The tribological performance of surface textured cylinder liner segments modified by Direct Laser Writing and Direct Laser Interference Patterning processes.

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Abstract

With the global call for the reduction of polluting emissions and the continual requirement for enhancing operating efficiency, the internal combustion engine (ICE) as the primary drive unit or in hybrid configurations for automotive, marine, power generation and light aerospace applications is undergoing comprehensive investigations to enhance the functional performance of its interacting components. Laser processing offers significant potential to realise the requirements by the modification of surfaces for lowing internal friction.

Direct Laser Writing (DLW) using ultrashort pulsed lasers and galvanometer scanning, has become an established process for surface texturing, allowing an extensive variety of feature geometries and texture designs to be produced. The minimum feature sizes that can be generated are however limited by factors such as the laser output power, beam diameter, beam wavelength and associated optics. To address the need to produce even smaller texture features, Direct Laser Interference Patterning (DLIP) has been developed, which utilises bespoke beam splitting and converging optics to produce periodic interference fringing and enabling surface textures in the micrometric size range to be produced.

In this study, the texturing of cast iron cylinder liner segments using DLW and DLIP processes is explored, to assess their tribological performance in high efficiency internal combustion engines, such as for hybrid applications. To facilitate the designs of textures and to capture high resolution data on surface interactions at specific points in the combustion cycle, the segmentation of cylinder lines and piston rings is undertaken. This requirement necessitated the development of bespoke fixtures to maintain conformal contact between the liner and piston ring segments. The results of tribology tests covering combinations of high and low speeds and contact pressures, have shown that the honing of cylinder liners could potentially be replaced with DLIP texturing, offering a more consistent alternative to the mechanical process.

Optimised texture designs using the DLW process achieved up to a 54% reduction in kinematic friction between the piston ring and textured cylinder liner surfaces, compared with mechanically honed cylinder liner segments. These results have indicated that DLW texturing offers the best improvement in friction performance in the boundary and mixed lubrication regimes at higher contact pressures, at both lower and higher sliding velocities. The results also provide useful comparative data on the performance of meso and micrometric scale textures and where they can be best applied.

Keywords: Friction, Wear, Laser, Texturing, Piston ring, Cylinder linear, Internal Combustion Engine, Direct Laser Writing, Direct Laser Interference Patterning

1. Introduction

The need for reduced emissions and improved efficiency of the Internal Combustion Engine (ICE) has been at the forefront of research in recent years, resulting from increasing global pressure over rising emissions [1]. The worldwide transport sector has continued to grow with 873 billion kilometres travelled in 2019, an increase of 11% over the previous decade, of which 84% is travelled by cars and light commercial vehicles [2]. Therefore, a large proportion of research has occurred to tackle the consequential losses within small to medium capacity ICEs and to improve efficiency, as frictional losses account for one third of fuel energy used, and 11.5% occurs within the ICE itself [3]. It has been shown that the piston compression ring is responsible for 2 - 5% of input fuel energy losses [4 - 5], which is significant for such a small component within the ICE. Some examples of methods examined to mitigate the unwanted losses are, but not limited to; low viscosity lubricant technologies, surface-active lubricant additives, thin surface coatings and surface texturing, which is the focus of this investigation.

The conditions within the combustion chamber of the ICE impart severe contact conditions onto the piston ring cylinder liner conjunction. The high temperature starved lubrication and transient lubricant entrainment throughout the stroke length results in mixed and boundary regimes of lubrication near stroke reversal and is hydrodynamic during mid stroke [6], [7]. This regime of lubrication, combined with the complex transient nature of the contact due to the contact kinematics, piston ring to cylinder liner conformity and ring dynamics results in harsh contact conditions [8]. The tribological behaviour of the piston ring is further influenced by the ring profile, width, material properties, ICE cycle and surface topography [9].

One of the key methods investigated for the palliation of friction between the piston-ring cylinder liner contacts is surface texturing. Surface texturing has the potential for improved tribological performance within the piston ring cylinder liner contact. Literature suggests a number of benefits of surface texturing such as an increase in load carrying capacity, wear resistance and improved frictional performance [10]. One key factor is that the application of the surface texture can generate either a beneficial or a detrimental effect on the frictional performance, depending on the regime of lubrication the contact is operating within[11]. This is due to the surface texture's effect on the lubricant film thickness within the contact. The micro-feature on the surface alters the effect on the contact depending on the regime of lubrication. Within hydrodynamic or full film elastohydrodynamic lubrication, it serves as a micro-hydrodynamic bearing [12 - 13]. Whereas, within mixed or starved lubrication conditions, the micro-features act as micro reservoirs, improving lubrication within the contact, thereby reducing friction [14 - 16]. Additionally, within boundary and mixed regimes of lubrication, where asperity interaction occurs, surface textures have been shown to trap wear debris in both lubricated and dry contacts. This aids in prolonging component life by reducing three-body abrasive wear within the contact [17 - 19].

The use of lower viscosity lubricants as a method for reducing friction within ICEs is now commonplace. However, due to the practical necessity of using the same lubricant throughout the ICE, the limiting factor in reducing the viscosity is the hydrodynamic load carrying capacity [6]. This is due to the fact that the load carrying capacity would be compromised at higher load intensity contacts. One of the noted benefits of surface texturing is the influence on the hydrodynamic load carrying capacity [20 - 23], resulting in a reduction in sliding friction due to an asymmetric pressure difference across the converging and diverging regions of the lubricant film [10], [24]. A surface texture's ability to generate additional load carrying capacity has been shown to be impacted by factors such as texture pitch, increase texture fraction area and texture shape [22], [25].

