Accepted Manuscript

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PII: S0263-4368(19)30412-3

DOI: <https://doi.org/10.1016/j.ijrmhm.2019.105034>

Article Number: 105034

Reference: RMHM 105034

To appear in: *International Journal of Refractory Metals and Hard Materials*

Received date: 29 May 2019

Revised date: 5 July 2019

Accepted date: 24 July 2019

Please cite this article as: S. Fang, S. Klein, C.-J. Hsu, et al., Fabrication and tribological performance of a laser-textured hardmetal guiding stone for honing processes, *International Journal of Refractory Metals and Hard Materials*, <https://doi.org/10.1016/j.ijrmhm.2019.105034>

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Fabrication and tribological performance of a laser-textured hardmetal guiding stone for honing processes

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Abstract.

Honing is often implemented as surface finish process by improving geometrical and form precision of workpieces. Guiding stones, usually made of hard materials with requirement of excellent tribological properties, play a key role as a supporting part in the honing tool. In this paper, cemented carbides are intended for guiding application as substitute of diamond or CBN composites. Innovative surface textures, namely crossing-line patterns and dimple arrays, are fabricated by means of short pulse laser on a cemented tungsten carbide (hardmetal) grade. ~~A laser ablation model for cemented carbides is used for estimating optimized laser machining parameters.~~ Implementation of these processing conditions yields satisfactory geometrical accuracy. ~~crossing-line patterns with similar dimensional and topographic features to those exhibited by honed workpieces.~~ The cemented carbide stones patterned by laser together with a traditional diamond guiding stone were tested on a lubricated pin-on-disc tribometer. Both cross-line patterns or dimple arrays are found to improve frictional conditions compared to the

traditional guiding stone, but ~~during lubricated pin-on-disc tribotests. In this regard,~~ the former are more favorable to build up a stable sliding scenario with minimized friction than the latter. Pattern density has a more significant impact on friction, diminishing in the case of dimple arrays.

Keywords: cemented carbide; honing; laser surface texturing; tribology.

1 Introduction

Surface modification at the level of microns or nanometers has been proven to be an effective approach to improve tribological performance of tools and components [1-2]. Enhancement of tribological functionality, namely decreasing friction, removing heat or reducing wear, usually results from the amelioration of contact conditions and lubrication regimes [3-4]. In this regard, several technologies (i.e. coating deposition [5], electrochemical machining [6], lithography, laser and 3D printing, among others) have been successfully implemented in different materials and for a wide range of applications, e.g. in the manufacturing of bearing and tools as refs in [7-8]. Among them, pulsed laser is an emerging technology attracting large industrial interest for texturing functional surfaces. Main reasons behind it are that pulsed laser is able to produce precise (small length scale) textures with defined geometry, and at the same time to minimize side effects on the surface integrity [9,10]. Compared to other surface modification technologies, laser has the advantage to realize tiny ablation, and then to achieve high precision [11-13].

Among the abrasive machining processes, honing is often implemented as surface finish process by improving geometrical and form precision. Guiding stones play an important role as a supporting part in the honing tool [14,15]. Due to the relative movement and contact between guiding stone and workpiece surface, mandatory

requirements for the former are excellent tribological properties, i.e. low friction and high wear resistance. Taking into account that guiding stones are usually made from hard materials, laser surface texturing becomes a potential technology to produce specific patterns on their surfaces, in order to reduce friction by changing the tribological conditions in the honing processes.

Within this context, the first goal is to find out suitable surface patterns on the potential cemented carbide guiding stone, i.e. aiming to improve the tribological performances of guiding stones. In practice, honed surfaces usually exhibit crossing-line patterns, as they are supposed to improve the supply and distribution of the lubricant during the reciprocal movement, for example the honed cylinder inner wall [16, 17]. Therefore, crossing-line pattern is selected as the first target pattern to be produced by laser in this study. Among those classic tribological patterns, dimple array is one of the most studied patterns [4], since such artificially-induced cavities are easy to produce and their shape can serve as tiny reservoirs of lubricants [12,18]. Therefore, besides crossing-line patterns, dimple arrays with different densities of cavities will also be produced by laser.

Once laser-textured patterns are made, a second goal of the investigation is to evaluate the tribological performance of the surface-modified hardmetal. This is done by determining frictional response as a function of sliding length, and it is conducted by using a precision tribometer under lubricating conditions. Finally, geometrical precision and surface conditions of the tested samples are assessed and compared.

