THE EFFECT OF ENGINEERED SURFACE ON THE WEAR PROCESSES AND FRICTION DURING RING COMPRESSION TEST[1]

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Abstract

This work aims to study the effect of engineered surfaces on wear and friction of AISI H13 steel tools under tribological condition similar to a mechanical working process. Ring tests were performed under controlled conditions. Results allowed to state that wear mechanism is as follow: (*i*) formation of junction points, (*ii*) plastic deformation and (*iii*) rupture of junction points (material transference from the ring to the tool). Wear intensity is lowered when engineered surfaces are applied given that grooves play the role of mechanical interlock to sliding. On the other hand, engineered surface promote increased friction coefficient.

Key words: Tribology; Engineered surface; Sliding wear; Adhesion; Friction coefficient; Metal forming.

EFEITO DE SUPERFÍCIES ENGENHEIRADAS NO DESGASTE E ATRITO DURANTE ENSAIO DE COMPRESSÃO DO ANEL

Resumo

O presente trabalho teve como objetivo estudar o efeito da topografia no desgaste e atrito de ferramentas de aço AISI H13, submetidas a condições tribológicas semelhantes à de um processo de conformação mecânica e foi conduzido em condições laboratoriais por meio do ensaio de compressão do anel. Os resultados permitiram concluir que o mecanismo de desgaste é formação de junção, deformação plástica do ponto de junção resultando na transferência de material do anel (contra-corpo) para a ferramenta (corpo) e a intensidade do desgaste é reduzida devido às características topográficas que atuam como obstáculos dificultando o deslizamento entre as superfícies de contato ferramenta/anel. Por outro lado, esta redução no deslizamento imposto pelas características topográficas resultou num aumento do coeficiente de atrito.

Palavras-chave: Tribologia; Superfície engenheirada; Desgaste por deslizamento; Adesão; Coeficiente de atrito; Conformação mecânica.

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1 BACKGROUND

Engineered surfaces are those with topographic features which enable them to perform special functions in their application. According to Costa and Hutchings(1), many applications can be proposed for artificial texturing of surfaces. They include tribological performance improvement, friction increase, sticking reduction, mechanical interlocking, adhesion increase, sealing ability increase, wettability control, mechanical resistance increase, promotion of tissue ingrowth in biomedical prostheses, aero- and hydrodynamic effects, aesthetic effects, and heat transfer enhancement. These special functions have motivated work on engineered surface aiming mechanical components enhancement.(1-4)

When cold forging is to be considered, there are some serious damages which results on macroscopic alteration and raising formation on the tool surface from plastic deformation and material transference. It is the so called galling.(5-7)

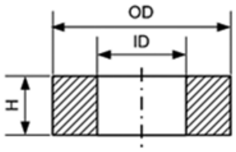
Kerridge and Lancaster(8) and Rigney, Chen and Naylor(9) discussed the role played by contact area on this wearing process. Relationship of the topographic effect of the tool with sliding wearing shall be done considering the important contribution about material transference on wearing by sliding made by the authors above.

Friction, faced on this work as resistance to movement, is generally related to wearing due to, usually, also be a consequence of the very same mechanisms. Measurements of topography effect on friction were made by ring compressing test.

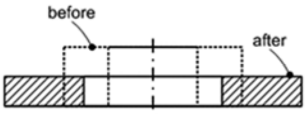
The ring compressing test comprises on compacting a test piece on a ring shape against plane faces tools. The friction coefficient (μ) or interfacial friction coefficient (m) is a function of the change of the ring inner diameter for a given deformation on its thickness. When μ is very low the ring deforms like a disc and each point on its bulk flows on the radial direction towards the outer radius (Figure 1b). When, on the other hand, μ exceeds a given critical value, there is a condition for which it becomes energetically favorable for part of the ring to flow on the radial direction towards the inner radius, while other part flows to the opposite direction (Figure 1c). (10-14)

Male and Cockcroft(15) were the first to show values of μ obtained from ring compression test. These authors established two limit conditions for friction coefficient value: one is the condition where the ring behaves like a disc and the friction coefficient is so said to be equal zero (this condition is experimentally obtained with wax rings at temperatures close to melting point, what results on excellent lubrication condition); the other is the condition where it is assumed total adherence between all contact points (this condition is experimentally obtained with aluminum rings deformed at 600ºC). Friction coefficient on the second condition must be superior or equal to 0.57, accordingly to the flow criteria adopted.

