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Tool surface texturing by shot peening: initial results and lessons learned

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Abstract. Abrasive and adhesive wear is a major issue in sheet metal forming processes. Although different solutions exist to reduce its impact, there is still room for progress. Surface texturing presents a big potential for tribological behaviour improvement by introducing oil retention voids on the surface. However, the economic efficiency of the surface functionalization is paramount for its implementation in industrial processes. In the present study, a widely known technology, shot peening, is applied for the creation of the voids. A grinding+polishing process is then applied to ensure a flat load bearing area. The textures are generated in 1.2379 tool steel blocks hardened at 60 HRc that emulate the tool. Different shot peening strategies are evaluated by carrying out strip drawing tests with AA5754H111 aluminium alloy sheets. Contact pressures up to 25 MPa are applied and the adhesive wear reduction potential is evaluated. First results point out the potential of this solution although the applied shot peening strategy needs to be carefully defined.

1. Introduction

All the metal forming processes, as sheet metal forming, have in common that a relative movement must exist between the workpiece and the tool in order to be able to deform the material. This leads to the generation of a friction force that opposes to this relative movement. The generated frictional force causes wear on tools and increases the total energy required to complete the process. It is estimated that around 30% of the energy generated globally is lost due to friction, so developed countries allocate approximately 5% of their GDP to develop strategies to minimize friction [1].

The most common method for reducing friction in processes involving relative velocity between the workpiece and the tool is the proper use of lubricant agents. Lubrication not only helps to reduce tool wear and the force required to complete the process, but also contributes to achieving better geometrical and surface tolerances [2].

It has been observed that liquid lubricant in conjunction with surface textures helps to reduce the coefficient of friction even more compared to the use of lubricant in the absence of textures [3, 4, 5]. However, these textures need to be within certain parameters to prevent friction from increasing instead of decreasing.

In terms of the geometry of the textures, it has been observed that the longitudinal channels perpendicular to the sheet's direction of movement have shown the greater reduction in the coefficient of friction, while longitudinal channels parallel to the sheet's direction of movement have demonstrated the greater increase in the coefficient of friction, as can be seen in the studies conducted

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by Costa et al. [6] and Sulaiman et al. [5]. However, the most versatile texture is the one with the pattern of dimples, as its geometry doesn't favour one direction over the other in the reduction of the coefficient of friction.

Regarding to the geometric dimensions, based on the studies conducted by Vorhold et al. [7], Costa et al. [6], and Saeidi et al. [8], it can be concluded that the diameter of the texture should fall within the range of 20 to 100 µm. If the diameter is too small, it leads to an increase of the coefficient of friction, and if it's too big, it doesn't reduce the coefficient of friction as much as the optimal diameter [7, 8]. So, a diameter of 50 µm is the most suitable choice.

For the depth of the texture, on the works realized by Godi et al. [1], Saeidi et al. [8], Sulaiman et al. [5], and Hazrati et al. [9], it has been seen that depth less than 7 µm have shown a coefficient of friction similar to the absence of texture, and greater than 10 µm have not shown significant improvement compared to 10 µm. Therefore, a depth of 10 µm has been considered the most appropriate one.

With respect to the textured area fraction, it has been observed in the studies conducted by Hazrati et al. [9] end Sulaiman et al. [5] that the greatest reduction on the coefficient of friction is achieved with a textured area fraction around 20%. It is also worth mentioning that high textured area fraction (higher than 25% for the study conducted by Hazrati et al. and 40 % for the study conducted by Sulaiman et al.) can lead to an increase of the coefficient of friction. Furthermore, Hazrati et al. have observed that very low textured area fractions (lower than 15%) can also lead to an increase of the coefficient of friction compared to the untextured tools.

Traditionally technologies such as laser texturing, micro-machining or chemical machining have been applied to the texturing of surfaces. Even though good results have been reported, the texturing or large areas is not industrially feasible nowadays. In the presence study, a more industrial approach has been carried out with the purpose of evaluating textures made by shot peening strategies. In order to ensure an appropriate load bearing area, surfaces have been polished after the texturing. The main driver of the analysis is the industrial readiness of shot peening technologies and the possibility of directly apply them in tool texturing. This way, dimples of different sizes have been created by shot peening and the response of the different textures has been evaluated by strip drawing tests with AA5754H111 aluminium alloy sheets. Contact pressures up to 25 MPa are applied and the adhesive wear reduction potential is evaluated.