2 Materials, experimental aspects and theoretical considerations

2.1 Materials studied

In practice, the applied guiding stones are usually made of composites consisting of middle or small grain size diamonds or cubic boron nitride particles and a metallic matrix [19]. For comparison purposes, the surface topographic features of a commercial guiding stone are characterized as reference conditions. In this regard, the guiding stone D76/710/6/100 (Kadia Produktion GmbH + Co) was chosen. It consisted of 25%_{vol} concentration of diamond grains with an average size of 76 μm embedded in a metallic binder. Figure 1(a) shows the surface topography of the inspected guiding stone. After dressing, Ra and Rz surface roughness parameters are about 3 μm and 35 μm respectively.

The required use of diamond or CBN composites as guiding stones not only leads to high costs but also might induce production quality issues, as extruding grains are sometimes either dislodged or broken during the honing process. As a consequence, fragmented or erupted hard grains or debris can scratch and damage the workpiece surfaces, as shown in Figure 1(b). Within this context, it is then proposed to use more conventional hard materials as substitute of diamond or CBN composites for guiding application in the honing processes, as long as their tribological and mechanical properties meet the required service demands.

(a)

(b)

(c)

Figure 1. (a) Surface topography of the guiding stone D76 with a fractured grain; (b) damage on the workpiece surface, eventually induced by broken or erupted diamond grains; and (c) microstructural aspect of hardmetal grade 15CoC.

A plain WC-Co cemented carbide (also named hardmetal) grade was selected in this study as substitute material for the traditional diamond composite commonly used for guiding application. It is referred to as 15CoC, and its basic microstructural and mechanical characteristics are listed in Table 1. Microstructural aspect evidencing the composite nature of the hardmetal grade is shown in Figure 1(c). The combination of medium binder content and a relatively coarse carbide size ~~results~~ yields an optimal hardness-toughness relationship, suitable for its intended application as supporting part. Moreover, aiming to ameliorate its tribological performance, surface laser-texturing was implemented, as it will be detailed below (section 2.3).

Table 1. Microstructural and mechanical parameters of 15CoC hardmetal grade studied [20].

Binder	W _{binder} (% wt)	d _{WC} (μm)	E (GPa)	Poisson's ratio ν	HV30 (GPa)	Fracture toughness K _{Ic} (MPa√m)
Co	15	1.7 ± 1.1	550	0.23	10.2 ± 0.1	17.0 ± 0.2

2.2 Preliminary study of the honed surface structures

Honing is a technology widely used for bore finishing process. The surface of a honed part describes a functional surface with form (geometry) and dimension accuracy as well as a very high surface quality (e.g. cylindricity less than 1 μm and roughness Ra less than 1 μm). Due to kinematics implicit to honing, this material removal process produces specific crossing-line micro-patterns on the finished surface [15,19]. The honing angle, i.e. cross-angle, can be adjusted by changing the machining parameters (Figure 2(a)). It is reported that these specific patterns are beneficial to achieve effective and even distribution of lubricant as well as to reduce the friction between the contact surfaces [21]. In this regard, an additional test was conducted attempting to obtain the topographic features of the honed surfaces. It involved a steel workpiece 16MnCr5 (1.7131) with elevated hardness (HRC60) and a diamond honing tool together with the guiding stone D76 (middle grain size), under full lubrication testing conditions. The characteristic honing angle α can be adjusted by changing oscillation (v_a) and rotation (v_t) speeds according to [15]:

$$\alpha = 2 * \arctan\left(\frac{v_a}{v_t}\right) \quad (1)$$

Hence, setting n_a and n_t values as 172 mm/s and 1000 rpm (419 mm/s) respectively, the process results in a honing angle of about 45° in case of honed bores with a diameter of 8 mm.

Figure 2(b) shows the topography of the honed surface, exhibiting a crossing-line pattern with the cross-angle of 45° . The lines have an interval of about $50\ \mu\text{m}$ between each other and average depth of about $1\ \mu\text{m}$, a dimensional arrangement amenable to be replicated by laser surface texturing. Accordingly, this was attempted on the contact surfaces of the selected hardmetal guiding stones.

Figure. 2. (a) Kinematics of honing processes and (b) 2D surface topography of honed steel workpiece where crossing-line patterns are evidenced.