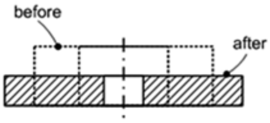
For Male and Cockcroft(15) intermediate values between 0 and 0.57 were identified due to the presence of abrasion marks, similar to the marks resultant from cold rolling tests with aluminum sheet made by Capus and Cockcroft.(16) Figure 2 shows the calibration curves for a ring with ratio of outer diameter (OD), inner diameter (ID) and height (H) of 6:3:2, respectively.



a) undeformed



b) low μ



c) high μ

Figure 1. Schematic representation of the ring deformed under different frictional conditions.

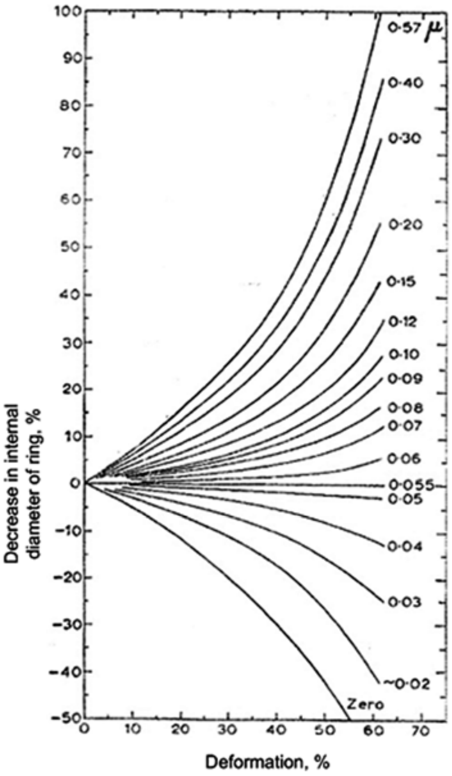


Figure 2. Calibration curves for the decrease in internal diameter of a standard ring (6:3:2) with amount of deformation, for different values of the acting coefficient of friction.(15)

On this scenario, this work intends to study the effect of topographic features on sliding and friction, aiming the application for cold forge tooling.

2 EXPERIMENTAL PROCEDURE

Wear and friction were evaluated by the ring test (in accordance to the method used by Leite(17)). Figure 3 shows a schematic representation of the ring test. An AISI 1020 steel rings were pressed against flat AISI H13 steel tools, with polished or engineered surface. Friction coefficients were estimated by ring inner diameter change for a given deformation in height.

It was used a hydraulic press (1470 kN) and grinded rings (# 220), under room temperature and room humidity. Tool velocities ranged from 0.06 to 3 mm/s and height reduction were between 20% and 55%.

Friction coefficients evaluation were made by Male and Cockcroft(15) method (ring's inner diameter and height measured after deformation). Wear were qualitative evaluated by naked eye examination and, whenever possible, by weight loss determination.

Wear mechanisms were evaluated by characterization of tool-ring contact surfaces in a determined area, as shown on figure 3. Profilometry, microscopy (optical and electronic) and energy dispersive spectrometry (EDS) techniques were used.

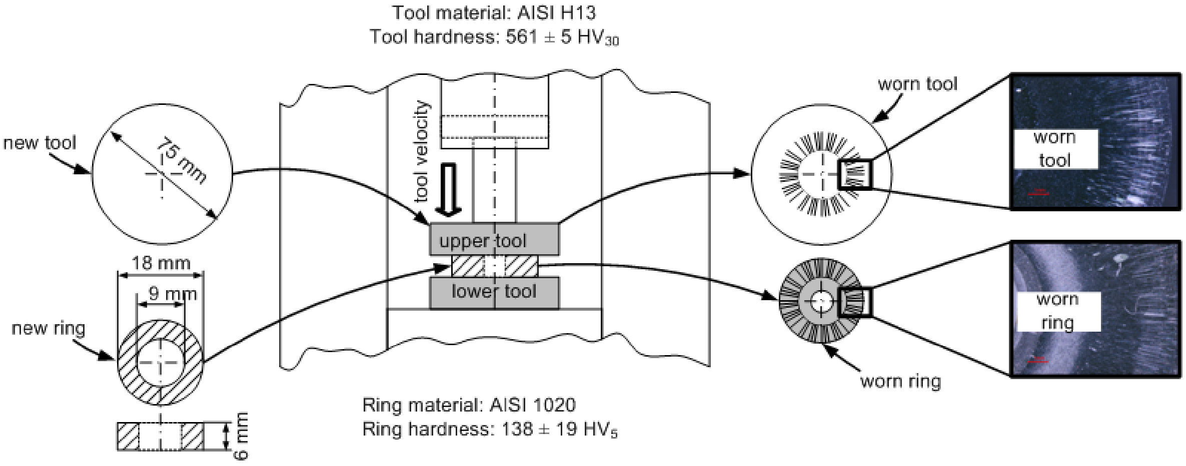


Figure 3. Schematic representation of ring test for evaluation of wear and friction coefficient between AISI 1020 rings and AISI H13 tools.

