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Efficient manufacturing of large scale structured 3D forming tools through combination of short and ultra-short-pulsed laser processing

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Abstract
Surface functionality is an increasing and crucial factor for the success and acceptance of a product. Structured surfaces are currently used for example in combustion engines for friction reduction or in LED lights for optimized lighting efficiency. Furthermore, not only technical properties but also optical and haptic functions can be created by surface structuring. Especially in the area of consumer products, these functions determine essentially the product quality. Currently there is a shift in automotive interiors from classical leather grain to technical surfaces.
Currently used manufacturing processes like photochemical etching are limited in precision (manual preparation and execution) and in flexibility (limited design). This paper investigates the possibility to create structured surfaces with a combined laser ablation process using short and ultra-short laser pulses.

Surface functionality, surface structuring, 3D free-form surface, ultra-short pulses, high precision, roughing, finishing

1. Introduction

Surface functionality is an increasing and crucial factor for the success and acceptance of a product. Especially in the area of consumer products, customers demand aesthetic designs that are unique to see and touch, and sometimes even enhanced with haptic features. Currently there is a shift in automotive interiors from classical leather grain to technical surfaces [1].

Manufacturing these structures in mass production is based on replication processes (e.g. injection moulding). Today structured interior surfaces are made by photochemical etched tools. This manufacturing process chain is characterized by many manual processing steps. To realize designs with subtleties on different levels the process steps have to be repeated several times. The precision and quality of the final product is extremely determined by the expertise of the employees due to the manual process steps [2]. Because of these limitations the manufacturing of tools by ablation with nanosecond (ns) laser pulses is currently competing with photochemical etching on an equal level in processing time and in quality [3]. The pulse duration of about several ns (10^{-9} seconds) leads to material removal with a significant amount of melting, which results in ablation depth of several micrometres. However, losses of precision and worse surface quality have to be considered [4].

In contrast to that, the use of ultra-short picosecond (ps) laser pulses with a pulse duration of 10^{-12} seconds is characterized by high peak intensities (> 10^{12} W/cm²) that lead to a direct vaporization of the material with minimal thermal damage. Hence high precision and even new design features are enabled.

This paper investigates the possibility of combining these two laser ablation processes. To increase the efficiency of the manufacturing process, short laser pulses with a pulse duration of nanoseconds pretreat the work piece and remove a large amount of the entire volume. A second laser process using picosecond pulses ablates the remaining volume and finishes the surface with design highlights.

2. Experimental setup

2.1. Machines and material

The experimental setup currently allows a combination of both laser ablation processes just on two different laser machine tools. The ns-machined structures are prepared by the project partner VW. A Lasertec 125 from DMG Mori is used, equipped with a 100 W fibre laser at a wavelength of 1064 nm and a characteristically pulse duration of 400 ns. The repetition rate amounts 200 kHz. The second laser machine tool, a DML 40 SI, provides ultra-short laser pulses with a pulse duration about 10 ps. The integrated Time-Bandwidth Duetto laser source offers an average power of 10 W at a wavelength of 1064 nm and an adjustable repetition rate between 100 kHz and 8.2 MHz.

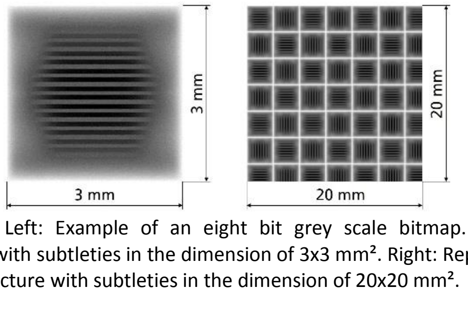

Figure 1. Left: Example of an eight bit grey scale bitmap. Pillow structure with subtleties in the dimension of 3x3 mm². Right: Repetitive pillow structure with subtleties in the dimension of 20x20 mm².

Experimental tests are carried out on hot-working steel 1.2311 blanks. The ablation process in a first step takes place two dimensionally, producing repetitive structures (3x3 mm²) in the dimension of 20x20 mm² and a depth of 150 µm. Bitmap files serve as basis for the ablation process and build the CAD/CAM interface (cf. Figure 1).

After machining, the produced structures are analysed by an optical microscope (Keyence VHX 5000) and a laser scanning microscope (Keyence VK 9700). Target figures to be analysed are the surface roughness (R_a) and the processing time (t). In a next step the structured tool is used for producing injection moulded parts that are analysed finally to see the influence of the tool quality to the product.

2.2. Combination of ns- and ps-laser ablation process

The level for transfer between the combined laser ablation processes is determined by the subtleties. For the pillow structure the level for transfer is set in a deep of 98 µm (grey value 89). So 65 % of the volume will be ablated by ns-laser pulses and 35 % by ps-laser pulses. Essentially two parameters are set up for each laser ablation process – a fast one that will produce worse surface quality and a slow one that promises to gain better surface quality (cf. Table 1). Due to the extremely rough surface of the fast ns-parameter set-up, the two ps-parameters are just combined with the slowest ns-parameters.

