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Combination of laser surface texturing and PVD coating for cold forming tools

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Abstract

Wear of cold forming dies is a major obstacle for tool making industries, as it causes increased die maintenance cost and scrap rate. Many aspects are involved in tool wear, such as lubrication, contact pressure and surface coating.
In order to cope with these wear issues, PVD coatings are widely used to improve hardness, wear resistance and oxidation resistance. On the other hand, Surface texturing is proved to be a promising method for improving tribological performance. The application of certain textures on one of the two surfaces of the sliding pair can entail many positive effects, such as reduction of friction and wear and increase in load capacity. In particular, the laser surface texturing offers a promising concept in terms of industrial exploitability, due to its high degree of automation and integration within traditional fabrication cycles.
In this work, the use of laser surface texturing technologies in coupling with thin hard physical vapour deposited coatings is presented. In particular, different approaches were analysed for combining both technologies. The effect of laser texturing parameters on the geometry of the patterns produced on different materials (ceramic coatings and steels) was studied. Finally, wear tests were carried out on different combinations of base steel, PVD coating and laser textured patterns.

Keywords: Laser surface texturing; hard PVD coatings; wear; cold forming tools.

1. Introduction

Tool wear of sheet metal stamping causes increased die maintenance cost and scrap rate. It produces a progressive damage to the die surface caused by the contact of two opposing surfaces and their subsequent

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motion relative to each other. Many control parameters are involved in tool wear, such as lubrication, binder pressure, surface coating and, in particular, surface texture, as stated by Wang et al., 2009. Surface texturing has been recognized as a method for enhancing the tribological properties of surfaces of mechanical components for many years.

Controlled topography (texture) produced on tribological surfaces (sliding contact interfaces) presents several advantages. First, texture patterns can trap wear debris and abrasive particles in both lubricated and dry conditions avoiding their presence between the two surfaces and therefore reducing abrasive wear due to third body effect at the rubbing surfaces. In addition, texture can carry away heat from sliding interfaces, as proved by Andersson et al., 2007. Both Huang et al., 2012 and Ding et al., 2012, showed that a decrease in real contact area caused by surface texturing could decrease adhesion and friction of the material. Texture patterns can also act as a reservoir for lubricants, which could be particularly useful in conditions involving high plastic deformation. Thus, each texture pattern can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication or as a micro-reservoir for lubricant in cases of starved lubrication conditions. Once (solid) lubricant is stored in the motifs, it can be progressively released to the contact interface and thus increases the service life of rubbed surfaces, as shown by Rapoport et al., 2009.

Among the different micro-surface patterning methods, Laser Surface Texturing (LST) offers the most promising concept in terms of industrial exploitability, due to its high degree of automation and integration within traditional fabrication cycles. Laser radiation is focused on a spot with very small dimensions, which results in a significant energy density, which produces the ablation phenomenon. LST provides an excellent control of the shape and size of the generated micro-sized features, which allows realization of optimum pattern designs (Etsion, 2006).

In this work, the use of laser surface texturing technologies in coupling with thin hard physical vapour deposited coatings is presented. In particular, different approaches are analysed for combining both technologies. The effect of laser texturing parameters on the geometry of the patterns produced on different materials (ceramic coatings and steels) is studied. Finally, wear behaviour of different combinations of base steel, PVD coating and laser textured patterns is investigated.

2. Materials and experimental procedure

The LST was applied on the flat surface of cylindrical samples with diameter of 24 mm and height of 7.9 mm. Different substrate materials (high alloyed tool steels) and PVD coatings were tested in this study. The steels, with commercial names of ASP 23 and REX 76, are commonly used in cutting, forming and punching tools due to their combination of high hardness and toughness.