Five sets of experiments were performed (each test condition was repeated three times):

a) Set 1 – wear and friction mechanisms (Figure 4a): Polished tool (0.01 μm Ra); effects of tool velocity and height reduction were analyzed. Flat surfaces of rings were marked before deformation and the movement of these marks was measured in order to establish material flow during plastic deformation.

b) Set 2 – effect of grooves orientation (Figures 4b and 4c): Engineered surface tool (laser techniques) and polished plateaus; radial grooves (on ring material flow direction) and circumferential grooves (orthogonal to ring material flow direction).

c) Set 3 – effect of grooves depth (Figures 4e and 4f): Engineered surface tool, with different depths of circumferential turned grooves and polished plateaus. Flat surfaces of rings were marked before deformation and the movement of these marks was measured in order to establish material flow during plastic deformation.

d) Set 4 – effect of grooves spacing (Figures 4d and 4e): Engineered surface tool, with different spacing of circumferential turned grooves and polished plateaus.
e) Set 5 – effect of lubrication on friction for two selected topography (Figures 4a and 4f): Engineered (circumferential turned grooves) and polished surface tools; lubricant polytetrafluoroethylene. Flat surfaces of rings were marked before deformation and the movement of these marks was measured in order to establish material flow during plastic deformation.
Figure 4 shows topographic conditions of the tests.

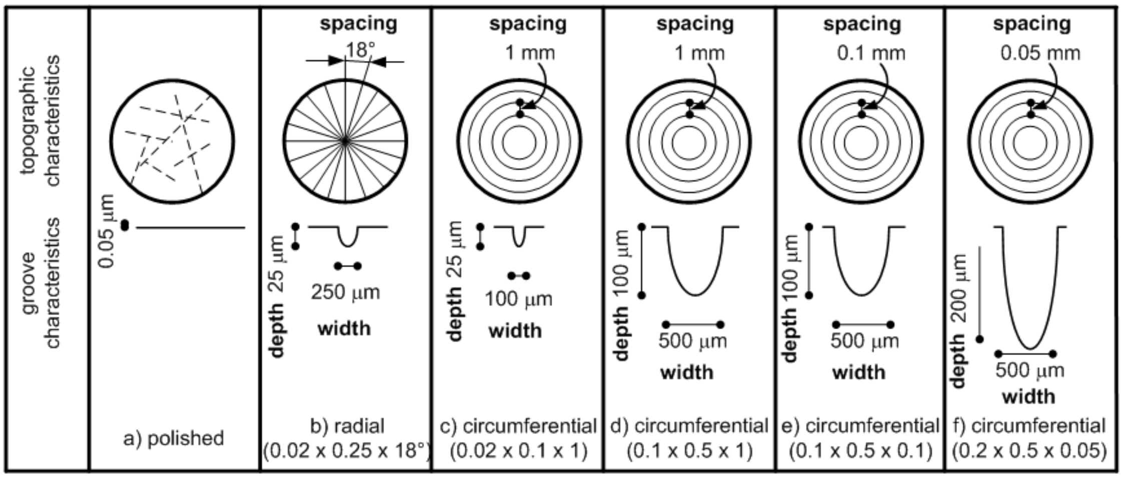


Figure 4. Topographic characteristics of tools for evaluation of wear and friction coefficient between AISI 1020 rings and AISI H13 tools.