3. Results

3.1. Hot-working steel 1.2311

The ns-laser ablation process is state-of-the-art and is needed for the combination process. Using ps-laser ablation process for combining means an additional process step, so that the entire processing time will be higher.

Table 1. Performed processes with their related output values.

		Output values	
process	**speed**	**R_a/µm**	**t/minutes**
ps 1	slow	0.73	216.0
ps 2	fast	1.12	176.4
ns 1	slow	1.7	17.0
ns 2	fast	3.6	8.8
combination 1	slow	1.23	107.3
combination 2	fast	2.01	80.6

Figure 2 shows the gained surface qualities of each process in relation to the processing time. In the following paragraph the results of each of the slowest ns-, ps- and combination-processes will be compared. The slowest ns-process needs 17 minutes and provides a surface roughness of R_a = 1.7 µm. The slowest ps-process needs 216 minutes and achieves a surface roughness of R_a = 0.73 µm. The combined process of both does take 107.3 minutes while gaining a quality of R_a = 1.23 µm. The ns-process is about 12 times faster than the ps-process and 6.3 times faster than the combined processes. However, the surface quality of the ns-process is 2.33 times worse than the ps-process and 1.38 times worse than the combined process.

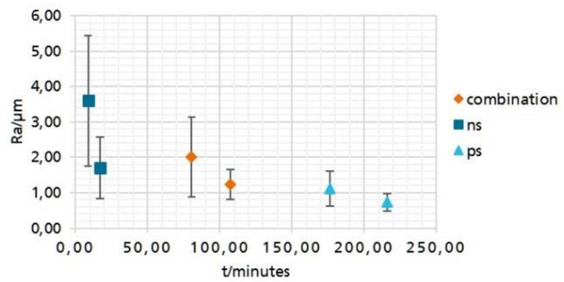

Figure 2. Surface qualities (R_a/µm) of each process in relation to the processing time (t/minutes) on hot-working steel blanks 1.2311.

Now the fastest ns-, ps- and combination-processes will be compared. At first it is obviously that the standard deviation of the surface roughness each of the processes is much higher than the standard deviation of the related slower processes. Furthermore figure 2 shows that the faster processes achieve worse surface quality. One phenomenon that is particularly striking is that only in the picosecond and combined processes the highlights of the structure are worked out with absolute clarity and utterly unambiguously. The profile view of the slow ns-process shows melt protrusion and the edges became warped.

3.2. PC-ABS

The injection moulded parts show that the surface quality of the hot-working steel is transferred to the final product made of PC-ABS. Especially warps at the edges of the subtleties are dominating the profile of the ns-machined structures (cf. Figure 3). In average warps are 15 µm high for both fast and slow ns-machined structures.

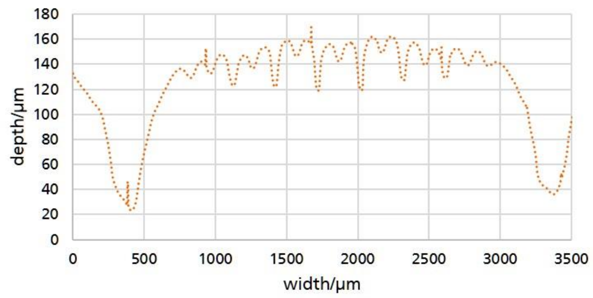

Figure 3. Profile view of the slow nanosecond ablation process.

Ps- and combined-machined structures are able to form the subtleties absolute clear. Figure 4 shows the profile of the fast combined process.

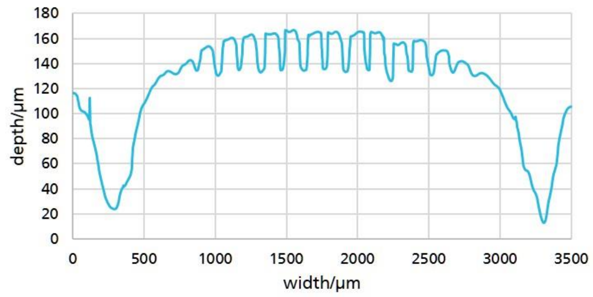

Figure 4. Profile view of the fast combined ablation process.

4. Conclusion

For laser ablation and structuring hot-working steel ns-laser radiation is the state-of-the-art. But it is limited in accuracy for a series of designs with subtleties. On the one hand the ablation process is fast, on the other hand it is dominated by melt protrusions (cf. section 3.2). Ps-laser radiation supports the production of subtleties in the structure. A 1.38 times better surface quality and avoided warps are the advantage of a combined process. The processing time is currently the biggest compromise to make. Currently a benefit in quality and design highlights cannot offset a 6.3 times slower processing time.

For future work there will be different tasks. First, optimizing the ps-laser process in processing time. Second, developing another combining strategy. Currently the ps-laser process has to start at the same level like the subtleties that implicate a 65 % ablation volume for ns-laser and should be shifted to 80 %.

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