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Laser texturing of imprinting dies using nanosecond pulses. Applications for automotive industry.

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Abstract. The machining response of imprinting dies when subjected to nano – second laser processing is investigated in this research. Laser texturing of different patterns were conducted in order to improve the surface functionality of metal sheets obtained during the imprinting process. The contribution of the material ejected from the inner crater and re – deposition on the substrate dominates the surface profile after the laser texturing process. In particular, when laser texturing of “open” structures (overlapped pulses) is considered, the surface profile did not match properly with the optimal structuring previously designed. The experimental results concerning to imprinting trials showed that the roughness transfer capability reached maximum values (~ 50%) when high contact pressure conditions were considered. This research shows the potential of the laser texturing technique in the field of micro-structuring deterministic patterns on imprinting dies, leading to the production of functionalized metal sheets for the automotive industry.

1. Introduction

Due to their unique technological properties, difficult – to – machine materials, like ceramics, titanium alloys, carbide and hardened steels, have attracted considerable interest for many years in the field of steel production and mould making for automobile and aeronautical industries. Therefore, it is important for a range of current and potential new application areas to develop new micro – manufacturing technologies, which provide excellent productivity and cost efficiency with good surface finish and integrity. The application area considered in this study is the surface modification of dies to improve the surface functionality of metal sheets obtained during the imprinting process. This functionality will be directly connected to the visual appearance of the painted steel sheet surfaces. Several studies have been published in the past in which the influence of the steel sheet surface on their appearance after painting is described [1], [2], [3]. From the literature, it is found that this phenomenon is mainly related to surface texture parameters including roughness and waviness. Traditionally, the roughening of mill rolls and coining dies has been carried out by shot blasting (SB) and Electrical

Discharge Texture (EDT) technologies. These technologies are characterized by the production of a fine stochastic surface roughness [4]. In this particular case, it has been found that the higher the roughness, the better the formability, but the poorer the appearance after painting. With the aim of producing a deterministic roughness, other technologies such as Laser Surface Texturing (LST) and Electron Beam Texturing (EBT) have been applied world-wide [5], [6]. Steel surfaces obtained by these technologies showed the best paint quality, related to the lack of waviness characteristic of the deterministic texturing [7].

Laser Surface Texturing (LST) due to its promising peculiarities (fast processing time, clean to the environment, no need of vacuum, control of the shape and size of the ablated micro-textures by tuning the characteristic of the laser spot) is probably the most advanced technique developed for surface texturing of mechanical components. As it was stressed above, textured rollers are commonly used for the manufacturing and processing of flat-rolled steels in the automobile industry to increase the grip on the steel sheet (improving friction between roller and sheet to facilitate the smooth rolling process) and impart a matte finish to enhance formability and improve the adhesion and appearance of paint. Other benefits that result from the textured strip include the quality enhancement of parts due to less galling and scoring during production as well as elimination of metallic lubricant coatings such as Titanium Nitride (TiN) or copper plating, frequently used in these dynamic components. High power CO_2 lasers have been traditionally used to create these deterministic patterns on steel mill rolls. The thermal effects of the CO_2 laser radiation on the material results in the formation of a crater and a raised rim of metal around the crater. These thermal effects on the material are higher than those observed when short pulsed lasers are used for micromachining of components. Additionally, CO_2 laser technology is about then times more expensive than short pulsed lasers (nanosecond pulsed lasers). Hence, the analysis of the effect of nanosecond laser pulses on the material integrity of imprinting dies is required to reduce thermal stresses on the die, as well as the production costs of textured steel sheets.