3 RESULTS AND DISCUSSION

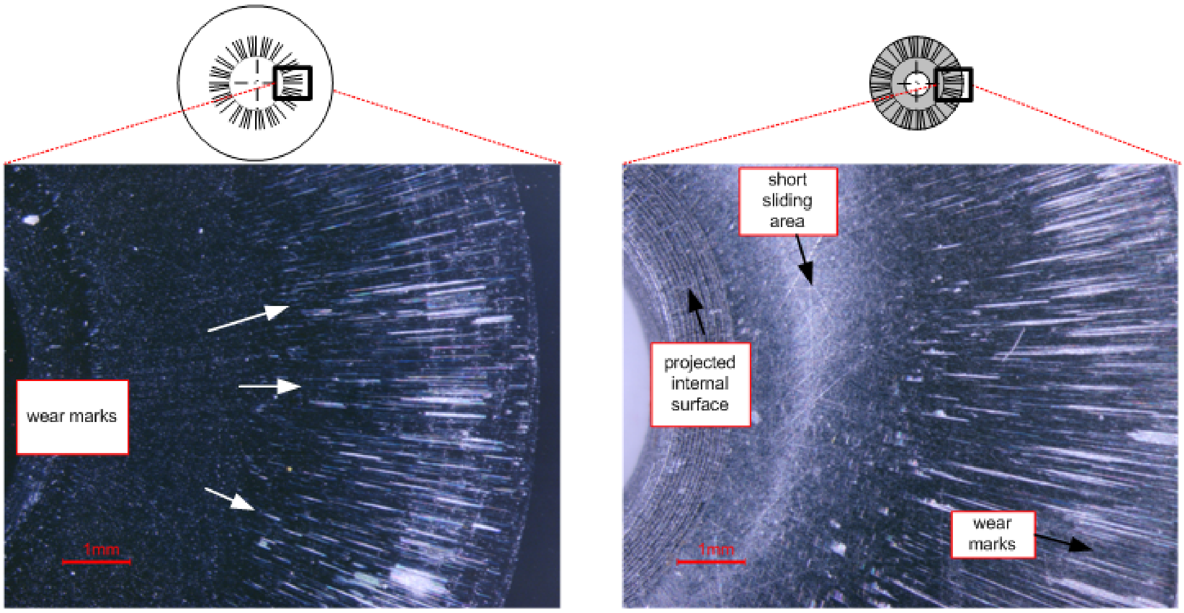
Table 1 summarizes obtained results.

Table 1. Experimental conditions and results of ring test for evaluation of wearing and friction coefficient between AISI 1020 rings and H13 tools

SET	Topography figure 4(*)	Tool velocity (mm/s)	Heigth Reduction (%)	Friction coefficient		Wear
				ID decrease (%)	μ	Qualitative
1	*(a)	0.3	20	9 ± 1	0.2	*None*
			50	40 ± 7	0.3	*Severe*
		3	20	9 ± 1	0.2	*None*
			50	45 ± 6	0.3	*Severe*
2	*(a)	0.06	38	26 ± 1	0.3	*Slight*
	*(b)			26 ± 1	0.3	*Slight*
	*(c)			25 ± 1	0.3	*Slight*
3	*(e)	3	50	56 ± 1	0.5	*None*
	*(f)			60 ± 1	0.57	*None*
4	*(d)	0.3	55	61 ± 1	0.4	*Severe*
	*(e)			60 ± 1	0.4	*Slight*
5	***(a)** lubricated	3	50	-26	0.02	*None*
	***(f)** lubricated			55	0.5	*None*

3.1 Set 1 – Wear and Friction Mechanisms

In this work, it was established that worn area were those surface modification, similar to ploughing marks, identified by naked eye examination. These modification show linear shape and radial orientation, as seen on Figure 5.

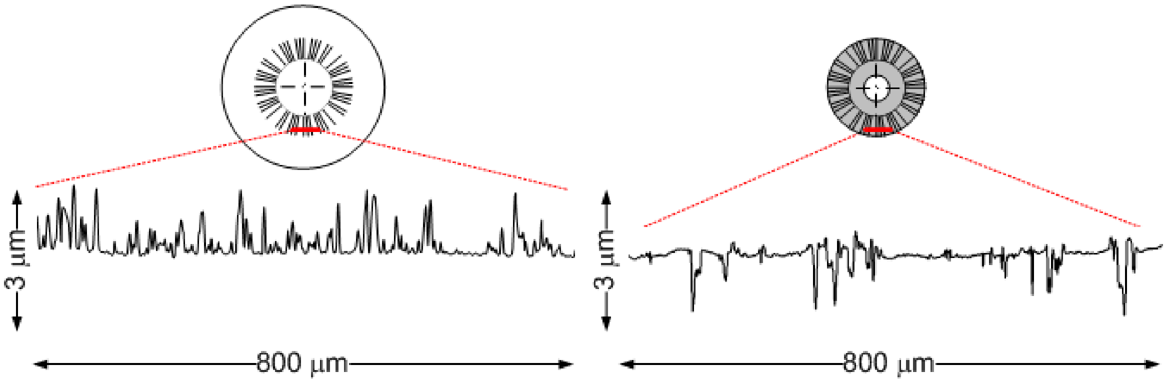


a) tool surface after test

b) ring surface after test

Figure 5. Worn area identification for evaluation of wearing and friction coefficient between AISI 1020 rings and H13 tools.

