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The Effect of Surface Machining Design on the Efficiency of Laser Surface Treatment

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Abstract

Laser surface treatment is increasingly used for surface hardening. In this series of experiments we studied the milling groove design effect on laser hardened surfaces at 42CrMo4 steel after corresponding laser parameters. Milled grooves of 0.25 mm, 0.50 mm and 0.75 mm depth were studied. The used diode laser and its set parameters had the same focus distance in all cases; however, the power and travel speed of the laser light were changed according to the previously developed experimental plan. Higher laser heat input resulted in a deeper hardened zone. The 45° V-profile milling, and hence the 45° angles of incidence of the laser beam increased the thickness of the hardened layer. The deepest hardened layers were formed at the highest specific heat input and at the deepest grooves.

Keywords: *42CrMo4 steel, diode laser, laser surface heat treatment, milling groove design.*

1. Introduction

Surface heat treatment of structural materials and shafts is a common practice in the industry today, in order to create durable, wear-resistant surfaces and edges. A common requirement is the use of a material whose microstructure can be made tough in the core and whose surface can be made hard and wear-resistant by a surface treatment process.

In the past, flame hardening has been used for individual production of case hardenable steels due to cost implications, while induction hardening has been used for large series to produce a thicker wear-resistant layer. Flame hardening does not necessarily produce uniform thickness for surface hardened layers.

In case of induction heat treatment, the thickness of the hardened layer also depends on the air gap between the inductor and the material surface. Grooves formed by milling are typically designed such that it is difficult to form the inductor with an uniform air gap.

The basic principle of laser surface treatment is the same as for any heat treatment process, which is to change the microstructure of the material by heating the steel to austenitic state and then rapidly cooling the material to achieve a martensitic microstructure [1, 2]. The thickness of the hardened layer formed on the surfaces as a result of laser treatment depends on the material of the workpiece (the effect of the alloying agents). The amount of heat input (energy absorbed) during laser treatment depends on the surface quality of the workpiece, the surface design and the angle of incidence of the beam on the surface. The size of the workpiece determines how much heat can be absorbed by the workpiece . In the case of laser heat treatment, the thickness of the hardened layer that can be created depends on the speed of the laser head, the distribution of the laser power and the wavelength of the laser light [3, 4]. Based on the literature data [5, 6], the reflection of CO_2 lasers with a wavelength of 10,64 μm on polished materials is typically above 90 %, but can be reduced to 20 % by surface roughening. The literature shows that the effect of surface roughness on the absorption of the laser beam is not as significant in case of solid-state lasers and diode lasers as in the case of CO_2 lasers [6, 7] (Table 1).

Table. 1. *Absorption coefficient at different surface qualities and laser technologies* [6]

Surface	Absorption, %	
	CO_2 laser, 10600 nm	Nd:YAG laser, 1064 nm
Polished	4	30
Turned	5–7	33–37
Sandblasted	6–8	36–43
Oxidised	21–23	46–51
Graphitised	60–80	60–80
Polished	70–80	70–80

While it can be seen in Table 1 that a rougher surface has a better absorption, conventional roughness values such as Ra, Rq and Rz are not suitable for directly predicting the absorption capacity of a metal surface. There are examples in the literature [8] where similar roughness values have shown different absorptivity. Bergström [9] proposed to use the mean slope of the surface profile instead of surface roughness values to describe the absorptivity.

According to Kügler [10], the dependence of laser beam absorption on surface roughness differs for different steel grades. The hybrid roughness value, Sdq, which is the root mean square gradient and therefore close to the proposal of Bergström [9[, seems not to be suitable for absorptivity predictions for the stainless steel (1.4301) and the tool steel (1.2344). For the spring steel (1.1248), there is a certain dependency. Regarding hardenability, spring steels and quality steels are comparable. The ideal hardenable section diameter can be calculated by Grossmann formula [11, 12]

According to the MSZ EN ISO 683-2:2018 standard the 42CrMo4 (1.7225) steel grade is widely used in industry because of its excellent machinability and good heat treatability. Due to its chromium and molybdenum content, it is a typical material for extremely tough, heavy-duty machine parts. It has 46 W/mK thermal conductivity. Its mechanical properties can be varied over a wide range with the aid of heat treatment [13].

Dewi et al [14] have studied the effect of laser beam angle of incidence (10°, 20°, 30°) on similar medium carbon steels (38MnSiVS5 and 44MnSiVS6). It was found that scanning the surface at constant speed but with higher angles of incidence resulted in a higher degree of indentation, but was material quality dependent.