2.3 Fabrication and characterization of textured surfaces

2.3.1 Determination of surface patterns on cemented carbide guiding stones

Two different laser-induced surface patterns are investigated in this study, namely crossing-line (aiming to replicate aforementioned honed surface patterns) and dimple arrays, the latter as supplementary case study. Two array densities are chosen for

each pattern, i.e. crossing-line patterns with intervals of 100 μm and 50 μm [L(100) and L(50)], and dimple arrays with intervals of 100 μm and 50 μm [D(100) and D(50)]. Meanwhile, the dressed guiding stone D76 and one surface finish corresponding to polishing condition are used as references, for comparison purposes. Table 2 lists all the surface patterns studied.

Table 2. Surfaces patterns (induced by either laser-texturing, polishing or dressing) considered in this investigation.

Designation	Material	Pattern	Characteristics
L(100)	15CoC	Crossing-lines	$R_a < 1 \mu\text{m}$, interval of 100 μm
L(50)	15CoC	Crossing-lines	$R_a < 1 \mu\text{m}$, interval of 50 μm
D(100)	15CoC	Dimple arrays	$R_a < 1 \mu\text{m}$, interval of 100 μm
D(50)	15CoC	Dimple arrays	$R_a < 1 \mu\text{m}$, interval of 50 μm
Polished	15CoC	Polishing lines	$R_a < 1 \mu\text{m}$
D76	Diamond	Random grain exposure	$R_a \sim 3\text{-}5 \mu\text{m}$

2.3.2 Laser configuration and machining parameters

Crossing-line patterns and dimple arrays were fabricated using a laser machining platform (Figure 3(a)), including a solid-state Nd:YLF, Q-switched laser set-up (Explorer® One™ Spectra Physics) and a 2-axis laser beam deflection unit (Raylase GmbH). The emitted laser beams have a Gaussian profile (Figure 3(b)) and possess a wavelength of 349 nm, a pulse duration of 5 nanoseconds (FWHM), and a nominal pulse repetition frequency of 1000 Hz

Figure 3. (a) Configuration of the laser machining platform employed; (b) symmetric Gaussian profile of the laser beam; and (c) laser scan route followed for the fabrication of crossing-line patterns.

The emitted laser beam is conducted by the two mirrors until it enters the deflection unit, which controls the scan route and speed of the laser beams on the working stage. The laser beam is 4 mm in width and its beam quality factor M^2 is 1.3. A confocal lens with a focus length f of 100 mm is set between the deflection unit and working stage. The spot size D at the working stage, theoretically equal to the diameter of the focus point d_f , can be calculated to be $19.6 \mu\text{m}$, corresponding to a spot area A of $3.0 \times 10^{-6} \text{ cm}^2$, using the following equation [22,23]:

$$d_f = \frac{4\lambda}{\pi} \frac{M^2 f}{d_L} \quad (2)$$

λ : wavelength (nm)
 M^2 : beam quality factor
 f : focal length (mm)
 d_L : beam with (mm)

Lines are created by superposition of consecutive dimples as the laser beam moves at the speed v of 2.4 mm/s. In order to produce this crossing structure, two arrays of lines are created superposing the 45° lines to the 0° ones. A schematic example of the

production of such structure is presented in Figure 3(c). The overlap (Equation 3) is a dimensionless parameter describing the superposition of two adjacent dimples produced by laser pulses [24], and it may be calculated using the following equation:

$$U = 1 - \frac{v}{f_z \cdot D} \quad (3)$$

U : overlap in percentage
 v : scan speed (mm/s)
 D : spot size (μm) equivalent to d_f
 f_z : pulse repetition frequency

Introducing above referred values (v : 2.4 mm/s, D : 19.6 μm and f_z :1000 Hz) for variables in eq. (3), it results in an overlap value of 87.8%, corresponding to an overlap distance of 17.2 μm .

