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A comparison of the tactile friction and cutting performance of textured scalpel blades modified by Direct Laser Writing and Direct Laser Interference Patterning processes

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Abstract

Moving surface interactions between rigid and compliant materials have a wide range of functional applications in the automotive, aerospace and medical industries. This study investigates the cutting and frictional performance of textured stainless steel scalpel blades using polyurethane as the counterpart material. Groove textures of controlled geometries, oriented parallel and tangential to the primary cutting edge were produced using DLW and DLIP processes. Empirical investigations were conducted to study the influences of groove width, depth, separation distance and orientation on the performance of the textured blades under dry conditions.

The results reveal that for both the DLW and DLIP generated textures, groove width and orientation have the largest influences on blade performance. The investigated textures showed significant improvements in friction and cutting forces compared to untextured blades, producing reductions of up to 17.0% and 5.8% for the DLW and 33.2% and 24.1% for the DLIP in the parallel orientation respectively.

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1. Introduction

The combinations of rigid and compliant materials can be found in a vast range of devices and applications that we are exposed to on a daily basis, including water taps, hinges, scissors, shears, shaving blades, knives, scalpels, stents, sewing and hypodermic needles and many others requiring controlled friction interactions between such materials. The mechanisms of friction such as those found between polymers or rubber against a rigid surface is governed by two main interactions of the compliant member, adhesion and hysteric deformation, caused by contact with asperities on a surface of the rigid component [1], [2]. In the case of polymers, the

interaction mechanisms of friction can however be more complex, particularly in the case of sliding movement. The adhesion component as a result of an applied load can result in significant hysteric deformation of the polymer of a low elastic modulus, forming Van Der Waals attractive forces between the surfaces. This mechanism can be enhanced through large areas of contact as the elastically soft solid deforms to the surface of the hard component [3]. Furthermore, a contact of this nature, which is under relative sliding motion, can have dynamic elastic instabilities due to opposing forces on the contact area. The hysteric (deformation) component manifests in oscillation forces leading to energy dissipation as internal friction within the polymer [3]. Furthermore, due to the elastic

nature of contact, the polymer experiences compression forces at the front of the contact and tension at the rear. The compressive forces lead to buckling of the comparatively softer counterpart, producing a detachment wave along the contact, as reported by Schallamach [3], [8].

Another prominent mechanism within this contact type is stick-slip which relates to a thermally activated molecular attachment of the polymer segment to a rigid counterpart. The relative motion of the two surfaces initially elongates the segment followed by a rapid breaking of the bond with the rigid counterpart, leading to an acceleration and subsequent deceleration, as the elastic material returns to its preferred energy state [9], [10]. Such mechanisms are highly dependent on the surface topography as these influence the adhesion forces of the interacting surfaces [3]. This presents an opportunity to engineer the contact surfaces of rigid counterparts to influence such mechanisms and enhance the contact responses of the interacting compliant components.

Surface functionalisation through laser surface texturing is employed across a wide range of applications, particularly for the enhancement of the contact characteristics between rigid materials [4–7]. In such cases, benefits are often derived from the incorporation of micro reservoirs, and with the presence of a fluid, results in an increase in hydrodynamic lift, which reduces friction and wear within the contact. While studies have been undertaken on the texturing of scalpel blades [11], [12], little has been revealed on the actual mechanisms of surface friction between rigid and compliant counterparts as a result of surface texturing.

This study was undertaken to explore the influences of a range of grooved surface textures of different geometries and orientations on the frictional performance for this contact type and evaluate the performance of textured scalpel blades in the cutting of polyurethane.

2. Laser processing

To allow the production of a wide range of texture geometries, both Direct Laser Writing (DLW) and Direct Laser Interference Patterning (DLIP) processes were employed on independent laser systems as shown in Fig.1.