The question arises as to how the grooves formed by different milling methods affect surface hardening. In our experiments, we studied how grooves made to a depth of 0.25 mm; 0.5 mm; 0.75 mm affect the laser hardening depth layer in the case of pre-hardened 42CrMo4 grade steel when diode lasers are applied.

2. Materials and technology

The applied material was a pre-hardened 42CrMo4 steel bar (C= 0.41 %, Si= 0.3 %, Mn =0.7 %, Cr =1.1 %, Mo=0.2 %). with 305HV2 hardness. The dimensions of the bar were 50×50×200 mm.

The aim of the experiments was to investigate the thickness of the hardened surface created by the diode laser on surfaces of different shapes. Based on preliminary literature research, we decided to produce „V" shaped grooves. For the groove milling, we needed a tool that could machine the surfaces with the right precision and to the right depth. The used technology was milling and the used milling tool was a solid carbide end mill tool (MC326-12.0W4L050C-WK40TF) with a 90° entering angle (KAPR), which created ‚V' shaped grooves in the surface.

The main parameters of the tool were: z=4 teeth, D= Ø12 mm. The tool constitution is fine-grained carbide. The coating used was TiAlN. The tool creates a R 0.,5 mm radius at the bottom of the „V" shaped grooves. In the case of side milling, the 50° helix angle cannot be neglected either, but since our largest infeed is 0.75 mm, the effect of this parameter on cutting is negligible. The applied cutting parameters were the same for all „V" shaped grooves. However, we must note that our cutting speed approaches zero at the axis line of the tool, but the maximum depth of the „V" shaped grooves of 0.75 mm mean that the change in cutting speed is negligible in this case. The set cutting speed was Vc=32 m/min and the feed rate was f=74 mm/min. The cutting parameters were defined based on tool catalogue data. The most important element of the present experiment is the infeed, which in all cases was the same as the depth of the „V" shaped grooves, the machining angle was 45° These infeed and groove depths were as follows, 0.25; 0.5; 0.75 mm (Figure 1).

It is important to point out that in all milling operations a MOL Emolin 505 of cooling-lubricating fluid was used, thus reducing the amount of heat introduced onto the surfaces and resulting in no changes in the microstructure.

The laser annealing of the surfaces was carried out at the Budai Benefit Laser Technology Ltd., where a 4kW diode laser was used, with three different technological data pairs. A focal length of 340 mm was used for the experiments.

Based on preliminary literature data, 150 Ws/mm, 200 Ws/mm and 240 Ws/mm specific laser heat input were used in the heat treatment of the sample surfaces.

The technological data for each sample designation is shown in **Table 2**.

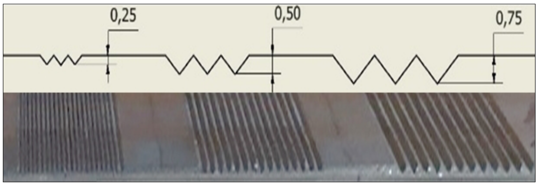
The surface-treated specimen was sawn off with a band saw at a thickness of 10 mm near the heat-treated surface using a cooling-quenching liquid. For metallographic analysis from the sawed plates were cut 40 mm wide samples at the center lines of the heat-treated strips, in such way to allow study of both the milled groove portion and the flat surface zone (**Figure 2**).

The samples were embedded perpendicular to the heat-treated surfaces in two component epoxy resin. After grinding and polishing several ranges the samples were etched by 2 % Nital. In this way the microstructure of samples can be analysed. The microstructure of the hardened layers were studied using an Olympus DSX 1000 tip digital light microscope.

The hardness of samples was measured by Zwick 3212 hardness testing apparat. The hardness evolution from the surface to the inside of the steel samples was taken perpendicular to the plane surfaces. At heat treated milled grooves the hardness measurements were positioned in middle of grooves. In order to measure hardness respecting the prescribed spacing between the indentations **[15]**,], the load was designed to be 1.962 N.

3. Results

On the metallographic specimens, we found that even at the lowest specific laser heat impute, the milled groove surroundings were more deeply hardened than at the flat surfaces. Even at the smallest energy input per unit length, it is striking that the surface where the angle of incidence of the laser beam with the surface is 45° (even at the first groove) has a deeper heat treated layer than the flat surfaces where the angle of incidence of the laser beam is perpendicular to the surface (**Figure 3**).