The use of surface grooves is a common surface texture used for lubrication and surface interaction control, such as plateau honing. This generates a bearing surface that is capable of sustaining the contact load while retaining lubricant within the crosshatch valleys and grooves [26]. Furthermore, this process of eliminating the asperity peaks to create the plateau, aids in reducing the wear and reduces time within the initial running-in phase, creating a more stable operating environment [27]. The honed surface texture is not restricted to rectilinear grooves as elliptic and circular texture honing patterns has shown promise to further reduce friction within the piston ring cylinder liner contact [28]. The advancement of manufacturing techniques such as Laser Surface Texturing (LST) led to investigations of manufactured surface shapes and combinations such as micro dimples, open and closed grooves and chevrons [10 - 11], [14 - 15], [29 - 31]. It is clear that from the literature, given a specific contact and the operating condition, the addition of LST micro-features can improve the frictional performance. However, due to the variety of system parameters which must be optimised, it makes it difficult to generalise a solution. Research has shown the relationship of parameters such as micro-feature depth, width, spacing and orientation have a significant impact on friction reduction as well as the importance of complete entrainment of the texture within the contact for optimal performance [11], [29], [32].

Although multiple surface texture types and conditions have been investigated for the piston ring cylinder liner contact and knowledge of the mechanisms is clearer, there is minimal literature that examines the performance of textures having a wide range of geometries over the different lubrication regimes. Given the significant influence friction within the combustion chamber of the ICE, which has a direct impact on the wear performance of the system, this study was undertaken to investigate the performance of a range of textures produced by Direct Laser Interference Patterning (DLIP) and Direct Laser Writing (DLW) processes, under representative contact conditions employing reciprocating tribometry.

2. Experimental setup

2.1 Cylinder liner and piston ring segmentation

In order to facilitate the laser texturing using the selected existing laser systems and their optical arrangements and also considering the tribological testing using a laboratory tribometer, the cylinder liners and piston rings were segmented for this study to provide a 20 mm contact length. To achieve geometrical conformance of the surfaces during laser texturing and critically for tribology testing, fixtures were designed, manufactured and pre-applied to the cylinder liners and piston rings prior to segmentation, as shown in Figure 1. Once the components were segmented, they were presented for laser texturing and subsequent testing.

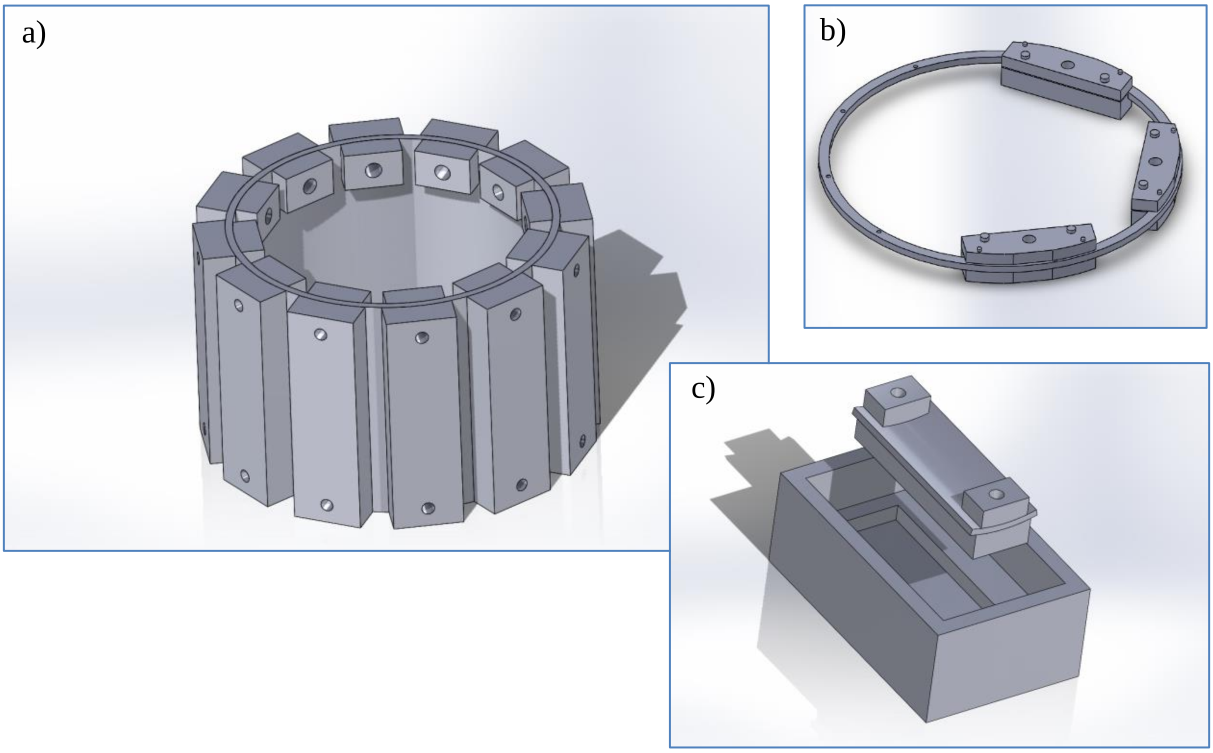


Figure 1: a) Cylinder and b) piston ring fixturing arrangements and c) segmented separation for laser texturing and lubricant tub tribology testing.