Profilometry evaluation shows evidences that ring material were transferred to the tool. Peaks in the tools and valleys in the ring show approximately the same depth (3 μm) but not the same distribution (Figure 6).

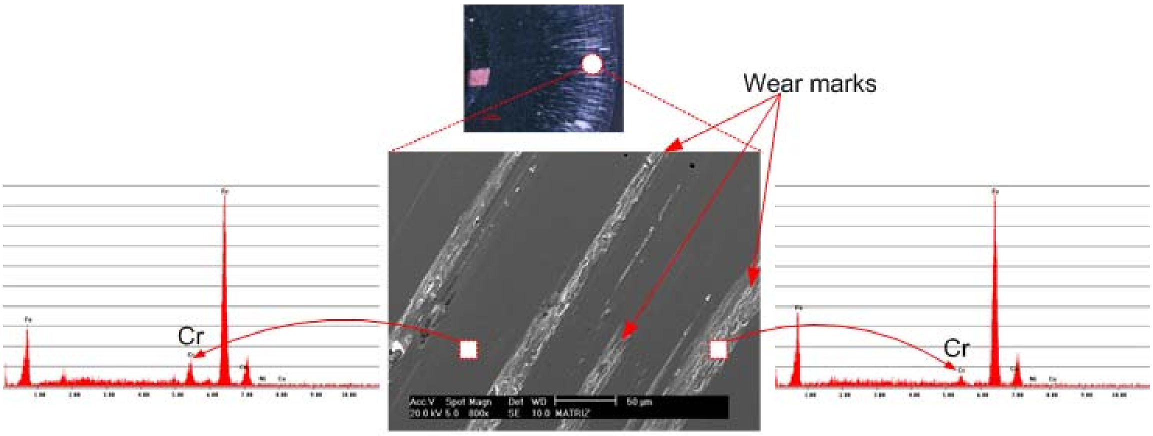


a) roughness profile of tool wear marks

b) roughness profile of ring wear marks

Figure 6. Typical primary profile for regions with radial marks at **(a)** ring and **(b)** tool, showing evidence of transfer material from the ring to the tool.

Energy dispersive spectrometry for Cr at different areas confirms the material transfer from ring to tool. There is evidence of lower Cr content material (ring-like material) adhered at the tool surface (which show higher Cr content), as seen in Figure 7. There is no evidence of transference of material from tool to ring.

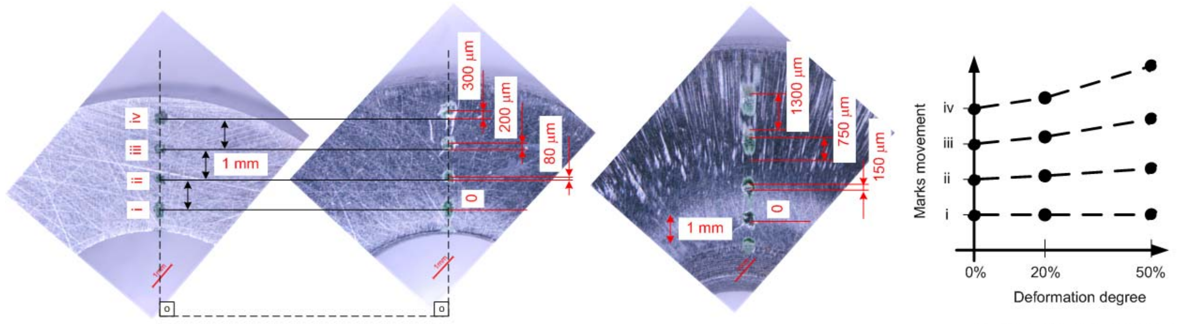


a) EDS without wear b) SEM of the polished tool c) EDS with wear

Figure 7. Typical EDS Cr content measurement at different areas in the tool for evaluation of wearing and friction coefficient between AISI 1020 rings and H13 tools, showing evidence of material transference from the ring to the tool.

Despite the ploughing characteristics, profilometry and EDS evaluation allows the establishment of material transfer as the main wear mechanism, which is caused by the formation, plastic deformation and rupture of junction points. Previous work,(18) in similar conditions, have misinterpreted wear to be ploughing marks.