1. ábra. *Az elkészített felületek vázlata és képe*

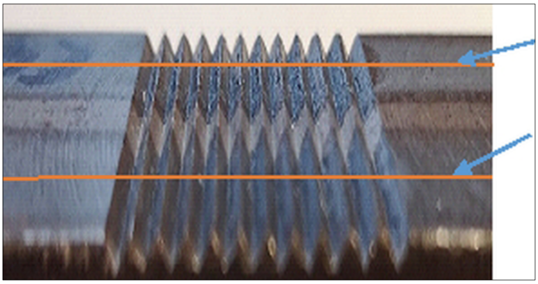


Fig. 2. *The appearance of 0.75 mm deep milling grooves after heat treatment The arrows show the position of the metallographic samples cutting line.*

Table 2. *Technological parameters for samples*

Laser parameters	Sample numbers and the milling groove size		
	0.25 mm	0.5 mm	0.75 mm
1.2 kW → 8 mm/s	1	2	3
1.6 kW → 8 mm/s	4	5	6
1.2 kW → 5 mm/s	7	8	9

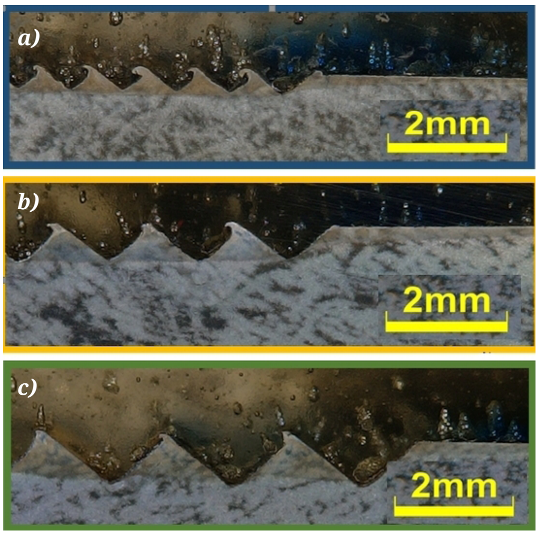


Fig. 3. *Micrographs after heat treatment with 150 W s/ mm specific heat input a) sample nr. 1 b) sample nr. 2 c) sample nr. 2.*

In agreement with the metallographic micrographs, the hardness variation plots show that the depth of the V-grooves created by milling increases the depth hardened layers on the machined parts. In the full depth of the teeth, the hardness exceeded 700 HV0,2 (**Figure 4**).

The deeper the grooves, the deeper the hardened surface layer occurred. The hardness measurements results suggest that the hardened surface layers are martensitic. The metallographic studies clearly confirm this, when high resolutions were applied (**Figure 5**).

Increasing the laser beam power from 1200 W to 1600 W and staying at 8 mm/s travel speed (200 s/mm specific heat input), the hardened layer thickness increased significantly, especially in the vicinity of the milling grooves (**Figure 6**).

In this case, when the specific heat input was 200 W s/ mm, martensitic microstructure was found below the flat surfaces up to 350 µm. In the zone where grooves were created by milling, the surface modification depth increased. Hardness measurements show that the hardened layer thickness was more than 850 µm for the 0.25 mm and 0.5 mm grooves, while it exceeded 1000 µm for the 0.75 mm groove depth (**Figure 7**).

Comparing to the first set of samples, keeping

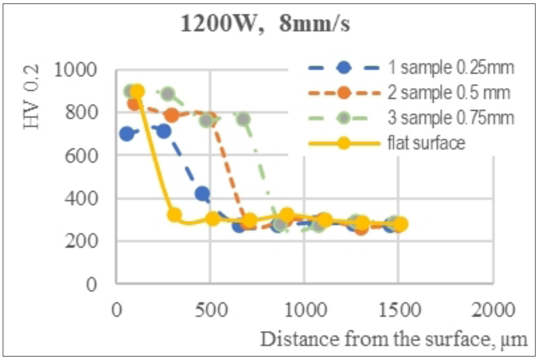


Fig. 4. *Hardness as a function of depth in the case of 150 W s/ mm specific laser heat impute.*