In the nanosecond regime, the ablation is a thermal based process, i.e. it involves melting and evaporation. Therefore, microstructural characteristics and thermal properties, i.e. melting and boiling temperatures as well as thermal conductivity, play a significant role in the laser-matter interaction mechanism for the particular case of the cemented carbides. In this regard, the composite nature of these materials should be highlighted, as they are constituted by two completely different phases, i.e. WC and Co, exhibiting also quite distinct thermal properties. On one hand, the melting temperature of WC (2870 °C) is very close to the boiling one of Co (2927 °C). On the other hand, the ceramic phase exhibits a much lower thermal conductivity than that of the metallic binder, i.e. 29 W/m K for WC as compared to 74 W/m K for Co. Therefore, Ablation threshold of WC is higher than that of Co in the nanosecond regime, and the binder cobalt will be first molten and evaporated [10,25]. As cobalt content increases, the ablation of tungsten carbides by nanosecond laser becomes more dependent on the removal of the metallic phase, i.e. carbide grains are expelled due to the evaporation of

~~the binder.~~ In this regard, studies conducted on laser drilling of cemented carbides have reported that while selective removal of cobalt required fluence values higher than 2.5 J/cm², complete ablation was not discerned until fluence level rose over 10 J/cm² [10,24,26]. In general, at higher fluence levels more material can be ablated per unit. However, it also implies increasing side effects, such as recasting, pore formation and subsequent surface integrity degradation. Hence, compromising moderate fluence values are recommended for laser surface texturing of cemented carbides. Accordingly, an intermediate fluence (F) value of 6.7 J/cm² has been adjusted by imposing an applied pulse energy E_p of 20.3 μ J, and using a spot area A of 3.0×10^{-6} cm² as obtained from the above calculation with Equation 2.

~~2.3.3 Theoretical estimation of laser ablation~~

~~In the nanosecond regime, the classical beam matter interaction occurs. Therefore, an ablation model based on the evaporation energy is then proposed in Refs. [27,28] to estimate the ablated mass. It is based on the consideration that absorbed laser energy heats up the material in certain volume and leads to its evaporation, within the context of energy conservation in the beam matter interaction. This may then be described according to:~~

$$m = \frac{N \cdot E_p}{C_p \cdot (T_b - T_0) + \Delta H_m + \Delta H_v} \quad (4)$$

~~where m is the ablated mass, N is the pulse number, E_p is the pulse energy, C_p is the heat capacity, T_b and T_0 are the boiling and the ambient temperature, and ΔH_m and ΔH_v are the melting and boiling enthalpy respectively.~~

This model assumes that the laser energy is absorbed 100% as well as that heat conduction and overheating of the metal vapour may be neglected. Referring to cemented carbides, the two constitutive phases exhibit very distinct thermal properties, i.e. large gap between melting and evaporation temperatures. Therefore, thermal reaction of the two hardmetal constituents to laser beam incidence are very different from each other. As metal binder content is significant (15% in weight) in the studied grade, its impact on the effective laser ablation should be taken into account. In this regard, two simplified cases, i.e. 100% WC and 100% Co, are here considered to estimate the laser ablation.

Calculation of the ablated mass and volume

Given the ablation conditions referred before and physical properties detailed in Table 3, the ablated mass can then be estimated as follows:

- Case 1: 100% WC

Mass m_{WC} of pure WC ablated by a laser pulse energy of 20.3 μ J is 3.46×10^{-9} g, corresponding to an ablated volume V_{WC} of 220.6 μ m³.

- Case 2: 100% Cobalt

Mass m_{Co} of pure Co ablated by a laser pulse energy of 20.3 μ J is 4.26×10^{-9} g, corresponding to an ablated volume V_{Co} of 479.1 μ m³.

Table 3. Physical properties used for the theoretical calculation of the ablated mass and volume of individual constitutive phases of hardmetal grade studied.

Parameter	Unit	Tungsten carbide (WC)	Cobalt (Co)
ρ : density	g/cm ³	15.7	8.9
C_p : heat capacity	J/(K.g.K)	238	421
T_v : boiling temperature	K	6273	3200
T_0 : ambient temperature	K	298.15	298.15
ΔH_m : melting enthalpy	J/K.g	445000	274873
ΔH_v : boiling enthalpy	J/K.g	42040825	6392190

Calculation of the ablation depth

As the emitted laser beam has a Gaussian profile in two dimensions, the maximum ablation depth per one pulse is determined by the amplitude of the laser beam. The two dimensional Gaussian function is given by the following equation:

$$f(x, y) = A \exp\left(-\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2}\right)\right) \quad (5)$$

where A is the amplitude, (x_0, y_0) defines the centre, and (σ_x, σ_y) describe the x and y spreads of the function respectively.