As expected, there were more wear at 50% reduction than at 20%, regardless the tool velocity. Weight loss measured at 50% reduction was between 0.1 and 0.3 mg, but was not detected at 20% reduction. This difference is to be attributed to sliding tool-ring contact surfaces. Figure 7 shows that sliding was up to 4 times greater at 50% than at 20%. Damages from transfer material are related to formation, plastic deformation and rupture of junction points. Increasing sliding increases junction points due to increasing contact area and, therefore, increases damage.



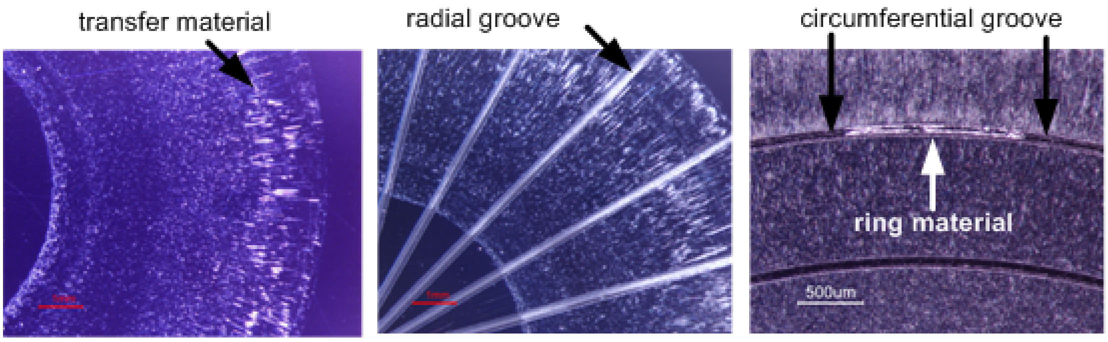
a) new ring b) after test with 20% c) after test with 50% d) schematic representation of marks movement

Figure 8. Tool and ring surfaces sliding measurements showing increasing sliding for increased deformation degree.

As shown in Table 1, friction coefficients were estimated to be 0.2 at 20% reduction degree and 0.3 at 50%, regardless the tool velocity. This difference may be related to the same mechanism proposed to wear (formation, deformation and rupture of junction points). According to Male and Cockcroft,(15) at the transfer material region, interfacial friction tension equals material shear stress. At this point friction coefficient is maximum and given by von Mises yield criterion, close to 0.57. Since the number of junction points increased (friction coefficient 0.57) at 50% reduction, then the average friction coefficient increased.

3.2 Set 2 – Effect of Grooves Orientation

Groove orientation, circumferential or radial, had no effect on friction coefficient (near 0.3 for both orientation and for polished tool as well). No effect was either observed on wearing (transfer material). It is to be noticed, however, that it was possible to identify ring material on circumferential grooves but not on radial grooves (Figure 9). This is to be related to the orthogonal orientation of the grooves to ring material flow.



a) polished

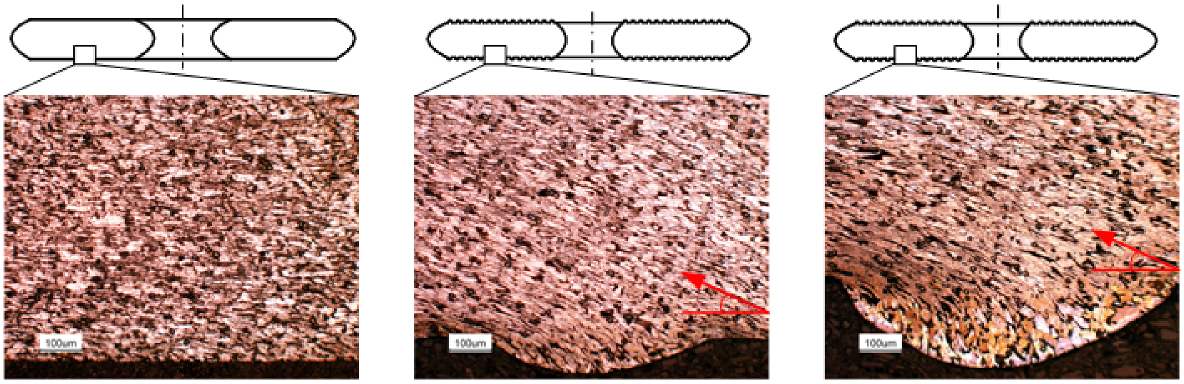
b) radial
(0.02 x 0.25 x 18°)

c) circumferential
(0.02 x 0.1 x 1)

Figure 9. Aspects of wear at tools surfaces with different grooves orientation for evaluation showing some ring material retained at circumferential grooves.