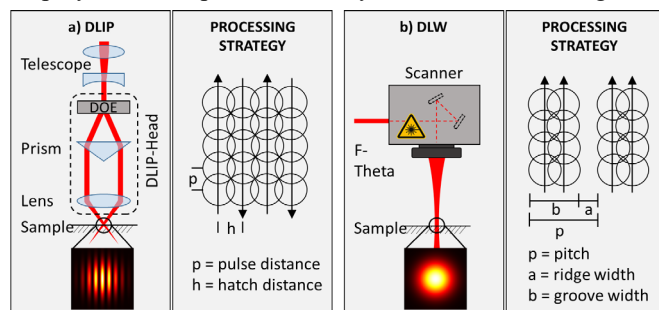


Fig. 1. Schematic diagram of a) DLIP and b) DLW arrangements and processing strategies

2.1. DLW texturing

Parallel groove texturing using the DLW process was carried out on a Georg Fischer Machining Solutions LP 400 U laser system incorporating a femtosecond pulsed source of near IR wavelength of Gaussian energy distribution from

Amplitude (pulse duration = 290 fs, max. pulse energy = 40 μ J, beam diameter = 50 μ m, beam quality = 1.2). Textures were designed having controlled ranges of width, pitch and depth as shown in Table 1a. These were produced on polished 316 stainless steel plates and on one side of commercially available scalpel blades, parallel and perpendicular to the primary cutting edge. Parallel scan paths were used with the following pre-optimized laser parameters; average power = 20 W, pulse frequency = 50 kHz, beam speed = 1500 mm.s⁻¹, hatch separation = 5 μ m. Groove depths of 5, 10, 15 and 20 μ m were produced using scan repetitions of 40, 80, 120 and 160 respectively.

2.2. DLIP texturing

The experiments were conducted using a TECH-1053 pulsed Q-switched diode-pumped solid-state near IR laser by Laser Export (pulse-duration = 12 ns, max. pulse energy = 290 μ J at a pulse repetition rate = 1 kHz). The optical path incorporates a DLIP module (Fraunhofer IWS, DLIP- μ Fab) which (1) is direct laser interference patterning by splitting the beam using a diffractive optical element, parallelisation of the beam using a biprism 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 overlapping angle, the laser wavelength and the angle between the beams. Groove textures were produced on polished 316 stainless steel plate and on scalpel blades, as presented in Table 1b.

Table 1. Parallel (Pa) and perpendicular (Pe) oriented textures produced by a) DLW and b) DLIP processes (All dimensions in μ m)

Texture	Groove Width	Ridge Width	Groove Pitch	Groove Depth
A - Pa & Pe	50	50	100	20
B - Pa & Pe	50	100	150	20
C - Pa & Pe	50	150	200	20
D - Pa & Pe	50	200	220	20
E - Pa & Pe	100	50	150	20
F - Pa & Pe	150	50	200	20
G - Pa & Pe	200	50	250	20
H - Pa & Pe	50	50	100	5
I - Pa & Pe	50	50	100	10
J - Pa & Pe	50	50	100	15
K - Pa & Pe	250	50	300	20
L - Pa & Pe	300	50	350	20
M - Pa & Pe	400	50	450	20
N - Pa & Pe	500	50	550	20

Texture	Groove Pitch
P4 Pa & Pe	4
P6 Pa & Pe	6
P8 Pa & Pe	8

Key: a=ridge width, b=groove width, p=pitch, h=height

3. Texture evaluations

3.1. Tribology tests

Laboratory friction measurements were undertaken on the laser textured stainless steel plates and on unprocessed polished plates of the same material to provide a comparative reference. The tests were carried out on a Bruker UMT TRIBOLAB, set up to allow continuous conformal oscillatory contact between the sample plates and a polyurethane counterpart as shown in Fig.2. The oscillation length was selected to accommodate transient deflections of the polyurethane at each end of the stroke, while providing a significant proportion of the stroke for sliding contact without the influences of the counterpart deflection. The contact load was set to emulate light finger touch. The parameters used for the tests are presented in Table 2.

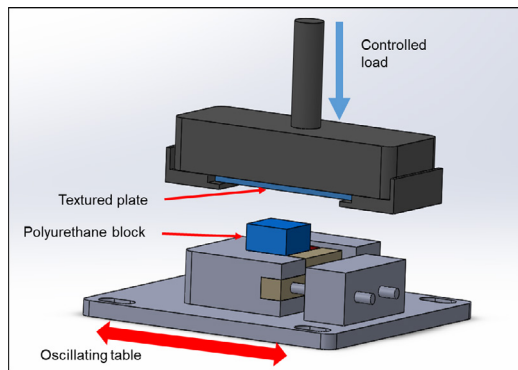


Fig. 2 Tribology test arrangement

Table 2. Tribology test parameters for friction measurements of the DLW, DLIP and reference samples against a 10 mm² polyurethane block.