2. Materials and methods

2.1. Materials and lubricants

Commercial-grade aluminium AA5754H111 alloy sheets with mill finish surfaces and 1.5 mm thickness have been used for the study. Mechanical properties were tested, and the results are shown in Table 1. Table 1 also shows the surface roughness of the tested aluminium sheets that has been measured with a 2D tactile Mitutoyo roughness meter following the DIN EN ISO 4288 standard. The chemical composition of the aluminium sheets is given in Table 2.

Table 1. Mechanical properties of tested material AA 5754H111.

Property	Symbol	Unit	Value
Yield stress	Rp0.2	MPa	124.9
Yield strength	Rm	MPa	216.3
Total elongation (A50%)	A50	%	23.96
Average roughness	Ra	µm	0.292
Peak roughness	Rz	µm	1.3
Root mean square roughness	RSM	µm	33.26

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Table 2. Chemical composition of tested material AA 5754H111.

A5754 H111	Mg	Fe	Mn	Si	Cu	Ti	Cr	Zn	Pb
	2.800	0.330	0.270	0.120	0.020	0.100	0.009	0.008	0.004

The strip drawing test blocks that emulate the drawing tools are made of 1.2379 steel with a contact area of 30 x 50 mm and a hardness of 60 HRC. Table 3 shows the chemical composition of the 1.2379 tool steel blocks.

Table 3. Chemical composition of tool steel 1.2379.

1.2379	C	Cr	Mn	Mo	P	S	Si	V
	1.550	11.530	0.320	0.780	0.025	0.004	0.470	0.780

And the lubricant used in the strip drawing test is Walter Zepf Schmierungstechnik AL-200WL; with a kinematic viscosity of 90 mm2/s. The used lubricant amount is 3 g/m^2.

2.2. *Blocks surface texturing*

First, the blocks have been grinded using a tangential griding machine to ensure that the surface is completely flat. As a result of the grinding, at the borders of the flat surfaces sharp edges have been created. To remove these sharp edges, the radius of the edge of the tools has been restored by the use of different abrasive stones.

Once the contact surface of the blocks is completely flat, and the sharp edges have been eliminated, the tools have been textured by shot peening. This texturing process allows the generation of dimple shaped texture, which consist of a bunch of pronounced peaks and valleys and is easily applicable in an industrial environment.

The desired texture should consist of a plane sustaining surface with dimples in it, so in order to turn the peaks into plateaus generating a bigger sustentation surface, the textured tools have been manually grinded with P1000 grain silicon carbide abrasive paper after their texturing. After the grinding, the tools have been polished with 6 µm size diamond particles. This way, the roughness of the sustentation surface is reduced to a mirror like roughness to eliminate the effect of the sustentation surface roughness on the test.

As a result of the previous procedure, three different surface topographies have been generated. A reference topography, with no texture, that has only been polished achieving a surface roughness Ra of 0.01 µm. Texture A, that has been textured and manually grinded during 3 minutes with a P1000 grain silicon carbide abrasive paper after the texture application, and texture B that has been textured and manually grinded during 12 minutes with a P1000 grain silicon carbide abrasive paper after the texture application. The three surfaces have suffered a final polishing with 6 µm size diamond particles.

During all this procedure the 2D roughness values and the 3D topography evolution of the surfaces have been traced. For measuring the roughness, a 2D tactile Mitutoyo roughness meter has been used, following the DIN EN ISO 4288 standard. For the area 3D surface topography measurement, a Sensofar Senox profilometer has been used, and the data obtained has been processed with the SensoMAP software.

2.3. *Strip drawing test*

Strip Drawing Test (SDT) has been used to analyse the response of the textures with respect adhesion phenomena. This method allows to emulate the contact between the sheet metal forming tool and the workpiece material under controlled conditions of pressure and velocity. This way, the movement of the strip generates a tangential fiction force that combined with the applied normal force allows the calculation of the coefficient of friction using Coulomb's friction force equation.