During the LST process, the laser beam hits the workpiece in an ordered sequence of pulses characterized by the pulse length and repetition rate (frequency). This allows the processing energy to be released in relatively short time intervals. Additionally, the laser radiation can be focused on a spot with very small dimensions, from sub micrometer to 50 μm, which results in a significant energy density (fluence) in the spot area. Therefore, an extremely high density can be achieved in the laser – material interaction zone which explains the capability of laser texturing to process materials that are difficult to machine. In addition, not only this high fluence but also high values of the scanning speed are imperative to identify laser texturing of engineering materials as a viable alternative to conventional machining processes and EBT. When pulsed laser texturing is performed, the process of ablating a material takes place within the pulse. Figure 1 shows the process conditions for ns laser pulses. The absorbed energy from the laser pulse melts the material and heats it to a temperature at which the atoms gain sufficient energy to enter into a gaseous state. There is enough time for a thermal wave to propagate into the material. Evaporation occurs from the liquid state of the material. The molten material is partially ejected from the cavity by the vapour and plasma pressure, but a part of it remains near the surface. After the end of a pulse, the heat quickly dissipates into the bulk of the material and a recast layer is formed. Thus, a compromise between high removal rates and the resulting surface integrity and quality should be taken into account when selecting the most appropriate ablation regime for performing laser texturing. Therefore, for optimal machining results a proper match between the laser parameters and the material should be achieved.

The focus of the research reported in this paper is on investigating the laser texturing process of imprinting dies, considering different deterministic surface patterns that were previously established by theoretical methods. The aim of this study is to evaluate the precision and surface quality reached by means of laser texturing technology as well as the roughness transfer capability during the imprinting process when different steel sheets and process set up were considered.

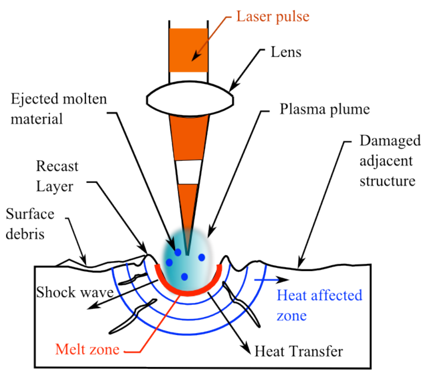

Figure 1: Nanosecond (ns) pulsed laser ablation [8].

2. Material and Methods

Imprinting dies were made of commercially available medium-alloyed cold work tool steel called Uddeholm Rigor®.This steel has an excellent combination of wear and chipping resistance and hardenability well suited for modern heat treatment processing. The dimensions of the imprinting polished disks are 70 mm diameter and 25 mm thickness. Surface roughness parameters were measured by means of a profilometer (Perthometer M2; Mahr GmbH, Göttingen, Germany). The values of these parameters are shown in Table 1.

Material	Hardness [HRc]	R_a [μm]	R_z [μm]	R_t [μm]	R_{pc}[/cm]
Uddeholm Rigor	63 HRc	0.017	0.14	0.21	~0

Table 1: Bulk and surface roughness parameters of the imprinting dies.

Low strength high – formability galvanized steel sheets [TATA Steel] were considered for the imprinting trials. The dimensions and surface roughness parameters of these metal sheets are shown in Table 2

Material	Dimensions [mm] (length x width)	Yield Stress [MPa]	R_a [mm]	R_{pc} [/cm]
(IF-DX56)	66x66, 66x50, 66x40, 66x30, 66x20	125	0.5	20

Table 2: Dimensions and surface roughness parameters of steel strips used during the imprinting process

Additionally, small circular samples of 20 mm diameter (coins) were considered to evaluate the effect of the pressure in different locations of the imprinting die. The press tests were performed in a simple TUWI compression rig, with a load capability of 100 tonnes. During the experiments, the contact pressure is tuneable by varying the load and/or sample size.

For surface modification of the imprinting dies we used a nanosecond pulse fiber laser which characteristics are summarized in Table 3. This laser is integrated into a micromachining workstation. Sample position can be selected with lateral resolution in µm-range and a depth control of roughly 10 nm through a machining table with X/Y axes and Z positioning system.

	40 W pulsed fiber laser (SPI lasers, UK)
Wavelength (nm)	1070
Average maximum power (W)	40
Beam Quality M^2	2.7
Fiber optic length (m)	3
Maximum peak power (kW)	18 @ 9 ns
Maximum pulsed energy (mJ)	1,3 @ 250 kHz
Pulse repetition rate (kHz)	30 - 250
Pulse duration (ns)	9 - 250
Power stability (%)	2

Table 3 – Main technical characteristics of the ns fiber laser for texturing of imprinting dies.