Load	1 N
Maximum speed range	0.8-65 mm.s ⁻¹
Stroke	15 mm
Test duration	3 minutes
Sliding orientation	Parallel and perpendicular
Test material	Natural polyurethane – Shore A40

3.2. Cutting tests

Using a bespoke test rig and data capture arrangement, cutting tests were carried out on textured scalpel blades and on untextured reference blades under controlled conditions. The capture of the normal (F_z) and tangential (F_x) force components were made in the region of cutting stroke where forces were stable. Cutting tests for each texture were repeated three times and the results averaged. The test setup is shown in Fig.3. and Table 3 provides the parameters used for the tests. The DLW and DLIP produced textures were evaluated under dry conditions for full length cuts in individual polyurethane blocks, (LxWxH) of 150mm x 150mm x 50mm.

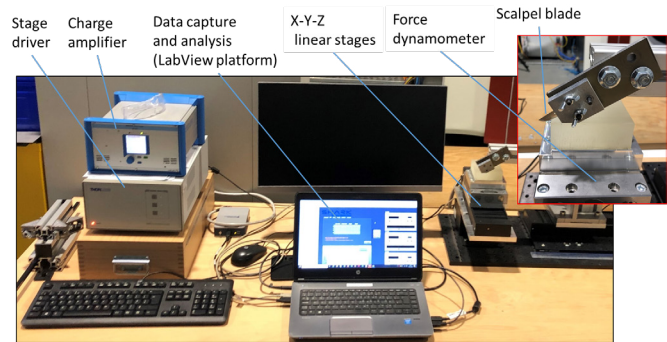


Fig. 3. Scalpel blade cutting test rig

Table 3. Scalpel blade cutting test parameters

Cut length	150 mm
Blade inclination	30°
Cutting speed	4 mm.s ⁻¹
Cutting depth	6 mm
Cut spacing (y-axis)	2 mm
Test material	Natural polyurethane – Shore A40

4. Results and discussion

4.1. Tribology tests

The average coefficient of friction (CoF) for each of the DLW and DLIP produced textures were computed from their respective captured forces over a 6 mm range (3 mm either side of the stroke centre) and compared with those produced by the polished untextured plates. The comparisons of the CoF values and the percentage change of friction forces from the untextured benchmark are given in Fig. 4a and Fig. 4b for the DLW and DLIP produced textures respectively.

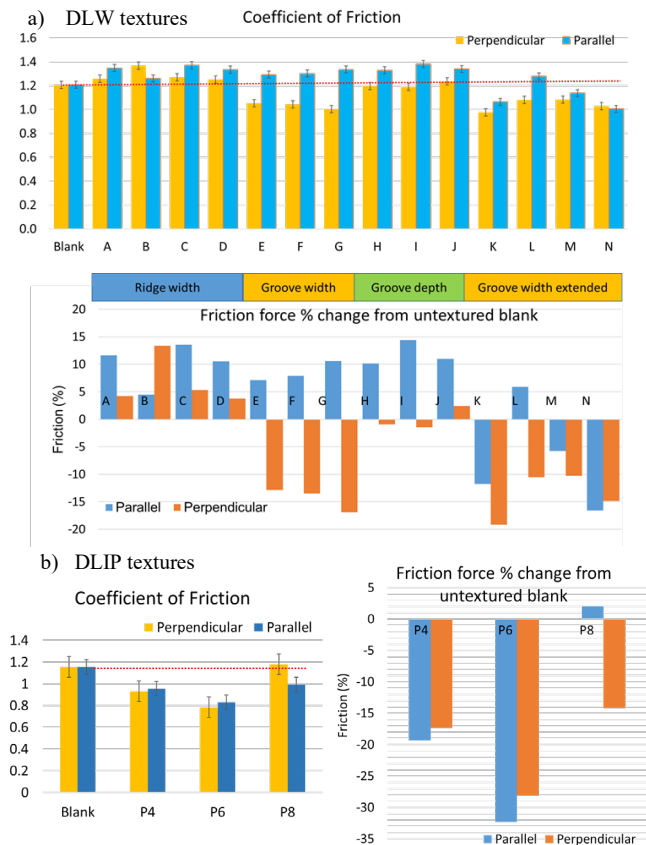


Fig. 4. Coefficients of friction and friction force % change from untextured reference plates for a) DLW and b) DLIP produced textures