As mentioned before, the tests have been carried out in order to compare the response of the three different surface finishes. The conditions at which the strip drawing tests have been carried out are shown in Table 4. During the set up of the testing, Fujifilm's Prescale Films have been used in order to verify an homogeneous pressure distribution in all the contact area between the sheet and the blocks.

Table 4. Conditions at which Strip Drawing Tests have been carried out.

Replicates	Contact pressure	Lubricant amount	Drawing speed	Sliding distance	Tool surface finish	Sheet rolling direction
6	25 MPa	5 g/s2	10 mm/s	150 mm	Mirror polish (Ra 0.01 µm) and shot peened (textures A and B)	Parallel to the strip movement

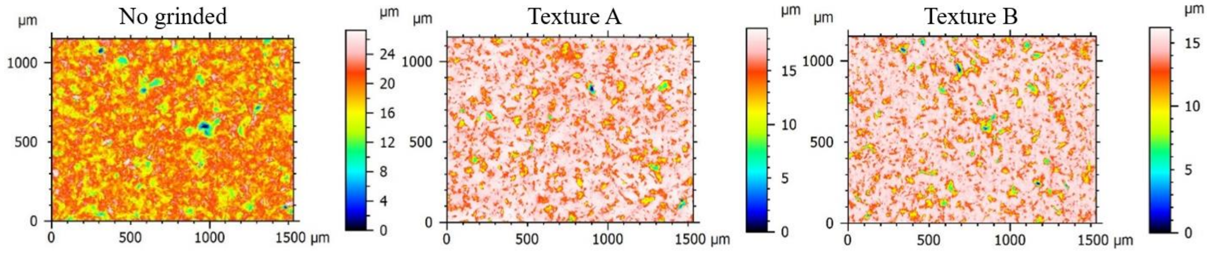
2.4. Post test surface analysis

After the realization of the strip drawing tests, an analysis of the surfaces of the blocks has been carried out. For the surface composition analysis, a SEM CI Nova Nanosrm 450 has been used, and the data obtained has been processed with the Aztec3.3 software.

3. Results

3.1. Surface texture

Figure 1 shows the evolution of the surface of the textured blocks. Figure 1a shows the surface after the texturing treatment. It can be observed that the surface is a combination of peaks and valleys what correlates to a surface textured by shot peening. As mentioned before, and in order to generate flat sustentation areas, Figure 1b shows the surface after a manual grinding process where the peaks have been eroded generating flat areas. And finally Figure 1c shows a surface that has followed the same approach as the one in Figure 1b but with the application of a longer manual griding process as explained before. It can be observed that the application of the manual griding process generates a sustentation area in both surfaces being this area greater in the surface that has been manually grinded for a longer time where larger areas colored in white are observed.



a) b) c)

Figure 1. Surface topography: after texturing (a), after texturing and manually grinding for three minutes (b) and after texturing and manually grinding during twelve minutes (c)

In order to make a more quantitative evaluation of the textured surfaces, Table 5 presents the most representative 3D roughness values for each of the surfaces. It must be stated that during the strip drawing tests the sheet is clamped between two blocks, and for this reason the table presents the results of both blocks for each kind of texture: texture A, texture B and reference blocks that were polished achieving a surface roughness of 0.01 µm.

Table 5. Topographical parameters of the textured surfaces.

		Vvv (0=80)	Sdr (%)	Sa [µm]	Sq [µm]
Textured but not grinded	Mean	0.427	25.606	2.177	2.855
	Deviation	0.020	0.272	0.133	0.168
Texture A	Mean	0.407	9.557	1.318	1.833
	Deviation	0.037	0.063	0.008	0.034

Texture B top	Mean	0.377	6.347	1.047	1.538
	Deviation	0.040	2.099	0.206	0.239
Mirror polish	Mean	0.006	0.002	0.038	0.048
	Deviation	0.0006	0.0009	0.0012	0.0021

3.2. Coefficient of friction
For each couple of blocks a total of six strip drawing tests were carried out. As mentioned in Table 4, the tests were carried out at a contact pressure of 25 MPa, at a sliding velocity of 10mm/s and the sliding distance at each test was 150mm. Figure 2 shows the results achieved when computing the coefficient of friction (COF from now on). First of all, it can be observed the high repeatability of the tests. The surface finish that offers the lowest COF is the mirror polish surface with values about 0.02. On the other hand, in the case of the texture surfaces, both of them offer higher values of COF being texture A the one offering the highest COF. Furthermore, the signal obtained during the testing of texture A surface presents a high scattering which is typical of stick-slip contact mechanism. However, and as it will be shown later, no galling or stick-slip phenomena was observed in texture A blocks after the testing. The reason for this noisy signal is the topography of the sustentation surface in texture A compared to texture B. A sustentation surface deeper analysis was carried out and it was observed that due to the shorter polishing time texture A had more and severe peaks in the sustentation area.