The material response to laser – machined regions was assessed using scanning electron microscopy SEM (Carl Zeiss XB1540). The crater depths and diameters were measured by confocal microscopy (Dektak 8, Veeco).

3. Results and discussion

3.1 Laser texturing of imprinting dies

Figure 2 shows the confocal and SEM images of a matrix of micro – dimples of ~ 60 μm diameter produced in the Uddeholm Rigor imprinting die by considering a specific laser pulse duration (τ=250ns), frequency (f=30 KHz) and Power (P=15.8 W). The image shows that the material was partially ejected by the vapour and plasma pressure and then re – deposited on the substrate. Part of the ejected material remains around 10 μm for all the dimples. Crater depth was fixed to 20 μm by increasing the number of laser texturing events over the same surface area.

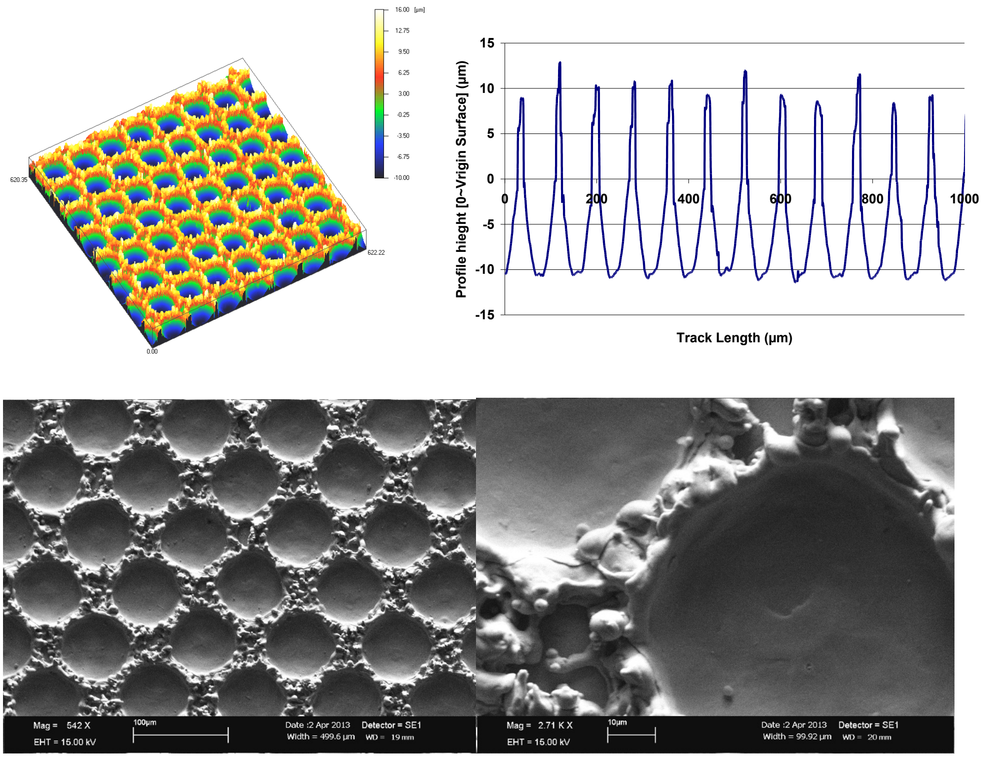

Figure 2: Confocal and SEM images corresponding to the laser texturing of the imprinting die considered in this work.