2.2 Laser processing

By employing both DLIP and DLW processes on independent laser systems, textures having a wide range of geometric sizes could be produced for this study. The DLIP arrangement (see Figure 2a) allowed textures to be designed and produced having similar geometries to those generated by the mechanical plateau honing process, while the versatility of the DLW process (see Figure 2b), enabled textures of larger geometries of sub-millimetric sizes to be designed, considering the contact conditions covered in this study.

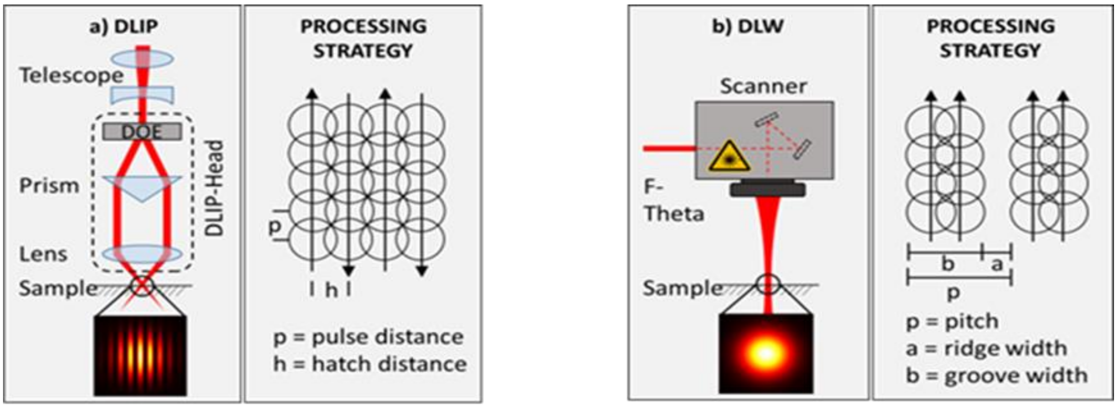


Figure 2: Optical arrangement for a) DLIP and b) DLW

2.2.1. DLIP texturing

The textures were produced using a pulsed Q-switched diode-pumped solid-state laser (pulse-duration = 12 ns, wavelength = 1064 nm, maximum average power = 180 W) using a pulse energy = 18 mJ at a repetition rate = 1 kHz. The optical path incorporates a DLIP module (Fraunhofer IWS, DLIP-µFab) which allows direct laser interference patterning by splitting the beam using a diffractive optical element, parallelisation of the beam using a biprism pair arrangement and convergence using an aspheric converging lens. A line-like interference pattern is created in the overlapping volume (interference volume) of the beams with a pattern period depending on the beam overlapping angle and the laser wavelength. The system was programmed to produce open groove textures, oriented transversally to the piston ring stroke direction on cast iron cylinder liners which had been segmented, employing the fixturing arrangement described above. The range of produced textures for the comparative study with the plateau honed liner surfaces are presented in Table 1. For the study, the textures were produced over the entire contact surface.

Table 1: DLIP texture geometries produced in cast iron cylinder liner segments.

Parameter	P_liner_04_09	P_liner_05_10	P_liner_06_08	P_liner_07	P_liner_02
Period (µm)	25.9	26.5	26	25.8	26.8
Pulses	20	100	50	200	100
Hatch distance (mm)	4.55	3.25	4.55	3.25	5.85
Mean structure height (µm)	3	10.1	4.4	16	9.8

All produced textures were measured using a Sensofar NeoX Profilometer to check the produced texture conformance and ensure no anomalies existed from for example, material recasting. The DLIP process has allowed textures to be produced which share close geometries and a pitch spacing of nominally 26 µm with the mechanically produced plateau honed groove texture in the reference samples. The DLIP produced texture P_liner_04_09 showed the closest geometry to the reference texture, having a nominal groove depth of 3 µm (see Figure 3), being the shallowest of the textures produced for this study. The laser process also enabled a range of grooves to be produced up to a maximum depth of 16 µm, as shown in Table 1.