With regard to the PVD coatings, three different TiAlN based coatings and an AlCrN based one were tested. The Alcrona Pro is an AlCrN based coating, suitable for cutting tools. Similar applications can be dealt with by the Futura Nano coating, although it is based on TiALN instead of AlCrN. The “Advanced” label includes a combined treatment of nitriding of the metal surface and PVD coating, which improves the adherence and overall performance of the PVD coating by itself. Finally, the Lumena is another TiAlN coating, which is more appropriate for forming applications. Some properties and abbreviations used hereafter for referring to the four PVD coatings are collected in Table 1.

Table 1. Characteristics of the PVD coatings

Commercial name	Abbreviation	Material	Thickness (µm)	Deposited on
Balinit® Alcrona Pro	ALC	AlCrN	3-4	ASP 23
Balinit® Futura Nano	FUT	TiAlN	3-5	REX 76
Balinit® Futura Nano Advanced	FUT_A	TiAlN	7-8	REX 76
Balinit® Lumena	LUM	TiAlN	11-12	ASP 23

Instead of studying all the possible combinations of two backing steels and four PVD coatings, each steel was coated with two PVD coatings, as indicated in Table 1.

Two different pulsed laser sources were employed for producing the textures on different samples, a picosecond (PS) laser and a nanosecond (NS) laser. The technical characteristics of these laser sources are shown in Table 2. Two types of motifs were selected for producing the texturing patterns: dimples and grooves.

Table 2. Technical characteristics of the laser sources employed for texturing

Laser Source	PS	NS
Max. Average Power (W)	4	40
Wavelength (nm)	355	1064
Pulse length	12 ps	5-250 ns
Frequency (kHz)	10-1000	30-1000
Spot diameter (µm)	~15	~60

In order to characterize the geometry of the texturing patterns, confocal microscopy and contact profilometry were used. Scanning electron microscopy combined with EDS (energy dispersive X-ray spectroscopy) semi-quantitative chemical analysis was used in order to determine whether the PVD layer was completely pierced by the laser ablation process. Finally, a tribometer was used in order to evaluate the wear behaviour of the coated/textured samples, with ball-on-disc configuration.

3. Results and discussion

3.1. Definition of the texturing motifs and strategies

Two different coating/texturing approaches were tested in order to select the best strategy: These strategies consisted of producing the texture before or after depositing the PVD layer.

It should be noted that in the case of carrying out the texturing over already PVD coated steels, the depth of the produced motifs is limited by the thickness of the PVD layer, as deeper motifs would completely eliminate the layer on the textured regions. On the other hand, if the steels are first textured and then PVD coated, the geometry of the motifs has to be deep enough to reproduce the texture even after coated. Thus, in this case, motifs significantly deeper than the thickness of the thickest PVD coatings were intended to produce.

Regarding the width/diameter of the motifs, typical aspect ratios (ratio of diameter/width and depth of the motifs) found in the literature were taken into account. Values ranging between 3 and 15 are employed in the majority of the laser texturing studies. These values were not always achievable, as in the thinner coatings, the depth of the motifs is highly limited, and the minimal diameters/widths that can be produced were limited by the laser spot size, which was too large for achieving the desired aspect ratio.

With all these considerations into account, the final geometries were defined, as shown in Table 3.

Table 3. Desired geometries for the motifs to produce

Strategy	**Coating**	**Depth (µm)**	**Width/diameter (µm)**
PVD+Texturing	Alcrona	<3	Minimal
	Lumena	<10	Minimal
	Futura	<3	Minimal
	Futura Advanced	<6	Minimal
Texturing+PVD	All of them	20-30	70-80
Texturing, uncoated	None	20-30	70-80

Once the final geometries were defined, the first step consisted in choosing the laser system to carry out the texturing experiments.

For textures to be produced directly on the uncoated steels, the picoseconds laser was used, in order to minimize the crests of re-melted material that form around the dimples and grooves, as shorter pulse durations produce less thermal effects in the irradiated region. Taking into account that the spot size of this laser was considerably smaller than the diameter/width of the dimples/grooves to produce, a strategy of concentric circles and overlapped lines had to be employed.