Taking into account the individual crater profile measured by confocal microscopy, different surface patterns were defined with the aim to produce functionalized surfaces (formability, wettability, paint appearance etc...) that contain "open" and "closed" topographic features. The process parameters selected for a single crater was τ=170 ns, f=41 KHz, speed (v =3.28 m/s), P=19 W and a four-time repetiton of laser shots over the same area. Figure 3 shows the confocal image of a trench of craters on the imprinting die by considering those laser process parameters. Figure 4 shows three kind of surface textures designed by changing the offsets and overlaps between individual craters, considering the same values of the crater depth and diameter than those showed in Figure 3. Additionally, two types of texturing setup was considered and described in Figure 4 (a). These patterns were designed to improve the visual appearance of the painted steel sheet surfaces after the imprinting process.

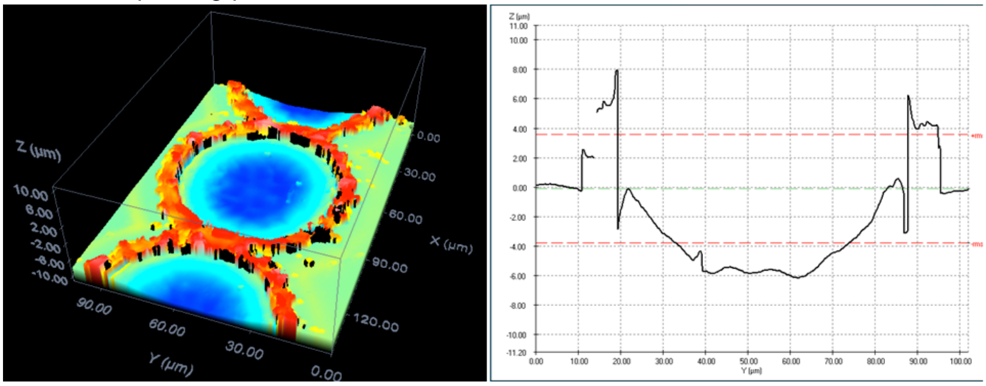

Figure 3: Confocal image corresponding to a trench of craters using the optimal laser parameters for the texturing trials.

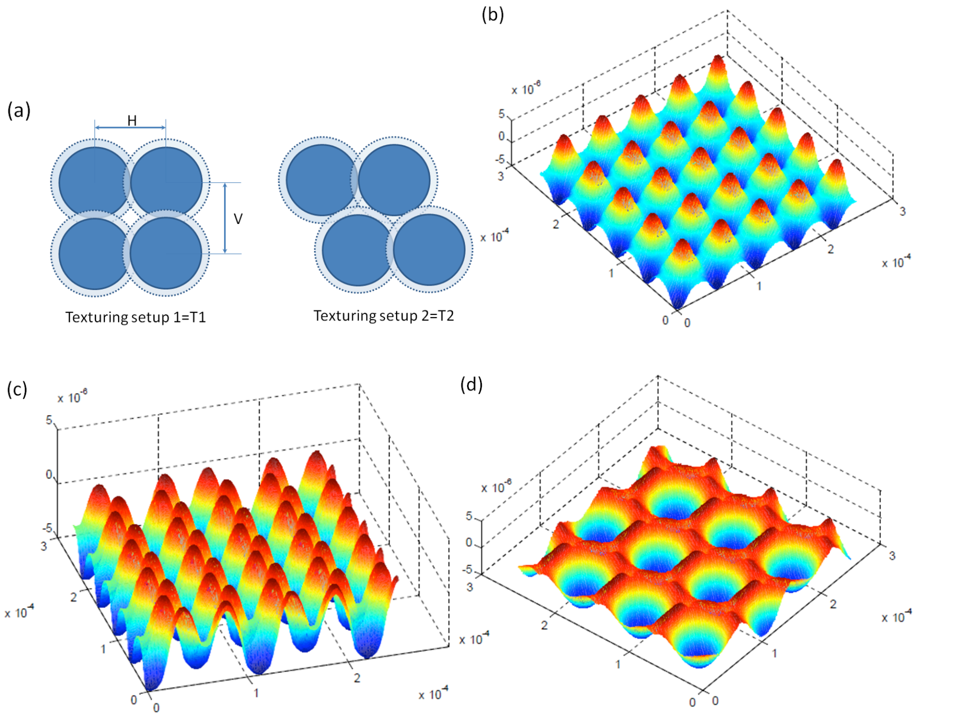

Figure 4: Surface texturing designs: “Open” structures (b,c), “close” structures (d).