Fig. 4a shows the CoF values and the percentage change of friction forces for the DLW textured plates in contact with the polyurethane counterpart material, for both parallel (Pa) and perpendicular (Pe) orientations to the sliding direction. The graphs indicate that groove widths, between 100 and 500 μm , have the greatest influence on friction reduction for textures orientated perpendicular to the sliding direction. However, the wider textures K, M and N performed well in both orientations; texture N Pa and Pe producing the most consistent friction reductions of 17% and 15% respectively. The groove depths and ridge widths tested had little impact on friction reduction in the perpendicular orientation and exhibited a detrimental effect on friction in the parallel orientation.

The graphs for the DLIP textures in Fig. 4b, indicate that the P4 and P6 textures produced significantly lower CoF values than the untextured reference, for both the parallel and perpendicular orientations to the sliding direction. These textures significantly outperformed the DLW produced textures, P6, producing the lowest friction of 32.3% and 28.2% in the parallel and perpendicular orientations respectively.

4.2. Cutting tests

While no overall correlation could be established between the texture friction responses and the blade cutting forces for all geometries tested, the reduced friction measured for the range of DLW produced grooves of increasing widths showed good agreement with the reductions in cutting forces for these

textures (results not shown). This agreement was also the case for the DLIP produced texture P4 but not for P6.

For a comparison of blade performance, the DLW produced texture N having the lowest friction response in the parallel orientation (Fig. 4a) and the DLIP texture P4 with the same texture orientation (Fig. 4b) were selected. The results of the percentage change in cutting forces against an untextured reference blade are shown in Fig. 5.

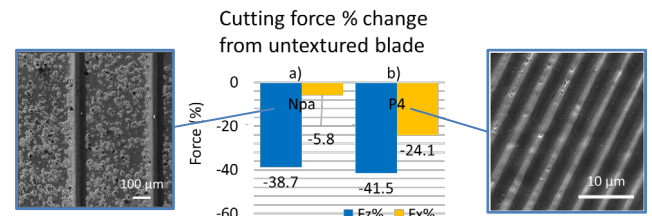


Fig. 5. Normal (Fz) and tangential (Fx) Cutting force % change from untextured reference plates for a) DLW and b) DLIP produced textures

The comparison reveals the DLIP processed P4 blade produced a greater percentage reduction in cutting forces compared with the DLW processed NPa textured blade. Both textures performed significantly better than the untextured reference, exhibiting the following percentage reductions: NPa: Fz = -38.7%, Fx = -5.8%, P4: Fz = -41.5%, Fx = -24.1%.

Images were taken of the cutting action of the scalpel blades and responses of the polyurethane blocks during cutting. Fig. 6a shows the cutting action of an untextured blade and Fig. 6b of the DLIP textured P4 blade.

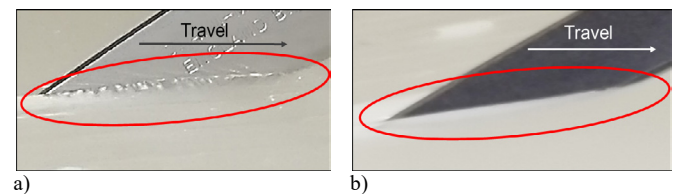


Fig. 6. Response of the polyurethane test material to cutting with a) an untextured scalpel blade and b) with the P4 textured blade

The images show the improvement in cutting action which was captured for both the NPa and P4 textures. The untextured contact depicts a pronounced stick-slip and buckling behaviour [17], [19] which has been eliminated by the modified contact resulting from laser texturing. This is likely to be due to a reduction in adhesion and the resulting elongation, acceleration and deceleration cycle in the polyurethane material in the region of contact. The rippling was found to be progressively less pronounced with increasing groove widths (Groove width extended, Fig. 4a), explaining their improved performance.

5. Conclusion

This study has demonstrated that laser texturing of parallel groove structures using either DLW or DLIP processes can significantly reduce surface friction of 316 stainless steel against compliant polyurethane at low sliding velocities in dry contact conditions. DLIP processing has produced the best performing textures in this study for the reduction of both friction and the resulting cutting forces. The DLIP processed

textures were also the least sensitive of texture orientation to sliding contact.

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