Concerning the PVD coated samples in which the laser texturing had to be carried out, and especially in the case of the thinnest coatings i.e. ALC, FUT and FUT_A, the width/diameter of the motifs was highly limited, if the desired aspect ratios were to be kept. With this in mind, the PS laser was the best choice for these three coatings, as it produces a smaller spot than the NS laser. Nevertheless, in the case of the samples coated with LUM, wider motifs could be produced, and the NS laser was chosen to deal with this material, which allowed comparing different laser sources.

The depth of the motifs was controlled by varying the number of repetitions of the texturing process. In the case of the steels, measuring the profile of the motifs by contact profilometry was enough for controlling the geometry of the texturing motif.

On the other hand, when dealing with the previously coated samples, especial care had to be taken in order to avoid piercing the coating until reaching the substrate steel. Thus, in order to prevent this effect, EDS analyses were carried out in the motifs with reasonable depths (neither deeper than the thickness of each PVD coating, nor imperceptibly thin). If the coating was not completely eliminated by the laser ablation, clear peaks of the component of the coatings (Al, Cr, and N for ALC and Al, Ti and N for FUT, FUT_A and LUM) appeared on the pattern with no traces of iron. On the other hand, if the coating was wiped out by the laser ablation process, even in a small region, a clear Fe peak raised (Fig 1).

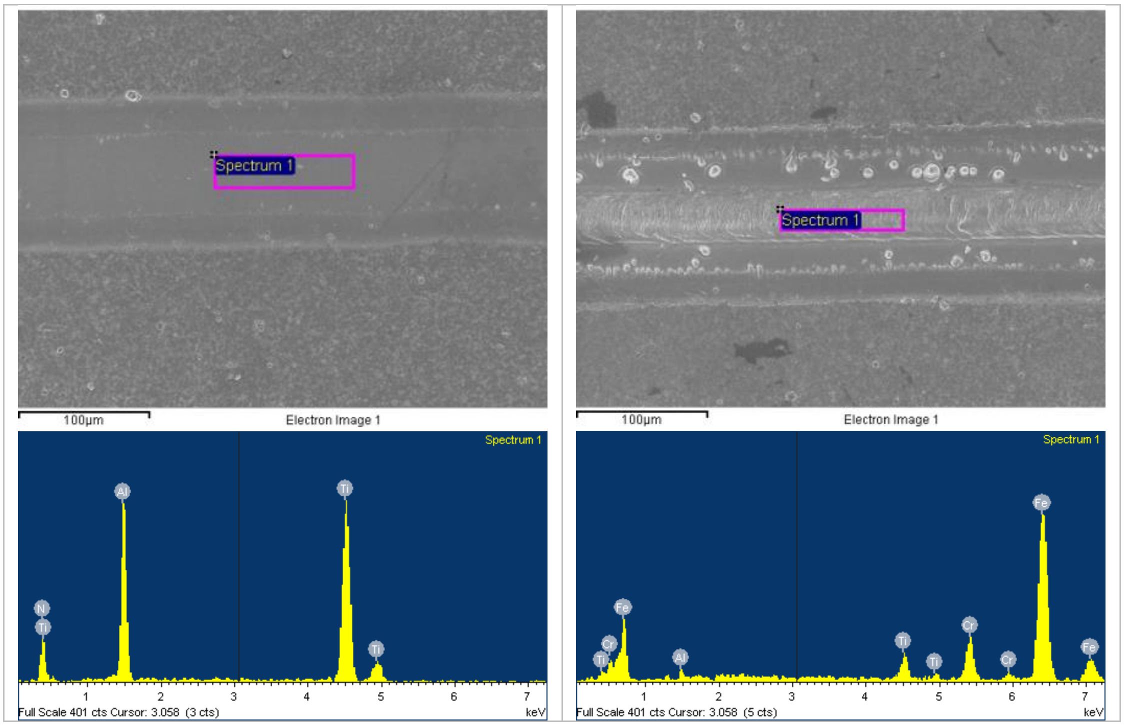

Fig. 1. EDS patterns measured in grooves where the Lumena layer was not completely removed (left) and where it was (right)