Figure 4 shows the two kind of topographical features considered in this research: “Open” structures, characterized by a different density of hillocks (Figures 4 (b) and (c)) and “close” structures, characterized by a matrix of craters of micro – dimples (Figure 4 (d)). Laser texturing of the imprinting die was performed considering the laser parameters identified in Figure 3 and the offsets and overlaps cited in Figure 4. Figure 5 shows the SEM images of single pulse craters produced in Uddeholm Rigor by selecting these process parameters. From this figure, it is clear that, in the case of the “open” structures, where a crater overlapping was considered (Figures 5 (a) and (b)), the surface profile did not correspond to the optimal (geometric) design shown in Figure 4 (b) and (c). In the case of “close” structures, however, the laser textured surface matches the optimal design presented above (Figure 4(d)) One possible explanation to this finding evolves the effect of the remelted material of a single event (crater) on the profile of the following event (overlapped crater). According to this, the dynamics of the molten pool depends on the surface topography of the substrate which changes when a trench of overlapped craters is considered. Additionally, the behaviour of the material ejected from the inner crater also depends on the surface characteristics of the substrate. These effects were not considered directly during the development of the optimal designs presented in this work.

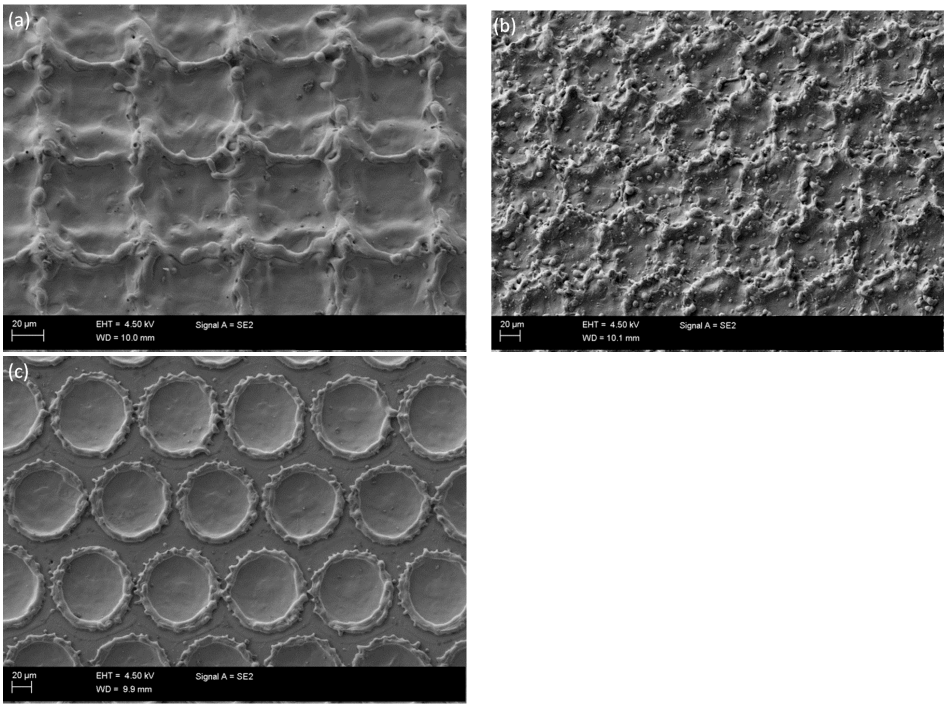

Figure 5: Laser texturing results on the imprinting die.