In the case of the circular Gaussian function, the side lengths alongside the X axis and Y axis are equal to the radius, i.e. $\sigma = \sigma_x = \sigma_y$, as shown in Figure 3(b). Therefore, the relationship between amplitude and volume under the Gaussian function may be given by the following expression:

$$V = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) dx dy = 2\pi A \sigma_x \sigma_y \quad (6)$$

Accordingly, the amplitude may then be obtained as:

$$A = \frac{V}{2\pi \sigma^2} \quad (7)$$

Giving the standard deviation σ is approximately the radius of the laser spot $d_f/2$, i.e. $9.8 \mu\text{m}$, the ablation depths of the two cases under consideration may be calculated using the above equations:

- Case 1: 100% WC

Ablated depth A_{WC} of pure WC by a laser pulse energy of $20.3 \mu\text{J}$ is $0.4 \mu\text{m}$.

- Case 2: 100% Cobalt

Ablated depth A_{Co} of pure Co by a laser pulse energy of $20.3 \mu\text{J}$ is $0.8 \mu\text{m}$.

Ablation estimation of 15CoC hardmetal grade investigated

Assuming that WC grains have homogenous distribution in the matrix and that volume fraction rules apply regarding laser ablation of the composite studied, the theoretical ablation of the 15CoC hardmetal grade under the aforementioned laser conditions can be obtained. In doing so, volume fraction values for metallic and ceramic phases of 0.24 and 0.76 respectively, as accounted from weight fraction ones, are used. Hence, estimated values for ablated mass m_{15CoC} , ablated volume V_{15CoC} , and ablated depth A_{15CoC} of 15CoC are 3.65g , $282.6 \mu\text{m}^3$ and $0.5 \mu\text{m}$ respectively.

2.4 Frictional tests on a precision tribometer

In the tribological tests, a reciprocating tribometer (Basalt®-N2, Tetra) was implemented to evaluate the frictional performance of the surface topography variants. Table 3 shows the experimental configuration of the tribotest. Lubricant Kadio50 with kinematic viscosity 5 mm²/s was fed in the experiments. Spheres with diameter of 3 mm of an AISI 52100 (100Cr6) steel (material commonly used for manufacturing bearings) were applied as the counterpart, and testing conditions were room temperature and environment. Contact pressure may be predicted on the basis of Hertzian theory [27,28], according to:

$$p_0 = \frac{1}{\pi} \left(\frac{6FE^{*2}}{R^2} \right)^{\frac{1}{3}}$$

$$\text{where } \frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \quad (4)$$

p_0 : maximum contact pressure,

F : normal load

E_1, E_2 : modulus of elasticity of the two contacting bodies

ν_1, ν_2 : Poisson's ratio of the two contacting bodies

R : radius of sphere

The contact stress was then chosen as 1.33 GPa. Considering that grains or debris usually have effective sections about several ten microns, the applied normal pressure on them may instantly reach very high levels during the cutting processes. In some few cases, the cutting process confronts a very high load due to the discrimination of microstructure, which could be up to ten times higher. However, the probability of finding such an extreme scenario is rather low. Instead, much lower normal forces, in the range of few Newtons or less, could be expected, although they still would yield relatively high Hertzian contact stresses values (at the level of GPa). Hence, a contact stress value of 1.33 GPa was used in this study.

Table 3. Experimental parameters of tribotest conducted.

Normal Load F_N (N)	Trajectory	Frequency (Hz)	Amplitude (mm)	Cycle
1	Sinus	1	1	1000

3 Results and discussion

3.1 Inspection of the laser-produced surface patterns

3.1.1 Characterization of geometrical features

Figure 4(a,b,c) shows array and individual features of the laser-produced dimples on the surface of 15CoC material. Dimples exhibit diameter and depth of 20 μm and 0.7 μm approximately, and are evenly distributed along x- and y- axis with a distance of 100 μm and 50 μm . They correspond to dimple density values of 100 mm^{-2} and 400 mm^{-2} respectively. Dimple depth experimentally measured using LSM are within the range between 0.6 and 0.8 μm . ~~is slightly larger than the theoretical estimation of 0.5 μm . It seems that laser ablation is sensitive to the microstructural properties of the cemented carbides, i.e. the cobalt content and the geometrical features of WC grains, including size and distribution, becomes more pronounced due to the relatively high content of the cobalt in the composite. The geometrical characteristics of the WC grains, including size and distribution, might also be important factors, as supported by the finding of deeper ablation as coarser microstructures are laser treated [25].~~

Figure 4(e,d,f) shows dimensional and geometrical characteristics of the crossing-lines produced on the hardmetal surface, aimed to replicate the surface topographic features of the honed workpiece. These lines cross each other with an angle

of 45° , exhibiting a width of $20\ \mu\text{m}$ and a depth ranging from 1.0 to $1.2\ \mu\text{m}$. Compared to the dimple depth produced by single laser pulses, the groove depth is increased by the moving laser beams, i.e. the overlap of laser pulses. However, it is still difficult to predict the exact increase of the ablation depth or the ablation volume by the overlap percentage, as it can be influenced by many factors, including the accumulative effect of thermal reactions resulting from continuously moving laser pulses in short time.

