Wear 376-377 (2017) 1611–1621

Contents lists available at ScienceDirect

Wear

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

Tribological behaviour of an electrochemical jet machined textured Al-Si automotive cylinder liner material

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ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form
20 January 2017
Accepted 23 January 2017

Keywords:
Surface texturing
Automotive
Al-Si
Friction
Wear
Electrochemical jet machining

ABSTRACT

This paper investigates the use of Electrochemical Jet Machining to surface texture a hyper-eutectic Al-Si cylinder liner material. Samples were lapped to a 6 µm finish followed by immersion in 1 mol NaOH to expose the primary silicon colonies above the aluminium surface. Texturing was carried out using a NC system comprising of a fine gauge nozzle (cathode) jetting a solution of 2.3 mol NaCl on the surface (anode) whilst applying a current density of 220 A/cm^2. An array of hemispherical dimples at 1.5 mm spacing was created, with an average diameter of 420 µm and depth of 40 µm, corresponding to an ε ratio of 0.095. Lubricated reciprocating sliding was carried out at stroke length of 25 mm in a bath of PAO (4 cSt) against a 52100 cylinder of 6mm diameter and 16mm length. Sliding frequencies were incremented at 1 Hz intervals between 1–15 Hz at 50 N load increments from 50-200 N. Stribeck curves indicated a reduction of the friction coefficient due to texturing of up to 0.05 in the mixed lubrication regime, representing a decrease of 38.5%. Optical profilometry and SEM indicated that abrasion and formation of a surface tribo-layer was mitigated in regions of the Al-Si surface where textured features were present parallel to the sliding direction.

1. Introduction

Projected increases in worldwide automotive vehicle numbers [1] place an ever increasing emphasis on improvements to vehicle fuel economy and reduction of environmental emissions in an effort to improve sustainability [2]. Vehicle light-weighting technology is one means to achieve this objective [3,4] and has seen increasing research and development of aluminium alloys and composites for use in engine components subject to wear, in particular the eutectic Al-Si system [5–10]. A recent study by Holmberg et al. [11] suggested that on average, 45% of energy losses in a typical internal combustion engine are used to overcome friction within the piston assembly. This has led in recent years to intensive research into the applicability of surface texturing to the cylinder bore surfaces. Early work by Etsion and co-workers [12–14] into the applicability of laser surface texturing to automotive contacts has led to a significant body of literature on the applicability of this technique for improving frictional performance of reciprocating engine components [15–28]. However the applicability of surface texturing for enhanced tribological properties is not universal and improvements in frictional response of sliding couples are sensitive to both the texture geometry as well as the contact environment. Dimple size (depth, diameter) has been identified as a key variable of texturing performance as well as the areal coverage of the feature density [17,18,21–23]. The sliding parameters that the contact operates under, namely the lubrication regime, fluid viscosity and contact geometry also strongly determine if texturing is beneficial or detrimental to the overall friction and wear performance [15,17,18,20,24]. As pointed out by Gropper et al. [29], the applicability of surface texturing is specific to the texturing parameters and contact conditions of each contact. Yet generation of micro elasto-hydrodynamic (micro-EHL) lubrication from pockets of constrained lubricant [16–19], debris entrapment [21,30] and reservoirs for starved contacts [15,18,21,31] have all been cited as beneficial mechanisms of surface texturing and as such worthy of exploration from a joint application-manufacturing perspective.

By far the greatest amount of research in this area as been applied to the use of laser textured surfaces. However, laser surface texturing of metallic surfaces are prone to a number of drawbacks linked to the energetic ablative nature of the process and the behaviour of the resultant recast layer. The microstructure in the immediate vicinity of textured features is often altered as a result of the heat energy input. Concurrently, the presence of surface lips or burs around features can compromise friction and wear performance without a further machining step to remove

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http://dx.doi.org/10.1016/j.wear.2017.01.085

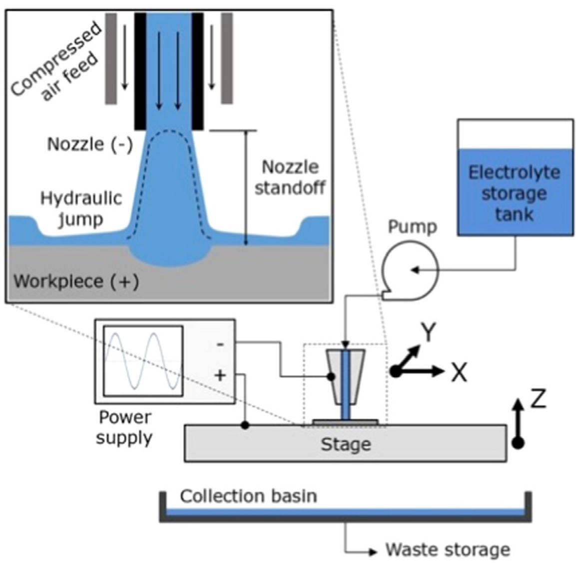

Fig. 1. Schematic showing the rudimentary application of the EJM process to a workpiece.

them [15,18,20–22,24,32], although femtosecond lasers can go some way to address this issue. However, the capital investment for such apparatus greatly influences the utility in automotive applications.