3.2 Imprinting trials

For the imprinting trials, a die with the texturing patterns shown in Figure 3 was considered. In order to analyzed the effect of the pressure effects on different locations of the imprinting die, a set of trials were done by considering four circular steel (IF-DX56) samples of diameter = 20 mm (coins) placed in different sites of the die as shown in Figure 6. The experimental setup is also shown in this figure and the pressure value considered in these tests was 125 MPa, corresponding to the yield stress of the substrate material. Figure 7 shows the confocal images corresponding to the roughness transfer capability in a surface area located at the central part of the circular samples (marked as bold circles in Figure 6). From these images, it is clear that the transfer capability during the imprinting process depends on the location of the steel sheet sample. In order to evaluate this effect, Figure 8 shows the surface roughness parameters of the metal sheets obtained after the imprinting process. The effect of the sample location on the roughness transfer capability is clearly noticed in this figure: In the case of Ra, the transfer capability is lower than 50% and for Rz, this values are in the range between 50 and 65 %, depending on the sample location. For RPc, however, this parameter reached higher values in the steel coins after the imprinting, with a maxima reached, before reducing tending to the peak count of the imprinting die. This result indicates a summation of surface peaks followed by a suppression of the peaks with increasing roughness transfer.

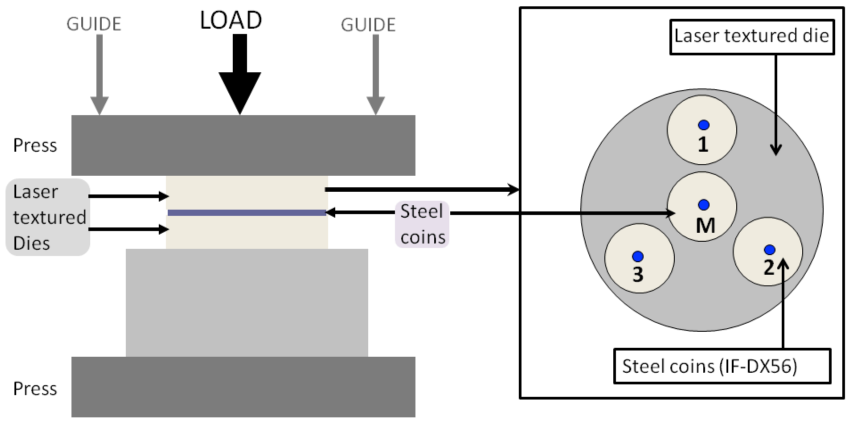

Figure 6: Experimental setup for imprinting trials considering four steel coins placed in different sites of the textured die.