Once the EDS patterns were completely analysed, the parameters for the final textures were determined. These parameters are shown in Tables 4 and 5. It should be noted that the scanning speed is not a relevant parameter when producing dimples by this method, as it only determines the distance between two subsequent dimples without affecting their geometry. Nevertheless, the variation of this parameter will allow producing textures with different fill factors.

The *Waveform* shown in Table 5 is just an additional parameter of the ns laser, which affects the pulse shape and duration. The waveform 0, which is the one with the longest pulse duration (250 ns) was selected for producing the dimples, as it was the one which was able to ablate a considerable amount of material without producing crests of re-melted material in the surroundings of the dimples. Concerning the grooves, an intermediate waveform (Waveform 3, with 30ns pulse length) was proved to be more suitable.

Table 4. Parameters for the best motifs produced on the three PVD coatings textured with a ps laser

	Alcrona		**Futura**		**Futura Advanced**	
Geometry	**Dimples**	**Grooves**	**Dimples**	**Grooves**	**Dimples**	**Grooves**
Frequency (kHz)	20	250	20	250	20	250
Scanning speed (mm/s)	-	500	-	500	-	500
Laser power (%)	100	100	100	100	100	100
No. of repetitions	6	4	10	4	25	8

Table 5. Parameters for the best motifs produced on the Lumena coating textured with a ns laser

	Lumena	
Geometry	**Dimples**	**Grooves**
Waveform	0	3
Frequency (kHz)	30	145
Scanning speed (mm/s)	-	580
Laser power (%)	100	100
Number of repetitions	6	3

Fig. 2 shows the final topographies of the individual patterns produced on the four PVD coatings. A higher amount of re-melted material can be observed around the motifs produced on the LUM coating as compared, which is explained by the thermal effects produced by the longer pulse duration of the ns laser as compared with the ps laser. Once the processing parameters for producing the individual motifs were defined for each coating, surfaces were textured with two fill factors (10% and 40%) for each combination of coating/motif, in order to carry out the tribological characterization.

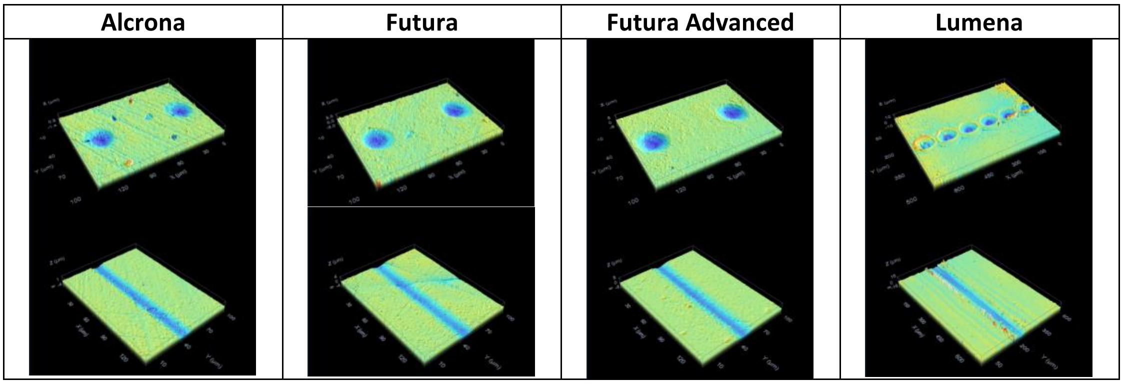

Fig. 2. Topographies of the individual motifs produced on each PVD coating, measured by confocal microscopy

3.2. Tribological characterization

The 46 samples produced were subjected to a tribological analysis, in order to study the effect of different surface treatments (coating and/or laser texturing) on their wear resistance. In total, 2 base metals (ASP23 and REX76), 4 PVD coatings (ALC, LUM, FUT and FUT_A) and 2 textures (dimples and grooves) with 2 different fill factors (10% and 40%) were tested.