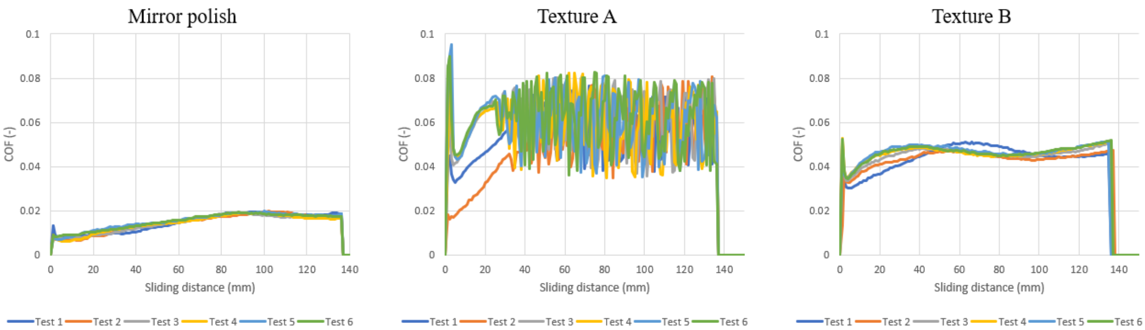


Figure 2. Coefficient of friction obtained for the different blocks surface condition.

3.3. Tool wear
After the realization of the strip drawing tests, an analysis of the surfaces of the blocks was carried out. The final situation of the blocks after the realization of the previous mentioned 6 tests for each block can be observed in Figure 3. For the sake of simplicity, only lower blocks are shown.

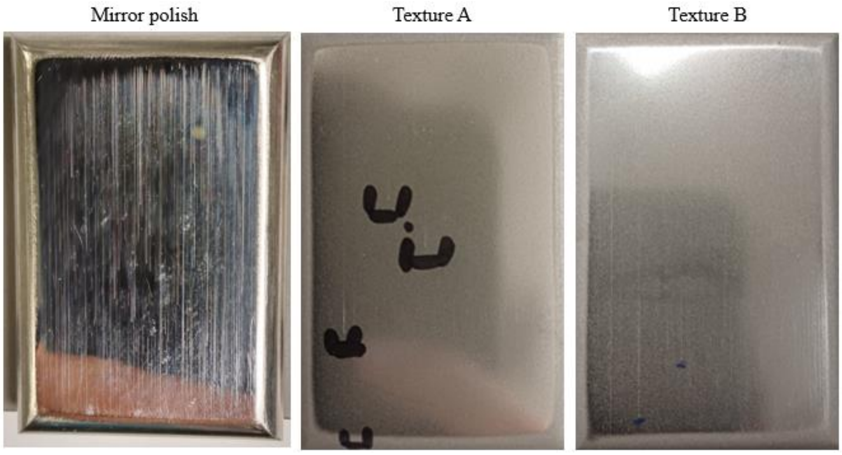


Figure 3. Blocks surfaces after the realization of the strip drawing test.

It can be observed that the mirror polished block is the one that has shown the greatest wear. It must also be stated that even there are many longitudinal traces all over the surface, the depth of these traces is not higher than 0.2 µm. However, and since the initial polish of the surface makes its roughness to be very low, the longitudinal traces are very easily observed.