3.3 Set 3 – Effect of Grooves Depth

Compared to polished tool, wear intensity was lower on engineered surface tools because grooves played the role of mechanical interlock to sliding. However, increase on groove depth from 0.1 mm to 0.2 mm had no effect on wear. This shall be related to the similar sliding behavior in both cases. However, the increase on groove depth increased friction coefficient from 0.50 to 0.57.
Microstructural characterization showed equiaxial grains in the portion of material inside grooves for 0.2 mm depth (Figure 10). This shows that ring plastic deformation occurs by internal shear and that 0.2 mm depth grooves interlocked sliding (all surface has friction coefficient about 0.57).



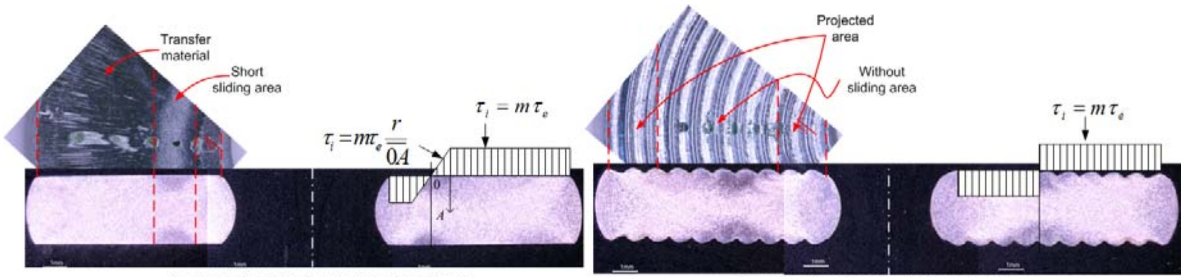
a) test with polished tool

b) test with circumferential
(0.1 x 0.5 x 0.1) tool

c) test with circumferential
(0.2 x 0.5 x 0.05) tool

Figure 10. Aspects of microstructures at transversal sections showing that the ring plastic deformation occurs by internal shear.

Unlike polished tools, when engineered tools are to be considered, movement resistance is mainly due to the mechanical interlock imposed by grooves, instead of formation, plastic deformation and rupture of junction points mechanism observed for polished surface.
According to the model proposed by Bay and Wanheim,(19) at areas close to the neutral radius, friction increases with increasing sliding up to a maximum which keeps constant with increasing force. For polished tools, this constant friction region is to be related to the material transfer region. In such case, friction interfacial stress (τ_i) distribution is shown in figure 10a. On the other hand, for engineered tool there was no measurable sliding. Once there is no relative movement, its behavior would be better described as static and, as a consequence, the friction coefficient that better describes this interface behavior is static friction coefficient. However, if one considers that at all contact region friction equals material shearing stress (τ_e), then there should be a constant interfacial friction through all contact area, regardless the force, and interfacial tension distribution should be as shown in Figure 11b.



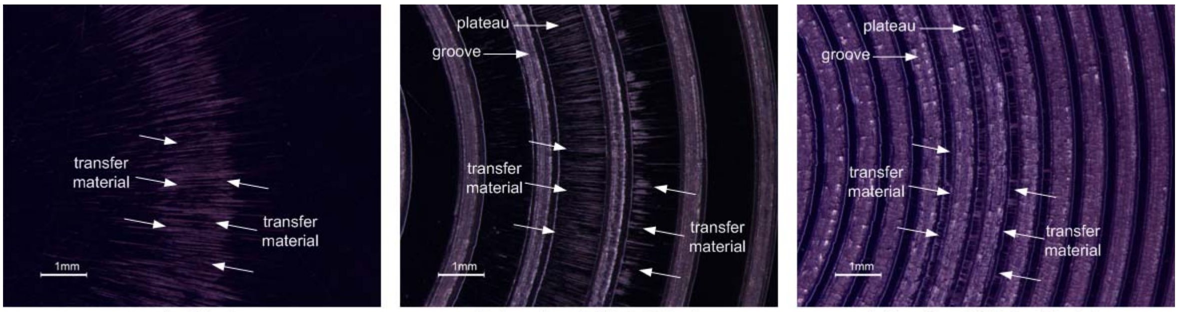
a) cross section of the ring after test with 50% and polished tool

b) cross section of the ring after test with 50% and circumferential (0.2 x 0.5 x 0.05) tool

Figure 11. Schematic relationship between wear and interfacial friction stress for **(a)** polished and **(b)** grooved tool.