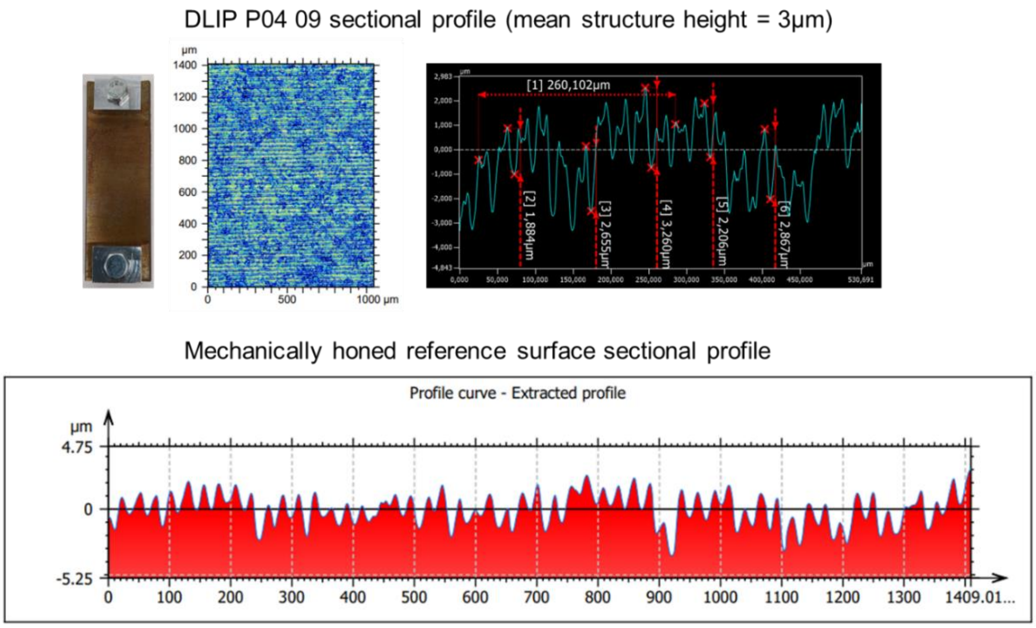


Figure 3: Sectional profiles of DLIP produced texture and the mechanically honed reference texture.

2.2.2. DLW texturing

The piston compression ring used for the investigations has been produced from 17% Cr steel with a contact diameter of 83 mm. The ring's contact profile is asymmetric, incorporating a 20 µm crowning bias to the bottom of the ring to encourage lubricant entrainment in the contact region during the upward strokes. A staggered rectangular groove texture design was selected to enhance lubricant entrainment and candidate textures were produced in a range of geometries (see Table 2) considering groove segment width and depth and plateau regions, defined by vertical and horizontal separation, as shown in Figure 4.

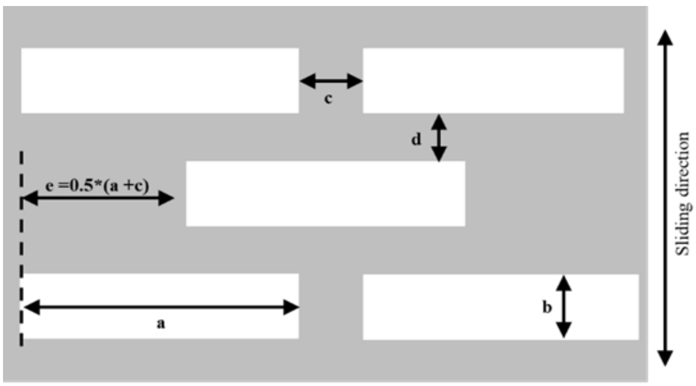


Figure 4: Staggered groove texture designs used in the study.

Table 2: DLW texture geometries produced in cast iron cylinder liner segments.

No.	Length, a (mm)	Width, b (µm)	Depth (µm)	Horizontal separation, c (µm)	Vertical separation, d (µm)	Transverse offset, e (µm)
1	1	100	10	100	500	550
2	1	100	20	100	500	550
3	1	100	10	100	1000	550
4	1	100	20	100	1000	550
5	1	300	30	300	500	650
6	1	300	60	300	500	650
7	1	300	30	300	1000	650
8	1	300	60	300	1000	650

The parallel segmented groove textures were produced in the pre-fixtured cast iron cylinder liner segments on a Georg Fischer Machining Solutions LP 400 U laser system incorporating a femtosecond pulsed source having a Gaussian energy distribution (beam diameter = 50 µm, pulse duration = 290 fs, wavelength = 1064 nm, maximum average power = 20 W). The textures were produced with a pulse energy of 40 mJ using a beam speed of 1000 mm.s^{-1} and a pulse frequency of 1250 kHz. A parallel linear scanning strategy was employed with a hatching distance of 10 µm and the texture depth was determined from a defined number of scan repetitions. Once produced, the textures were similarly evaluated using the Sensofar NeoX profilometer. Results showing the sectional profile of texture 2 is presented in Figure 5.

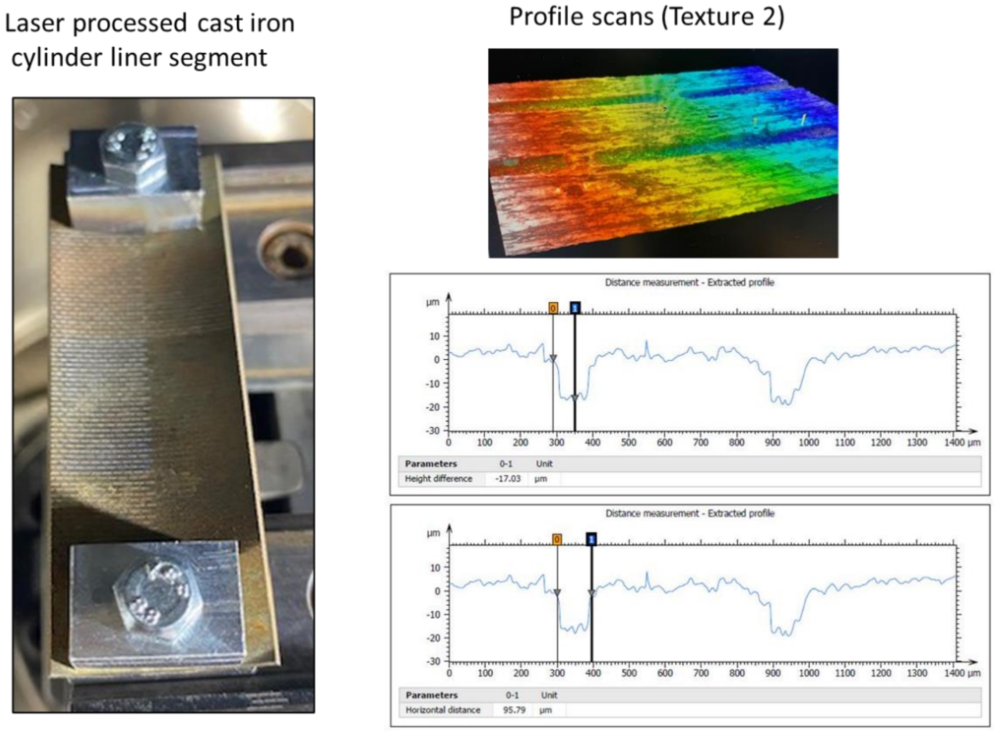


Figure 5: DLW textured cylinder liner segment and 3D and sectional profiles of Texture 2