Figure 4. LSM images of laser-induced surface topography: dimples with $100\ \mu\text{m}$ (a) and $50\ \mu\text{m}$ (b) intervals, and 3D image with cross-sectional analysis (c); and crossing lines with $100\ \mu\text{m}$ (d) and $50\ \mu\text{m}$ (e) intervals, and 3D image with cross-sectional analysis (f).

3.1.2 Surface integrity assessment of the laser produced patterns

Surface integrity of the produced dimples has been assessed by combined scanning electron microscopy (SEM) and focused ion beam (FIB) for cross-sectional analysis.

The shaped dimples are arranged regularly along x- and y-axis and the grooves cross each other with an angle of 45° , forming the crossing-line patterns. Figure 5 shows the dimple arrays and crossing-line pattern with intervals of $100\ \mu\text{m}$ and $50\ \mu\text{m}$, i.e. D(100) and L(50) as examples.

Figure 5. SEM images of laser-induced surface topography for (a) D(100) and (b) L(50) arrays.

One specific dimple on the surface of the D(100) sample is illustrated in Figure 6(a). A processed zone and a heat affected one (HAZ) may be discerned. The processed zone is located within a circle of diameter about $20\ \mu\text{m}$, i.e. close to the spot size of $19.6\ \mu\text{m}$ at the focus point. It should be noticed that binder is completely removed by the evaporation, while left WC grains form a skeleton structure. Some pores can be found between adjacent WC grains. The remaining molten material, together with some micro-cracks, expands from the center to the surroundings. The expansion complies with the Gaussian profile of the laser energy, from maximum to minimum levels. The

HAZ situated adjacent to the processed one just outside the referred circle, is about 2 μm in width. The binder close to the processed zone is found to be slightly molten. The material in this zone is not directly ablated by the laser beams, but rather due to thermal effects such as heat diffusion from the processed zone, as often observed in laser welding processes. Hence, HAZ may be described as a transition region between processed and non-affected zones. In general, application of an ultra-short pulse can effectively diminish or avoid the heat affected zone, as the thermal reaction is no longer dominant during laser ablation [29,30].

Figure 6. SEM image of surface topography for: (a) one dimple on D(100), and (b) cross-line intersection on L(50).

Figure 6(b) shows the intersection position of the cross-line structures on the L(50) pattern. In the processed zone, molten material was oriented along the laser scan direction and formed a layer by layer stack of 'scales'. Meanwhile, molten material spreads towards both sides and covers ablation borderlines, as marked by red lines in such figure. The measured distance between two adjacent scales is about 2.3 μm

approximately, close to the theoretical overlap gap of $2.4\ \mu\text{m}$, i.e. that corresponding to the overlap value of 87.8%.

Figure 7. SEM image of (a) scale structure and (b) laser processed zone (FIB-milled cross-section) on crossing-line pattern.

Figure 7(a) shows details of the ‘scale’ structures covering the processed zone, exhibiting irregular morphological features. Tiny cracks and pores are dotted among those randomly distributed ‘droplets’, resulting from re-solidification of the molten material. Cross-sectional analysis (figure 7(b)) proves that thickness of the recast layer is different depending on specific location regarding microstructure, i.e. thinner as it is linked to WC grains instead of Co binder, being about 500 nm for the latter. The laser pulse removed both Co and WC constitutive phases; however, as laser pulse penetrated deeper into the binder, this experienced more ablation than the ceramic phase. These findings agree with theoretical estimation that binder Co is more sensible to the laser beams than WC grains, as the former has lower melting and evaporation temperatures. Side effects induced by the thermal reaction, such as pores and cracks, are only evidenced at the recast layer. The applied fluence $6.7\ \text{J}/\text{cm}^2$ is able to carry out a moderate ablation of the 15CoC material ~~by melting and evaporating both components.~~

However, the ablation mechanism of both components, especially the evaporation of WC at the corresponding fluence, should be ratified by future experiments.

