic nanocrystalline surface modification (UNSM) and high-frequency ultrasonic peening (HFUP) techniques are one of the newly developed surface modification techniques in which spherical balls are bombarded into the workpiece at a high-frequency of 20 kHz. The continuous strikes and bombards induce compressive residual stress and work-hardening to the surface region of the workpiece. It has been demonstrated among the different surface modification techniques that these techniques are an effective and economical method to produce a nanocrystalline surface layer (NCSL) by refining the coarse grains into nanometer scale without changing the chemical composition of materials [15,16]. It has also been reported earlier that the UNSM technique could mitigate the fretting wear and reduce the friction coefficient of commercial pure Ti and Ti–6Al–4V alloy [17]. Hence, the investigation on fretting wear of Al–Si alloy is of great importance in the effort to mitigate the fretting and to reduce the vibration of automotive engine blocks during operation. More details of UNSM and HFUP techniques can be found in previous studies [15–18]. Hence, the objective of this study is to evaluate the effectiveness of UNSM and HFUP techniques on the microstructure and fretting wear resistance of Al–Si alloy with the aim of avoiding fretting wear consequences and vibration of engine blocks. This paper analyzes the microstructure, fretting wear resistance and scratch behavior of Al–Si alloy subjected to UNSM and HFUP techniques.

2. Experimental details

2.1. Specimen preparation

In this study, a series of Al–Si alloy specimens, which were cut into disk specimens from the engine block, with dimensions of 20 mm in diameter and 7.9 mm in thickness were used. The chemical composition of the specimens is listed in Table 1. The engine block material was prepared by tilting gravity die casting process, which is widely used for the manufacture of castings parts made of non-ferrous alloys due to the low melting temperatures not exceeding 1000 °C. At the beginning of the process, the mold is tilted towards the pouring side, resulting in minimal metallostatic casting height. The tilting towards the pouring side results in a low feed rate in the gate, helping to reduce oxide and foam formation, and the liquid metal can flow into the mold cavity smoothly and with low turbulence. The melt is metallurgically treated in the holding furnace, which is positioned near the dies. The quantity of melt for one casting is transported in a ladle and poured into the riser system of the mold by tilting the ladle. The melt fills the mold cavity smoothly from the bottom up until it appears in the risers positioned above the casting. Afterwards, the engine block was heat treated (solution and aging treatments were done at temperatures of 535 °C and 155 °C for 8 and 6 h, respectively) in order to reach the mechanical properties. Some of the specimens were treated by UNSM and HFUP techniques under the parameters as shown in Table 2. The UNSM treatment is an effective in hardening the surface region of the specimen, striking the specimen by a WC tip attached to a horn, while the HFUP treatment imparting small indents and/or dimples and causing plastic deformation at the specimen surface layer by impact of the balls. Prior to surface treatments, the specimens were cleaned in acetone and benzene mixture for 10 min using an ultrasonic bath.

Table 1
Chemical composition of the specimens (in wt.%).

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
wt.%	12.6	0.13	0.18	0.1	0.45	0.1	0.2	Bal.

2.2. Fretting and scratch tests

The fretting wear resistance of the specimens was investigated using a schwingung reibung verschleiss (SRV4, Germany) ball-on-disk tribometer under dry and oil-lubricated conditions at a temperature of 25 °C with a relative humidity (RH) of 60%. All the tests were performed according to ASTM: G204 standard at normal loads of 20 N and 50 N, frequency of 50 Hz with a stroke of 100 μm for 20 min. A bearing steel ball with a diameter of 10 mm was used as a counter surface specimen, which was selected because of its wide application in the automotive industry. The hardness of the counter surface ball was about 63 HRC. Each specimen was tested at least three times due to the data scattering. SP-4M oil, which is commonly used in ICEs, was used as a lubricant. The schematic view of the tribometer used in this study can also be found in previous study [18].

The surface hardness of the specimens with respect to depth from the top surface were made using a micro Vickers hardness tester (Akashi Corp. AAV-4M, Japan) with a diamond pyramid Vickers indenter at a load of 10 N and constant indenter dwell time of 30 s. All indentation tests were carried out under ambient laboratory conditions.

Micro-scratch tests were carried out according to ASTM: G171 standard using a Rhesca TB-01 scratch tester equipped with a conical diamond tip in order to study the effectiveness of the UNSM and HFUP techniques on the resistance to scratch. During a single stroke scratch test, the load was applied incrementally up to a prescribed 10 N over a scratch distance of 2 mm at a speed of 4 mm/min. Scratch-induced damage during the scratching process is monitored by normal load and tangential (friction) force measurement. All the specimens were subjected to three scratches in order to ensure reproducibility of the tests results. Details of scratch test can also be found in a previous publication as well [18].

2.3. Surface characterization

The surface morphology and fretting wear scar that formed after fretting wear tests on the surface of the specimens were investigated using a field emission scanning electron microscope (FE-SEM, SUPRA40, ZEISS, Germany). Cross-sections of the specimens for SEM observation were prepared by metallographic polishing followed by etching in 5 ml HF + 25 ml HNO_3 + 75 ml HCl solution. The thin foils for transmission electron microscopy (TEM, JEM-2100F) observation were prepared using a Gatan PIPS691 at proper angles and beam energies. Chemical composition of the

Table 2
UNSM and HFUP techniques treatment parameters.

Technique	Frequency, kHz	Amplitude, μm	Impact load, N	Feed-rate, mm	Speed, mm/min	Treatment time, min	Number of balls	Ball material	Ball diameter
UNSM	20	30	20	0.07	3000	5	1	WC	2.38 mm
HFUP			–			3	22		2 mm