2.3 Tribology tests

Tribometry experiments were carried out to replicate, as closely as possible, the contact conditions experienced by the interaction of the piston ring and cylinder liner, using a Bruker UMT Tribolab. The test arrangement was carefully configured to obtain conformal contact between the piston ring and cylinder liner segment. The cylinder liner segment was contained in a lubricant reservoir thereby applying flooded lubrication and mounted to the tribometer's reciprocating stage, as shown in Figure 6.

The tribometry experiments were conducted at two pressures and linear reciprocating speeds, selected to represent the near end of stroke and near mid stroke conditions in the combustion cycle. The test combinations for pressure and speed are presented in Table 3 as well as other key experimental parameters. The contact pressures were determined using Hertzian contact theory for an elastic line contact [33]. Therefore, to enable the required contact pressure, a sample contact length of 20 mm was selected, the maximum contact pressure p_0, is given by:

$$p_0 = \frac{4}{\pi} P_m = \left(\frac{\bar{P}\,R}{\pi E^*}\right)^{\frac{1}{2}} \quad (1)$$

where P_m is the mean contact pressure, $\bar{P}$ is the normal load per unit length, R is the radius of contact and E^* is the effective (reduced) Young's modulus of elasticity defined as:

$$\frac{1}{E^*} = \frac{1}{\left(\frac{E_1}{1-{\upsilon_1}^2}\right)} + \frac{1}{\left(\frac{E_2}{1-{\upsilon_2}^2}\right)} \quad (2)$$

where, $E_{1,2}$ and $\upsilon_{1,2}$ are their moduli of elasticity and Poisson's ratios respectively of the contacting tribopair. In this case, the steel properties were taken as 210 GPa and 0.27 and the Cast Iron properties as 140 GPa and 0.22 for the moduli of elasticity and Poisson's ratio respectively [34 – 37].

Table 3 – Tribometer experimental conditions

Test load, pressure and speed combinations		
Normal load (N)	Pressure (MPa)	Speed (mm.s^{-1})
2	20	10
14	45	10
2	20	100
14	45	100
Test parameters		
Test duration (mins)	15	
Test ambient temperature	20	
Stroke length (mm)	20	
Lubricant	SAE30 mineral engine oil	
Lubricant application	Flooded	

For each test, a run-in period of 5 minutes was applied using a 2 N load at 10 mm.s^{-1} to ensure a full and uniform conformal contact and stable conditions were achieved prior to initiating the friction test.

The applied load and resulting friction force signals were captured over the dynamic range of the tribometer's oscillation stroke (see Figure 6), and the kinematic Coefficient of Friction (CoF) extracted for the range of 1 mm on either side of the stoke centre for both the mechanically honed cylinder liner segment used as a reference, and subsequently for each of the textured segments evaluated.