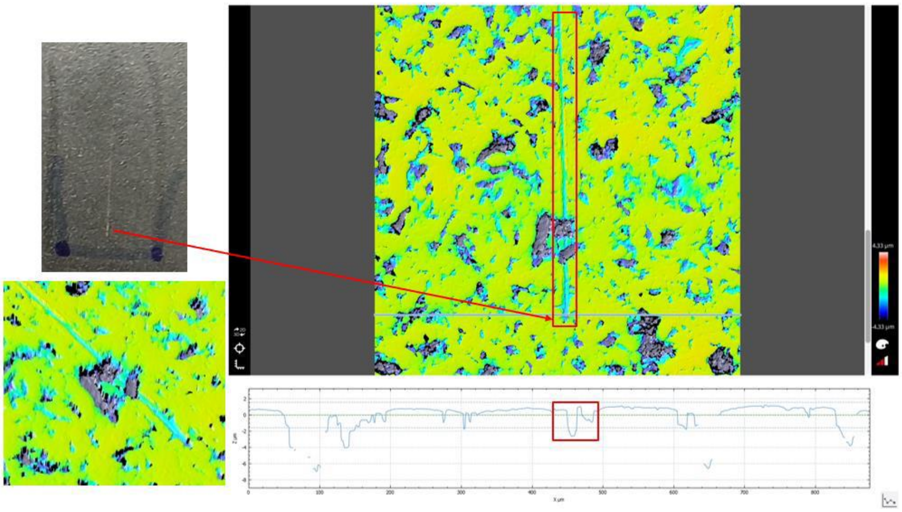


Figure 4. Detail of a longitudinal wear trace observed in a textured surface. Measurement carried out at surface with texture A.

On the other hand, the textured blocks do no present many traces or signs of wear at their surfaces. After analyzing the origin of the longitudinal wear traces, it has been observed that the traces start in areas where ceramic grains used during the texturing of the surface were initially embedded (see Figure 4). So the hypothesis is that the ceramic grains are embedded during the texturing, and when realizing the strip drawing tests, they are detached from the surface creating a wear trace during all the travel until leaving the surface of the block.

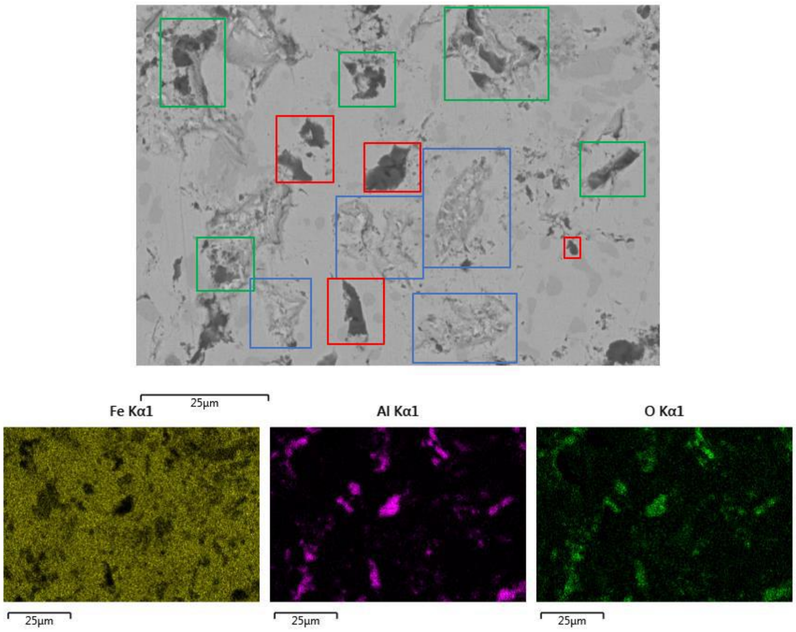
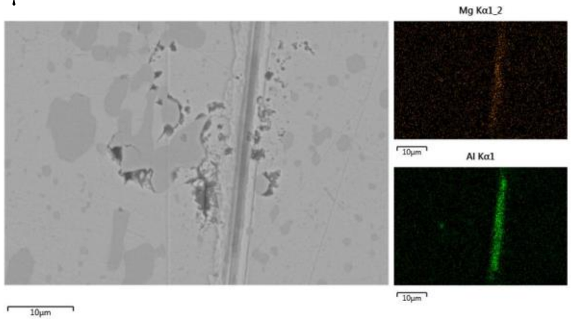
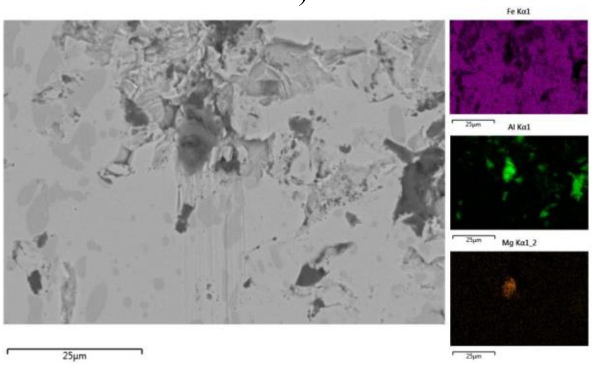