The idea was to produce on the discs a deep enough wear track to be measurable and comparable between different texturing strategies, without completely removing the whole coating layer in a given test time. In order to reduce the test time, an Al_2O_3 ball was used as the counter-material, instead of a typical steel used in cold forming, as this kind of steels were not able to produce a significant wear track on the PVD coated discs. Moreover, the wear tests had to be carried out under quite aggressive conditions, in order to produce measurable wear tracks on the analysed surfaces.

Nevertheless, due to the different wear behaviour of the four PVD coatings, the test conditions for each coating were chosen independently. The samples coated with ALC showed a much higher wear resistance than the rest and under the conditions that suited best for this coating, the rest were be completely removed. Thus, in order to keep some reference to compare between the different coatings, the load, amplitude and frequency were the same in all cases and just the test time was different, as it can be observed in Table 6.

Table 6. Conditions for the wear tests of the different studied coatings and steels

Coating	Load (N)	Amplitude (mm)	Frequency (Hz)	Temperature (°C)	Time (min)
Alcrona	100	3	50	25	45
Lumena	100	3	50	25	15
Futura	100	3	50	25	10
Futura Advanced	100	3	50	25	10
Uncoated ASP23	100	3	50	25	15
Uncoated REX76	100	3	50	25	10

Fig. 3 shows the results of the wear tests for all the 46 samples, divided in four graphics, each corresponding to a PVD coating.

In the case of the ALC coating, which was by far the coating that provided the best results under the tested wear conditions, much better wear resistance than the uncoated steel was obtained. With regards to the texturing strategies, it seems that the best performance is obtained when texturing the already coated metals instead of doing it the other way. The wear resistance was slightly improved by texturing the coated surface with the four texturing strategies, but especially with the surface textured with dimples and a fill factor of 10%, where a track with 1 µm depth was obtained while the non-textured sample presented a 2.5 µm wear track. When carried out the textures before the PVD coating, in none of the samples the original wear resistance of the coating was improved.

The samples coated with LUM showed just a slightly improved wear behaviour as compared with the uncoated ASP23 steel. Here, similar results were achieved when texturing before or after the coating process, but in every case the textured samples presented a slightly worse wear resistance than the non-textured sample, with minimal differences between the different texturing approaches.

The results obtained with the FUT coating were not very promising. Even if the tests took no more than 10 minutes, the wear track completely eliminated the coating layer in all cases, producing highly dissimilar results. Once again, the coated sample showed a slightly better performance than the REX76 steel, but the different texturing approaches produced so variable results that no clear conclusions could be drawn.

Finally, the FUT_A coating improved the wear resistance of the uncoated steel, just like the other PVD coatings. Nevertheless, texturing the coating did not significantly improve or worsen the wear behaviour of the non-textured sample, and worse results were obtained when the PVD coating was produced after texturing, especially in the textures with the highest fill factor.

It should be noted that texturing the base metal without any PVD coating always produces worse results than the non-textured surface, thus, using the laser texturing approach with no PVD coating is not a sensible option for improving tool life.