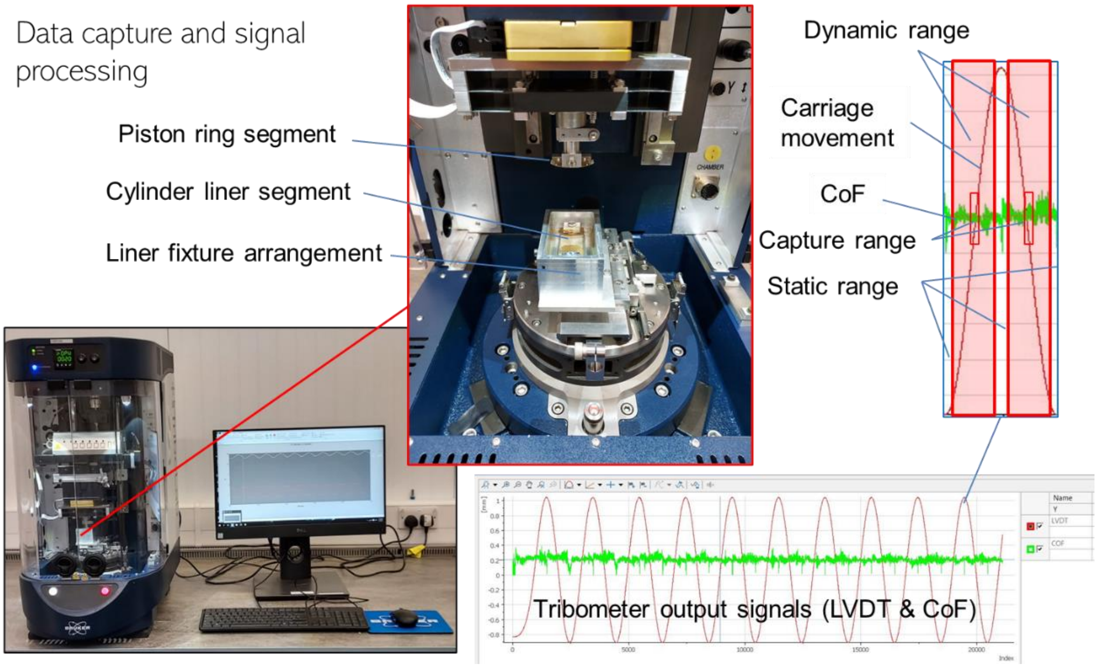


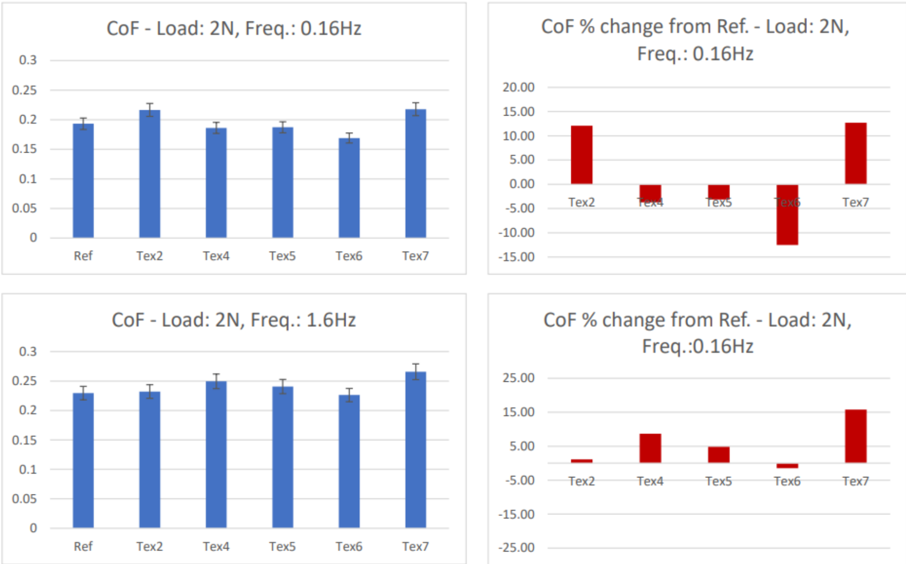
Figure 6: Tribology test arrangement for fixtured piston and cylinder liner segments and dynamic ranges for data capture.

3. Experimental results

3.1 DLIP produced texture performance.

The averaged kinematic CoF results determined from the 2 mm displacement range (1 mm on either side of the stoke centre) for the forward and reciprocating strokes of the piston ring and cylinder liner contact pairs for each DLIP produced texture and contact condition, is represented graphically in Figures 7a and 7b respectively. The percentage change of the averaged CoF for each textured surface, compared with the mechanically honed reference surface, is shown alongside.

a) Radial contact pressure: 20 MPa, Vmax: 10 and 100 mm.s^{-1}



b) Radial contact pressure: 45 Mpa, Vmax: 10 and 100 mm.s^{-1}

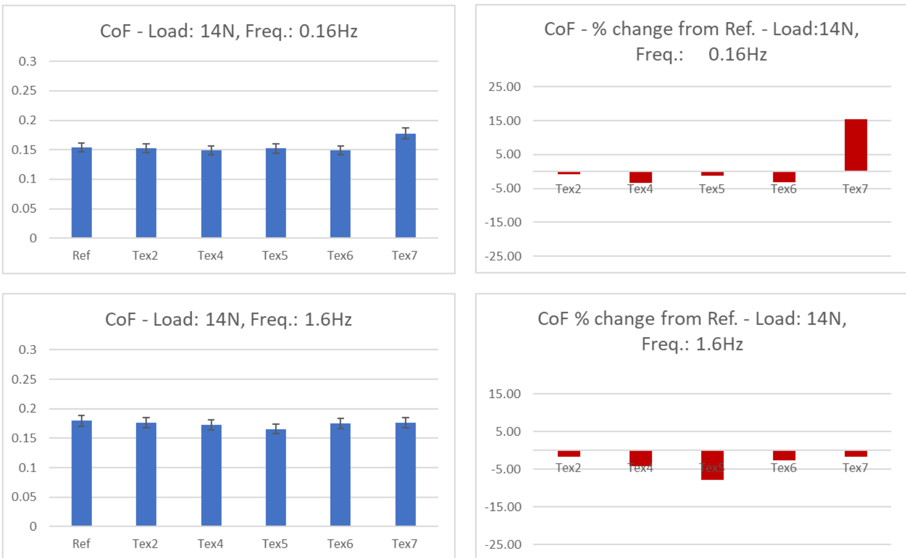


Figure 7: Kinematic CoF at a) low and b) high contact pressures and speeds for DLIP produced vs mechanically honed textures.

The comparative friction results between the DLIP produced textures shown in Figure 7a for the contact pressure of 20 MPa revealed no identifiable trends in the CoF values for the range of texture depths for both speed and contact pressure parameters selected. At 100 mm.s^{-1}, the elevated CoF values were produced by the DLIP textures over the honed texture.

At 45Mpa contact pressure and at 10 mm.s^{-1}, the differences between the CoF values produced by the DLIP produced and mechanically honed textures were generally reduced, apart from texture 7, as can be seen in Figure 7b. At 100 mm.s^{-1}, the CoF values produced by the DLIP textures were generally lower than for the mechanically honed texture, and the textures having depths in the vicinity of 10 µm, or less, performed better. Texture 5 produced the best result, achieving a 9% reduction in CoF under these conditions.