Alternative methods for surface texturing of metallic surfaces include Electrochemical Machining (ECM), with Byun et al. [33] demonstrating a reduction in friction coefficient values of an ECM textured AISI 440 C steel surface compared to an un-textured control test. Electrochemical Jet Machining (EJM) is a highly localised variant ECM of whereby conductive materials resistant to shear based machining methods can be easily processed. However, unlike traditional ECM it does not require specialist tooling or masking to create high precision surface geometry [34]. Using a nozzle (cathode) electrolyte is jetted towards a substrate surface (anode) and an electrical potential created allowing anodic dissolution of the interaction surface, Fig. 1. Removal is limited to the area under the jet due to the phenomenon of the hydraulic jump [35]. The electrolyte is expelled from the nozzle at a supercritical speed and on impinging the work surface it forms a thin film radially around the jet column creating a high resistance area [36]. The current density field is therefore concentrated directly beneath the nozzle in a Gaussian distribution and not in the thin film area surrounding [37]. Further precision is gained by the use of a co-axial air shroud further restricting the jet on impingement [38]. The Gaussian current density distribution can be demonstrated by the shape of the resultant removal profile and changes in the profile being due to the energy density seen by the interaction surface [39]. Surface texturing can enhance a range of engineering components through functionalisation of the surface altering wetting, tribological, or bio-compatibility characteristics [19,40–42] and EJM has previously been successfully used for research into non-deterministic micro texturing in complex alloys [43,44], meso scale superhydrophobic surfaces [45], enhanced cutting surface of saw wires [46] and influence of micro dimples on fatigue life of roller bearings [47].

This study investigates the applicability of EJM to surface texture a hyper-eutectic Al-Si alloy for lubricated reciprocating tribological testing. There is limited evidence of the effect of texturing a dual phase Al-Si alloy for enhanced tribological performance [48,49], with most studies focusing on ferrous alloys. This study explores the influence of a range of reciprocating sliding parameters on the friction and wear behaviour of Al-Si, utilising optical non-contact profilometery and scanning electron microscopy to determine the wear behaviour arising from a textured surface.

2. Experimental

2.1. Sample preparation

A hyper-eutectic A390 Al-Si alloy, nominal composition indicated in Table 1, was obtained from MS International GmbH, Germany, in the form of a cylinder liner blank. Rectangular samples 58 $\times$ 20 x 4mm were prepared using an electro-discharge machine (Sodick SLC600G), such that the long dimension was parallel with the cylindrical liner axis. Samples were then parallel flat lapped using a Kemet 15 lapping machine with 25μm diamond suspension. Surfaces for tribological testing were further polished using the same lapping procedure down to a 6μm diamond suspension finish. In order to expose the load bearing primary silicon colonies from the matrix, each sample was immersed in a 10% NaOH solution for 180 seconds before being cleaning in de-ionised water. Vickers micro-hardness tests were performed on both the etched A390 surface and the 52100 G5 roller bearing element used as the counter surface in tribological testing, using a Matsuzawa Seiki MHT 1 with an indentation load of 50 g applied for 15 seconds. Care was taken with the A390 alloy to indent separately on both the matrix phase and primary silicon phase. A minimum of six measurements were taken from each surface, with average and standard deviation values calculated.

2.2. Surface texturing

The process used to create the surface features in this study was carried out using a three axis (X, Y, Z) precision NC EJM platform [43] where tool paths and all control parameters are preprogrammed, Table 2. These remained constant across all samples.

Using a fixed current and floating voltage a 12 $\times$ 19 array of dimples (ø 420 μm x Depth 42 μm) were created using a bouncing type tool path, Fig. 2, taking $\approx$ 20 minutes per sample. The diameter of the features was the minimum obtainable using a nozzle diameter of 152 μm. Dimple depth was selected based on an ε-ratio (depth/diameter) of 0.1, which had been previously been reported in the literature to be the optimum ratio of low friction performance [12–14,28]. A dimple spacing distance of 5D was created, where D is the dimple diameter. Between each dwell point used to create the dimple, the end-effector arcs rapidly away from the surface to ensure dissolution only develops at the desired point. This occurs by rapidly increasing stand-off therefore the in-jet resistance, so no stray current is able to affect dissolution and maintains pattern precision. Repeatability of the array positioning relative to the workpiece was maintained throughout the generation of all samples by use of a touch sense datum system. This allows the start point (X,Y) and nozzle stand-off (Z) to be set relative to the workpiece surfaces using the nozzle for positional feedback [51].

2.3. Tribological testing

Textured samples we tested in a lubricated reciprocating

Table 1
Nominal weight percentage of an A390 alloy [50].

Si	Cu	Mg	Zn	Al
17.0	4.5	0.6	0.5	Bal.