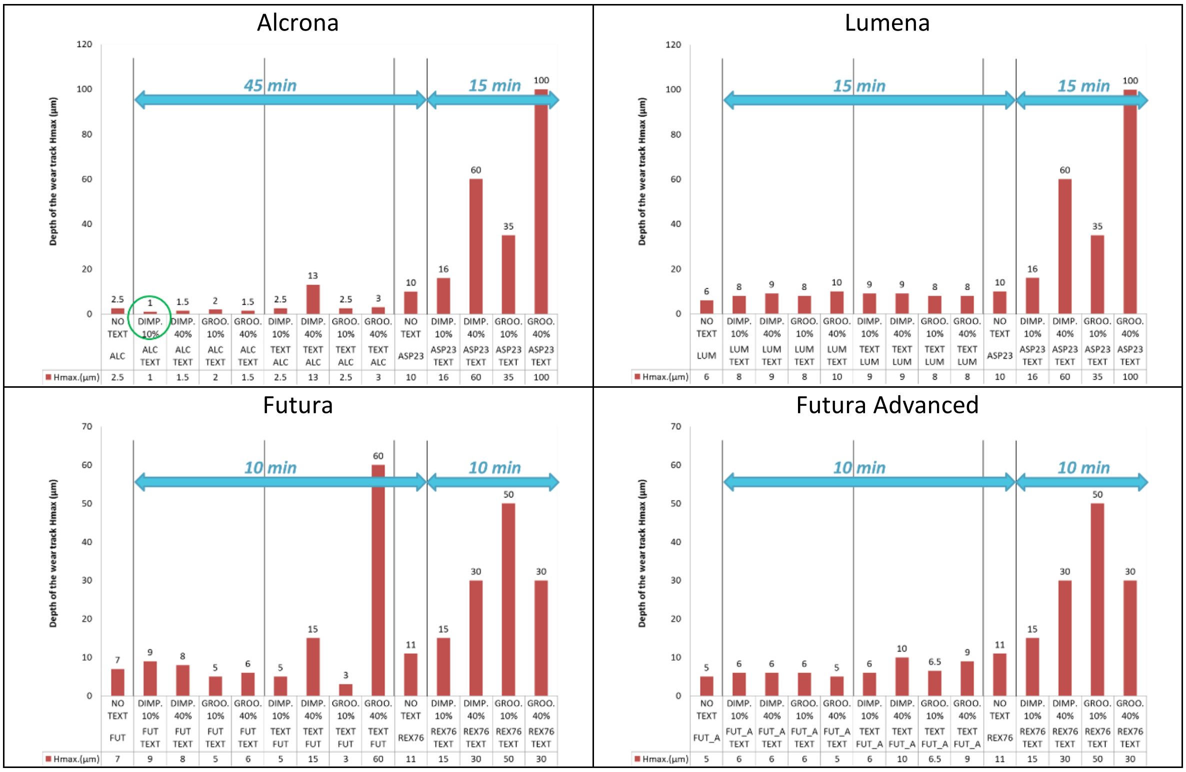

Fig. 3. Results of the wear tests for each coating

4. Summary and conclusions

A comprehensive tribological study was carried out in order to evaluate the effect of the different surface states of the samples (PVD coated and/ or textured). Due to inconvenients found during the set up of the wear tests, the conditions and counter-materials used for this study had to be modified. Moreover, the tests were not carried out under the "limit lubrication" conditions, where the textures provide an additional advantage as lubricant reservoirs. Taking these two facts into account, the results of this study have to be considered as merely illustrative, and should not be fully trusted until the process is validated with real pieces and working conditions. In any case, some preliminary conclusions were drawn, as a result of this tribological study:

- PVD coatings always improve the wear behaviour of the base steel.
- Texturing the steels without coating always deteriorate the wear properties of the non-textured steels
- Better results are achieved when texturing the already coated surfaces instead of using the opposite approach of coating after texturing
- Textures with the lowest fill factor (10%) tend to produce better results than the ones with the highest (40%), although this is not always the case.
- Only the wear behaviour of the ALC coating could be slightly improved, especially when texturing the coating with dimples and a fill factor of 10%.

• Regarding the 4 studied coatings, ALC is by far the most resistant coating followed by LUM and FUT_A which show a very similar wear resistance, and finally FUT where the PVD layer was completely removed by the wear tests.

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