Figure 5. SEM analysis of textured surface after the texturing and manual grinding process. Squares in red represent ceramic grains flushed in the sustentation surface. Squares in green represent ceramic grains at the bottom of the texture valleys. Squares in blue represent valleys without the presence of ceramic grains. Measurement carried out at surface with texture B.

In order to verify this hypothesis, the composition of one of the textured surfaces has been obtained in a SEM CI Nova Nanosrm 450 before the realization of the strip drawing tests. It must be noted at this point that the material used during the texturing of the surfaces has been alumina (Al2O3). This way, by looking to the presence of these elements, the next conclusions have been extracted as shown Figure 5. Traces of alumina have been found at the textured surface. Some of the alumina traces are found at the bottom of the valleys, where they are not detrimental. However, some other traces of alumina have been found flushed at the sustentation surface. These traces are assumed to be the ones that during the strip drawing test realization detach from the sustentation surface and generate longitudinal wear traces in the textured surfaces. Different longitudinal traces have been measured and their height is lower than 2 μm in all the cases.



a)



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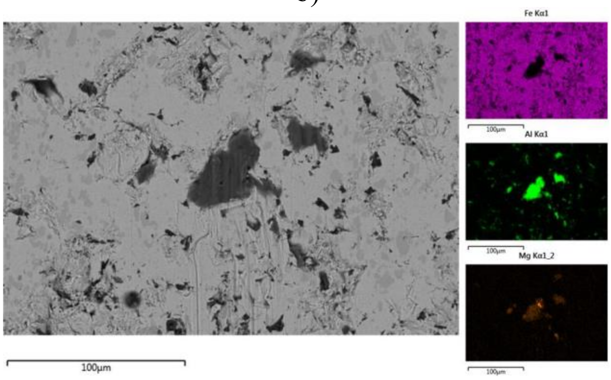

c)

Figure 6. Surface composition analysis of the different blocks by SEM analysis. Results from the mirror polished surface block a), results from the textura A surface block b) and results from the textura B surface block c).

And finally it has also been analyzed if there has been any transfer of aluminum from the sheets to the blocks. For doing so, a surface composition analysis of the different blocks has been carried out using a SEM CI Nova Nanosrm 450 after the realization of the strip drawing tests. Figure 6 shows the results of this analysis. It can be observed in Figure 6a that aluminum and magnesium traces have been found in the mirror polish surface after the realization of the tests. This means that aluminum transfer phenomena has taken place from the aluminum sheets to the blocks. On the other hand, in the case of the texture blocks, it has been observed that although aluminum and magnesium transfer has also been taken place from the aluminum sheets to the steel blocks, the aluminum has concentrated in the valleys of the texture not finding any aluminum and magnesium traces in the sustentation area. Anyway one question arises here at this stage and is the how the transfer of the material would affect the overall performance of the textured surfaces for longer periods of contact time.

4. Conclusions

In the present work a combination of shot peening technologies and post-polishing techniques has been carried out in order to generate functional anti-galling surfaces. The main objective was to develop surface with valleys able to retain lubricants combined with flat sustentation areas able to support the contact between the surfaces. Next conclusions have been observed:

- Even if no aluminum transfer to the sustentation area of the textured surfaces has been observed, traces of aluminum have been detected in the valleys of the textured surfaces.
- A deeper analysis of the transfer mechanism and the impact in the long term contact periods is necessary to understand the severity of such phenomena.
- Furthermore, wear traces generated by the detachment of alumina particles used during the shot peening process have been observed after the strip drawing tests.
- As a result, it is proved that ceramic particles can not be used for the generation of the textures by shot peening and new analysis will be focused in the texturing of the surfaces using metallic particles.

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