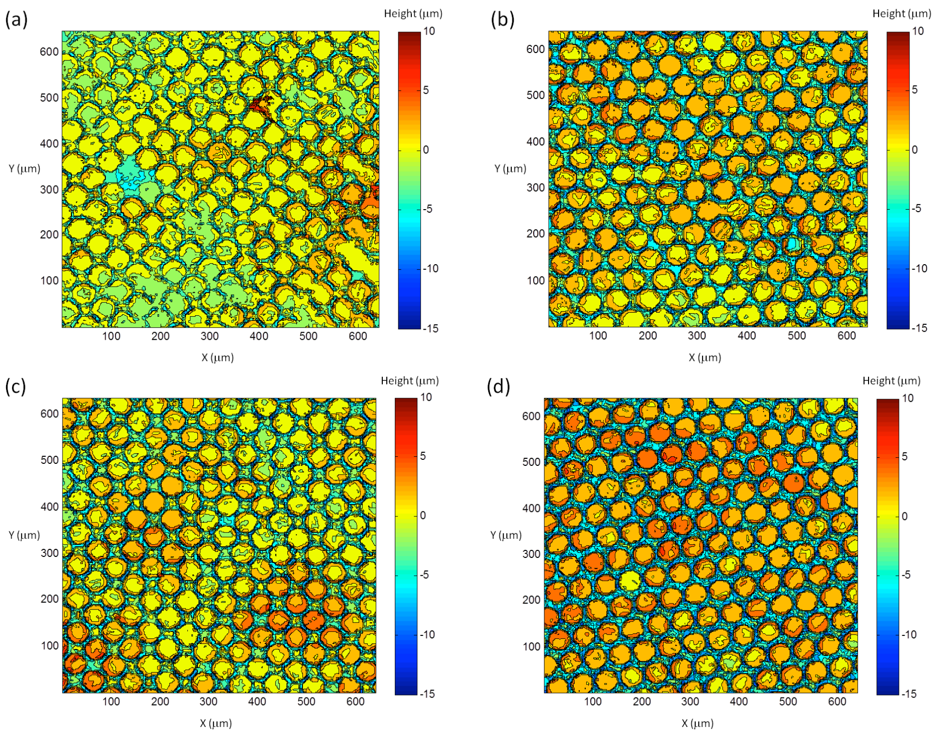

Figure 7: Confocal images corresponding to the imprinting trials on steel coins.

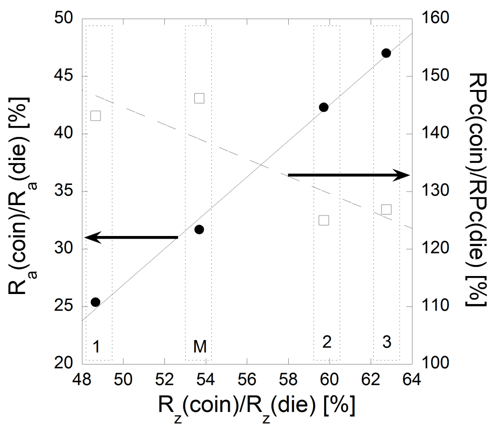

Figure 8: Surface roughness dependence of steel coins after imprinting trials on the sample location.

The roughness transfer capability was also analyzed by considering 5 DX56 steel strips of different sizes, as given in Table 2 resulting in contact pressure ranges between 200 and 800 MPa were considered during the imprinting trials. Figure 9 shows that the roughness transfer capability reached similar values than those observed by considering steel coins (Figure 8) over a wide range of contact pressure conditions.

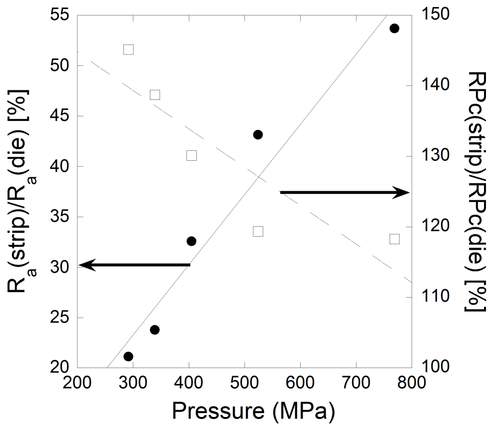

Figure 9: Surface roughness dependence of steel strips after imprinting trials as a function of the imprinting pressure.

Further investigations are in progress to analyze the forming capability, wetting behavior and visual appearance of (painted) steel sheets textured surfaces alongside the influence of geometric changes in the surface design on these functional aspects and roughness transfer properties.

4. Conclusions

In this paper, we have reported experimental data corresponding to laser texturing of dies to improve the surface functionality of metal sheets obtained during the imprinting process.

- Laser texturing with short pulses (in the range of nanoseconds) is characterized by a matrix of craters (single and overlapped craters) where the thermal contributions (material ejection and re-deposition) dominate the final surface profile.

- The quality of the patterns is directly connected to these thermal effects. In particular, the effect of the remelted material on the final surface topography is more relevant when “open” structures (characterized by a crater overlapping) were considered.

- Imprinting of circular steel coins placed at different locations of the die reveals that the roughness transfer capability depends on the coin location. When different steel strips are considered, as well as different pressure values, the roughness transfer capability reached maximum values (~ 50%) for high contact pressure conditions.

In summary, the investigation shows that laser texturing with nanosecond pulses is a promising technique for micro-structuring imprinting and stamping dies. The micro - machining of a deterministic pattern with high precision can be achieved, enabling the production of functionalized metal sheets for a wide range of applications.

5. Acknowledgments

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