3.2 Frictional performance of different surface patterns

Figure 8 shows the evolution of the coefficient of friction (COF) as a function of the sliding length for the studied surface patterns during the tribotests. In general, all the surface patterns investigated, including the guiding stone, exhibit similar trends. At the beginning of the test (sliding distance lower than 250 mm), due to unstable contact conditions, a relative abrupt drop from relative high values was observed for COFs. For sliding distances longer than 250 mm, the evolution of COFs gradually slows down until reaching steady state conditions. This is not the case for the polished surface variant, an exception to the described response. Based on these observations, the frictional evolution of the surface patterns can be divided in two main stages: a running-in state, when the sliding distance goes from 0 to 250 mm, and a steady one, when the sliding distance ranges from 250 to 2000 mm. Accordingly, experimental findings are now discussed in terms of this classification.

Figure 8. COF as a function of the sliding length for all the surface patterns investigated.

- Frictional response during the running-in state (sliding from 0 to 250 mm)

It is noted that all the samples had a similar running-in state: COF curves first drop abruptly and then keep decreasing smoothly. This is not the case of the polished one, which instead increases gradually after the drop (yellow line in Figure 8). A hypothesis is here proposed to depict the phenomenon observed. During the running-in state, the applied oil was not evenly distributed on the contact surface yet. A higher amount of oil than the one predicted could be accumulated in the contact area. The temporary thicker oil film then leads to a decrease of COF in the running-in state. The film thickness at the contact area will finally fit the estimated value, only once the oil had been perfectly spread.

- Frictional response during the steady state (sliding from 250 to 2000 mm)

It is found that COFs achieved by the non-laser textured surfaces, i.e. guiding stone (0.14) and polished one (0.12), are higher than those obtained by the laser-textured ones,

i.e. dimple arrays (0.11) and crossing lines (0.10) for both densities. Once sliding response gets into steady state, crossing-line pattern achieved the lowest friction during the whole test, followed by the dimple arrays and then the polished surface. On the other hand, the guiding stone achieved the highest COF, as it exhibits a quite higher surface roughness values. The interval of the dimples, i.e. pattern density, has an impact on the frictional performance. For example, higher dimple density on the contact surface results in a more obvious drop of COF at the beginning of the frictional test. However, this correlation does not apply for the case of crossing-lines. In this tribological system, under non-continuous lubricant feeding, crossing line-like pattern is more beneficial to maintain a stable tribological performance, as the lubricant reservoirs are connected to each other. Thus, it becomes easier to compensate the lubricant volume as it is being consumed. On the other hand, dimples are not connected to each other. Accordingly, as certain dimples run out of lubricant, they cannot be refilled as there is not any channel-like connection among adjacent dimples; therefore, contact becomes rough and unstable. Lack of lubricant is more obvious when dimple density is higher. This viewpoint is supported by the instability occurred during the tests in the cases of the guiding stone and dimple arrays with 50 μm interval, directly related to severe changes discerned in the corresponding COF curves. They could be rationalized on the basis of the significant changes taking place in surface condition, related to either eruption of abrasive grains or dimples running out of lubricant.

The curve of the polished surface exhibits a slow increase at the beginning of the steady state, yielding then a higher value of COF as compared to those determined for the laser patterned samples. According to Hamrock and Dowson [31] a lambda value, describing the ratio of minimum film thickness divided by surface roughness, can be evaluated.

The calculation of minimum film thickness is given by:

$$H_m = 3.63G^{0.49}U^{0.68}W^{-0.073}(1 - e^{-0.68k}) \quad (5)$$

where G, U and W are the dimensionless parameters of material properties, speed and load, respectively. The lambda value of the test of the polished surface was evaluated as 0.002, indicating that the average oil film thickness is much less than surface roughness (previous fine polishing reaches a surface roughness about 0.1 μm). Accordingly, the lubrication condition can be determined as the boundary lubrication regime [32]. In this condition, asperities are involved in the contact mechanism that causes unavoidable wear [33]. As a consequence, the gradual increase of COF of the reference sample can be attributed to a transition of the boundary lubrication before reaching the steady state. However, the laser patterns, providing extra lubricants on the surface, changed the lubrication condition of the sliding test. The structure produced by laser, performing as lubricant reservoirs, can effectively increase the volume of oil storage in the contact area. The resulting lubrication condition was modified subsequently to the mixed lubrication regime due to the surface structuring, which improved the tribological performance. Therefore, lower values of friction coefficient were observed compared to the specimen without patterns.