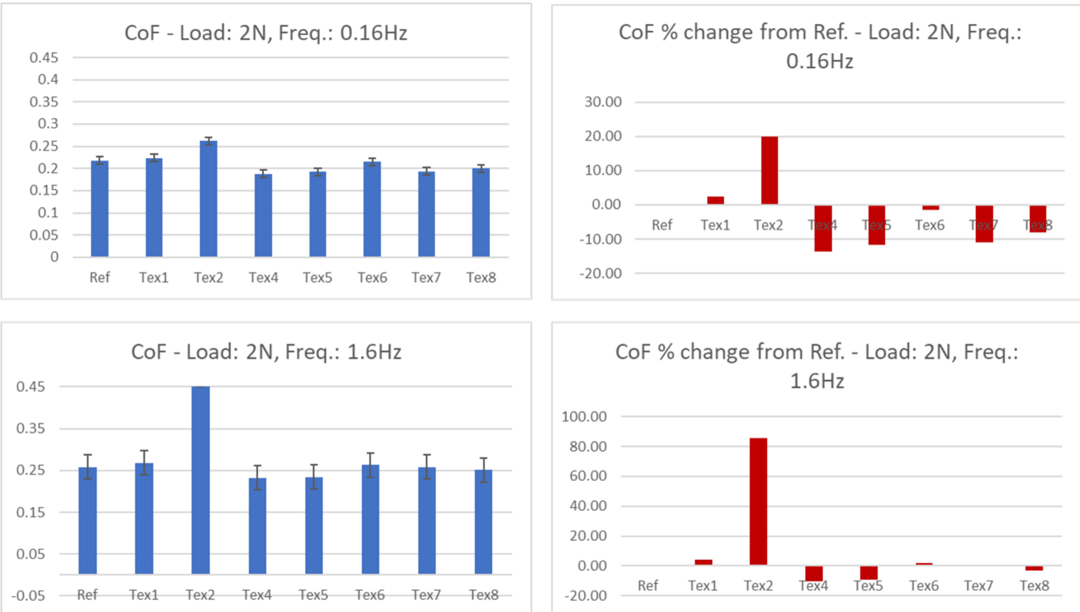
3.2 DLW produced texture performance.

The tribology results for the eight DLW produced textures (see Table 2) are presented in Figure 8. The average CoF values were obtained as discussed previously in the displacement range of 1 mm on either side of the stoke mid position. The percentage increase of the average CoF for each textured surface compared with the mechanically honed reference surface is similarly presented.

The frictional performance of the range of DLW produced staggered grove textures applied to the surfaces mechanically honed cylinder liner segments were captured for the lower and higher contact pressure and speed conditions. While no trend in friction performance in relation to the texture geometry could be readily established, improved CoF values were generally evident compared with that for the mechanically honed surface for textures 4, 5, 6, 7 and 8 at 20 MPa contact pressure at 10 mm.s^{-1} (texture 2 results appeared anomalous and the data from texture 3 was not usable so these will be ignored from this comparison). At 100 mm.s^{-1} under these contact conditions, the above DLIP textures and mechanically honed texture could be considered to have similar frictional performance.

At the 45 MPa contact pressure, significantly reduced CoF values were produced by all the considered textures at both speed conditions tested, compared with those produced by the mechanically honed cylinder segment. The best frictional performance was achieved at 100 mm.s^{-1}, where all considered textures achieved over 50% reduction in CoF over the mechanically honed cylinder liner segment.