3.4 Set 4 – Effect of Grooves Spacing

Decreasing groove spacing from 1 to 0.1 mm had no effect on friction coefficient, which remained close to 0.4 for both cases (for polished tools it was near 0.3). However, decreasing groove spacing (or increasing grooves amount for a given area) decreased wear, as shown in Figure 12.



a) polished

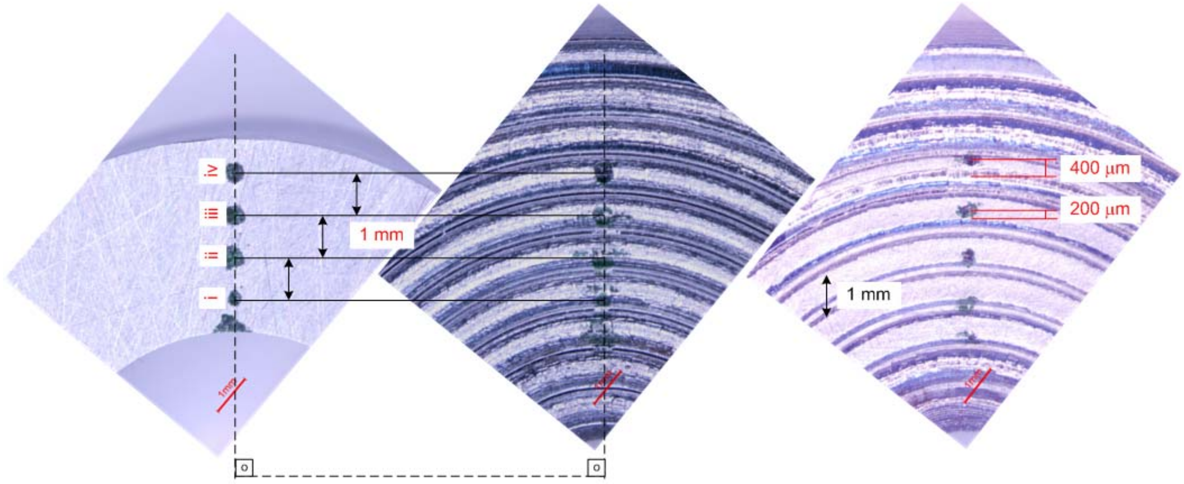
b) circumferential (0.1 x 0.5 x 1)

c) circumferential (0.1 x 0.5 x 0.1)

Figure 12. Tool wear for **(a)** polished, **(b)** 1 mm and **(c)** 0.1 mm spaced grooves showing decreasing wear for decreasing groove spacing.

3.5 Set 5 – Effect of Lubrication on Friction

It was observed a relative small effect of lubrication on grooved tool. Friction coefficient felt from 0.57 to 0.50. When compared to effect observed on polished tool, where friction coefficient dropped drastically from 0.3 to 0.02, it is confirmed that wear mechanism on a grooved topography is related to mechanical interlock to sliding, provided by grooves. There is, however, some effect of lubrication on grooved surface as shown in Figure 13, where it was possible to identify and measure some sliding on the lubricated tool (which was not detected on the unlubricated evaluation).



a) new ring

b) after test with 50% and unlubricated

c) after test with 50% and lubricated

Figure 13. Sliding marks after lubricated (b) and unlubricated (c) test.

4 CONCLUSION

Wearing of tools and rings is a result of the transference of ring material to the tool surface. This process is due to junction formation and plastic deformation followed by junction rupture. This mechanism was not dependent on tool surface topography and ring height reduction degree at the levels evaluated in this work. For polished tools, friction is related to same mechanism above. Tool velocity variation had no effect on friction, while increasing height reduction increased friction coefficient due to increased ring sliding over the tool surface.

The topographic orientation of shallow grooves obtained by laser techniques had no effect on wearing and friction when compared to a polished tool surface. However, deeper grooves (turned), orthogonally oriented in reference to ring material flow, increased friction coefficient due to the mechanical interlock to sliding imposed by the grooves. This same mechanical interlock decreased sliding and, therefore, decreased wearing.

There was no effect on friction coefficient by changing groove spacing. However, decreasing spacing (or increasing amount of grooves per area) increases mechanical interlock to sliding and, therefore, decreases wearing.

This work has shown that engineered surface can decrease wearing damages but, on the other hand, increase friction. When considering possible technological application, there should be a compromise on enhancing wearing useful life for tooling and increasing energy consumption due to increased resistance to flow (friction).

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