3.3 Inspection of surface condition after the tribotest

After rubbing for 1000 cycles, sample surfaces were examined to evaluate the condition of the structure produced by laser surface treatment. In general, no measurable wear damage was found by white light interferometry. Figure 9 shows surface aspect of rubbed area for laser-textured hardmetals used as guiding stones in tribotests conducted. Along the orientation pointed by the arrow, it is hardly to observe any wear tracks. It

indicates that the crossing-line pattern remained intact after sliding test. Accordingly, the function of the laser structure (for both dimple arrays and crossing-line patterns) was still effectively operating, i.e. providing lubrication as reservoir. The results show that wear was not the main factor for explaining the difference of COF values, since no damage can be found at the contact area. It yields further support to geometrical differences referred above as main reason behind the distinct lubrication conditions.

Figure 9. LSM image of contact area after rubbing for different laser-induced patterns: dimple arrays with 100 μm (a) and 50 μm (b) intervals; and crossing lines with 100 μm (c) and 50 μm (d) intervals. The reciprocating rubbing was along the orientation pointed by the arrow.

4 Conclusions

In this paper, two types of surface patterns with different density, i.e. crossing-line patterns and dimple arrays, have been fabricated on a hardmetal grade using a nanosecond laser machining platform, aiming to be applied as guiding stones for honing processes. Frictional performance has been tested using a precision tribometer under lubricated condition and the surface integrity of these patterns have been assessed.

Regarding the fabrication of the textured hardmetal guiding stones, it is found that:

- ~~Crossing line patterns produced by laser have achieved similar dimensional and topographic features to those exhibited by the honed workpieces.~~
- ~~Laser ablation on the studied cemented carbide grade meets the theoretical calculation of ablation mass, volume and depth, on the basis of thermal reactions induced by the nanosecond laser.~~
- Both constitutive phases (Co and WC) of the hardmetal have been removed by the chosen fluence parameter; however, it turns out easier to ablate Co than WC, as more penetration has been found in the binder. In addition, the ablation of WC whether by melting or evaporation should be clarified in the future. ~~This observation complies with the theoretical estimation.~~
- Side effects, such as pores, recasting and cracks, are induced by the nanosecond laser on the processed zones. However, cracking features are found at a very shallow subsurface layer. In this regard, it is recommended to use laser with shorter pulses to reduce the thermal effects.

Regarding the tribotests of laser-textured hardmetal guiding stones, it can be concluded that:

- Compared to the conventional guiding stone, both LST patterns can effectively reduce friction during the tribological tests. Their frictional performance turned out even better than the polished surface, which obtained a mixed lubrication regime according to the calculation.
- Crossing-line patterns not only achieved the lowest COF but also a stable frictional performance. Array density of dimples has a strong impact on the frictional performance, since the isolation of those lubricant reservoirs is not favorable to maintain the lubricant film stable. In this regard, further investigation addressing lubricant distribution during the sliding movement should be carried out to verify the observation.
- Surface inspection after the tribotests suggests that surface damage was not induced by the sliding movement between the sphere and flat plat in the tests. It yields further support to geometrical differences referred above as main reason behind the distinct lubrication conditions for the laser produced patterns.

Acknowledgements

The work leading to this publication was supported by the German Academic Exchange Service (DAAD) with funds from the German Federal Ministry of Education and Research (BMBF) and the People Program (Marie Curie Actions) of the European Union's Seventh Framework Program (FP7/2007-2013) under REA grant agreement n° 605728 (P.R.I.M.E. – Postdoctoral Researchers International Mobility Experience). The authors would like to express their gratitude to Hyperion Materials & Technologies for supplying the studied materials. Finally, this contribution has also been partly funded by the Spanish Ministry of Economy and Competitiveness through Grant MAT2015-

70780-C4-3P (MINECO/FEDER).

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- Reproduction of honed surface topography on cemented carbide grade
- Satisfactory surface integrity and geometrical precision obtained by nanosecond laser
- Crossing-line patterns achieved better frictional conditions than dimple arrays
- Pattern density has a significant impact on frictional performance