a) Radial contact pressure: 20 MPa, Vmax: 10 and 100 mm.s^{-1}



c) Radial contact pressure: 45 MPa, Vmax: 10 and 100 $mm.s^{-1}$

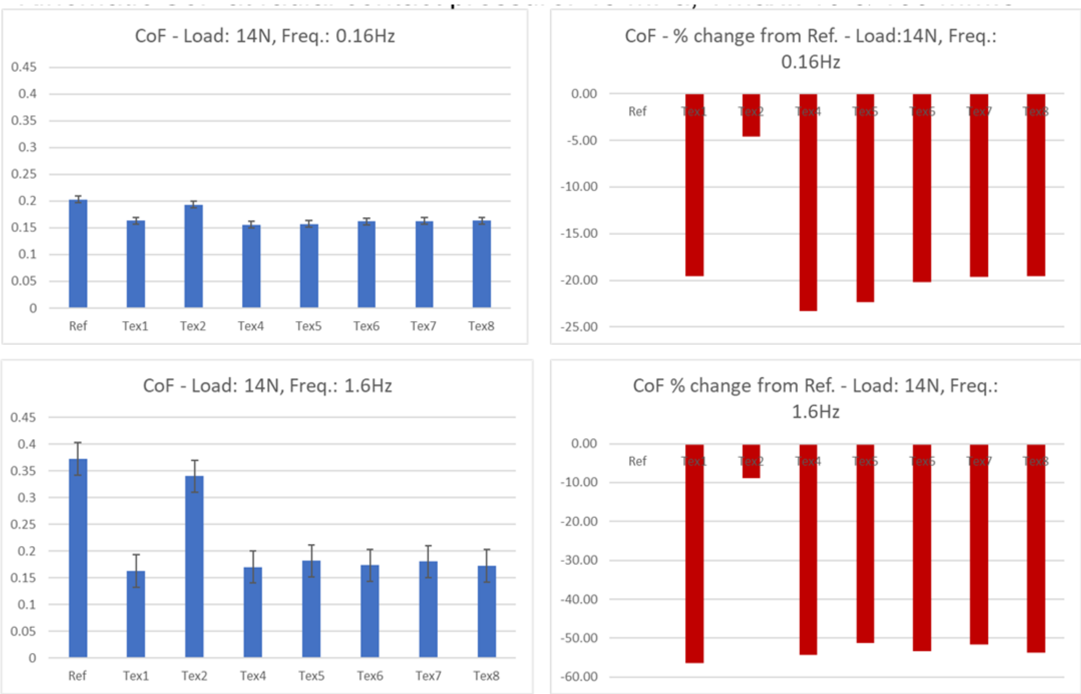


Figure 8: Kinematic CoF at a) low and b) high contact pressures and speeds for DLW produced vs mechanically honed textures.

4. Discussion on results

The tribometer experiments were designed particularly to capture the frictional performance of DLIP and DLW produced textures on ICE cylinder liner segments and compare them with the results produced by a mechanical plateau honing process. The parameters of contact pressure and surface speed utilised in the tribology test were derived from data from a candidate ICE to emulate 4 conditions in the combustion cycle as the piston ring approaches stroke reversal and in the vicinity of the centre of its stroke where surface speed is the highest. The tribology tests were designed to be comparative to enable an evaluation of the laser applied texture performance to that of mechanical plateau honing.

Considering the frictional performance of the DLIP textures under 45 MPa contact pressure at 10 $mm.s^{-1}$, where boundary lubrication could be experienced, DLIP texturing provided a small improvement in frictional performance over mechanical honing. By the reduction of contact pressure or increasing contact speed from the above, it follows that mixed lubrication could be experienced with the 20 MPa, 10 $mm.s^{-1}$ or 45 MPa, 100 $mm.s^{-1}$ parameter combinations. Under these conditions, a small improvement in frictional performance can again be observed from the majority of textures in the study, the latter parameter combination producing better frictional results. Under the combination of 20 MPa contact pressure at 100 $mm.s^{-1}$, where hydrodynamic lubrication could be expected, the DLIP produced textures showed elevated CoF values over mechanical honing, which could be indicative of increased hydrodynamic drag as a result of increased oil film thickness.

Under these described boundary and mixed lubrication conditions, the small improvement in the frictional performance of the DLIP textures of up to 9% over the mechanically honed reference surface, having similar interspatial geometries is likely to be due to the improved topographical consistency of the laser produced textures, thereby enhancing the hydrodynamic effect produced by the combination of texture grooves and plateaus, as described earlier. A relationship between the texture pitch and optimal depth may indicate that for a nominal 26 micrometre texture pitch, a depth limit of 10 micrometres should not be exceeded to achieve optimal CoF for the test conditions considered.

The results have indicated that DLIP texturing has the potential to replace mechanical honing for cylinder liner applications, and with the emerging capability of internally applied DLIP texturing, the texturing of full cylinder liners is now becoming a possibility. While this texturing process is likely to be slower than the honing process, it offers the potential to produce a wide range of textures that can be readily optimised for the intended application.

In the case of the DLW produced textures, similar conditions would apply regarding the test parameter combinations and the associated lubrication regimes. It follows that at 45 MPa contact pressure at 10 $mm.s^{-1}$ contact speed, where boundary lubrication would be experienced, all considered textures produced over 18% reduction in CoF compared with the mechanically honed reference surface. In the anticipated mixed lubrication regime for this contact pressure, at 100 $mm.s^{-1}$, the benefits of the DLW produced textures become more pronounced, producing up to 56% reduction in CoF compared with the mechanically honed reference cylinder liner. Very little difference could be detected in frictional performance between the DLW textures and mechanically honed texture in the hydrodynamic lubrication regime, expected to be produced by the lower contact pressure and higher surface speed combination.

5. Conclusion

The DLIP process, through its capability to produce texture periods in the micrometric scale and the optical configuration used, has enabled textures to be produced with periods similar to those found on the selected mechanically honed surfaces. The results have indicated that DLIP texturing has the potential to replace mechanical honing for cylinder liner applications, and with the emerging capability of internal DLIP texturing, the DLIP texturing of full cylinder liners is now becoming possible. While this texturing process is likely to be slower than the honing process, it offers the potential to produce a wide range of textures that can be readily optimised for the intended application.

The DLW process, which can produce significantly larger texture geometries, has enabled textures to be designed and produced with substantially higher lubricant carrying capacities. The increased fluid volume in the entrainment area between the piston ring and cylinder liner, coupled with the resulting increase in hydrodynamic pressure from the enlarged feature sectional areas and their adjacent plateaus, would contribute significantly to an increase in oil film thickness, and maintain hydrodynamic lubrication and surface separation even at the high contact pressures typically experienced in ICEs. The reductions in friction produced by the DLW generated textures in the tribology tests, suggest that meaningful performance improvements can be achieved in ICEs, particularly where piston ring to cylinder liner contact pressures is the highest. The reduced friction under harsher conditions experienced in an ICE is also likely to extend engine life through increased hydrodynamic lubrication and most importantly reduce engine heat and associated harmful emissions.

Acknowledgements

The author gratefully acknowledges the financial contribution from the European Union's Horizon 2020 Framework Programme for research and innovation for funding the Prometheus project under Grant Agreement No. 825503. The Authors would also like to thank Dr E. Humphrey for his contirbutoin to the literature review.

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