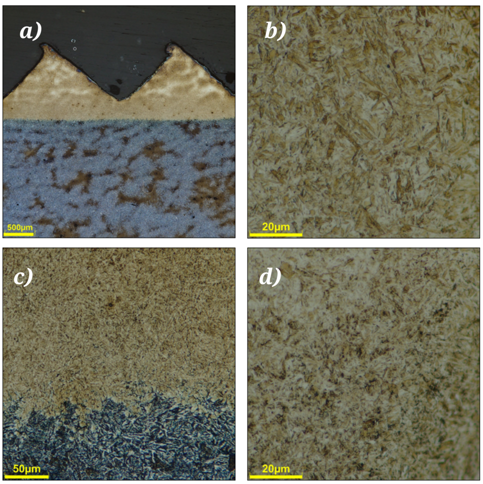


Fig. 5. *Micrographs from hardened surface layer a) Microstructure of 0.75 deep milling grooved zone b) high resolutions micrographs martensitic microstructure near surface c) transition zone between surface layer and core of bar d) heat treated zone under grooves*

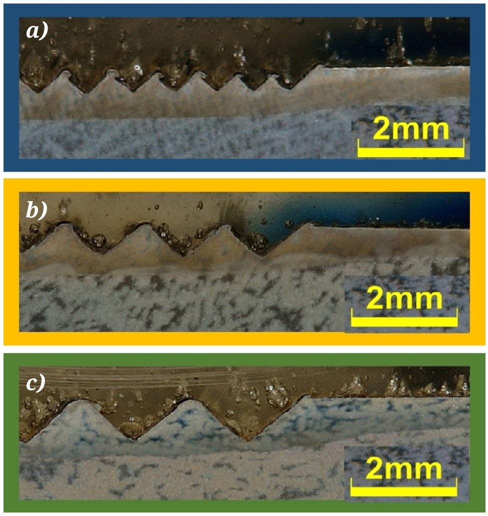


Fig. 6. *Effect of laser hardening at 1600 W and 8 mm/s on grooved surfaces a) 0.25 mm grooves, sample nr. 4, b) 0.5 mm grooves, sample nr. 5, c) 0.75 mm grooves, sample nr. 6.*

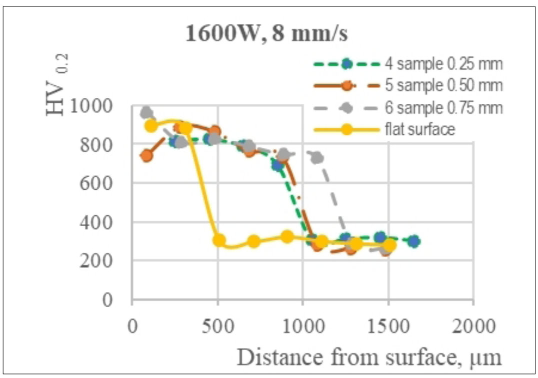


Fig. 7. *Hardness versus depth curves for 200W s/mm specific laser heat input.*

the laser beam power at 1200 W and reducing the scanning speed to 5 mm/s (applying 240 W s/mm specific power), the hardened layer thickness reached 500 µm even for flat surfaces. The groove design enhanced the depth of the hardened surface layer (**Figure 8**). Preparing the milling grooves in 45°, and hence, the 45° angel incidence of laser beam caused an increase in the thickness of the hardened layer. The effect of incidences angle modification of the laser beam on the hardened layer thickness is particularly visible on the micrograph in **Figure 8.c)**.

At the application of 240 Ws/mm specific power, the thickness of hardened layer in case of 0.25 mm grooves did not reach 1 mm, but in case of 0.5 mm depth grooves the martensitic microstructure was still detectable at 1100 µm distance from the surface. In case of 0.75 mm deep grooves, the hardness exceeded 600 HV0.2 at a depth of 1200 µm (**Figure 9**).

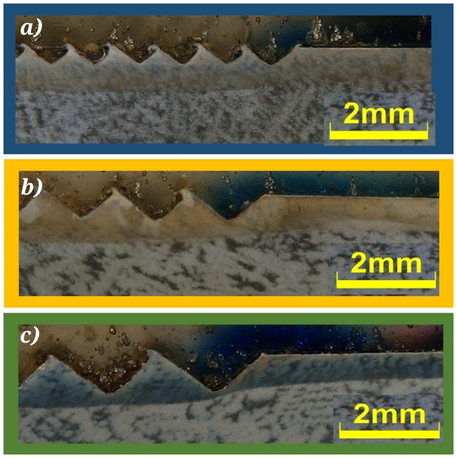


Fig. 8. *Micrographs taken after heat treatment with 240 W s/ mm specific laser heat input a) 0.25 mm depth grooves, sample nr. 7, b) 0.5 mm depth grooves, sample nr. 8 c) 0.75 mm depth grooves sample nr. 9.*

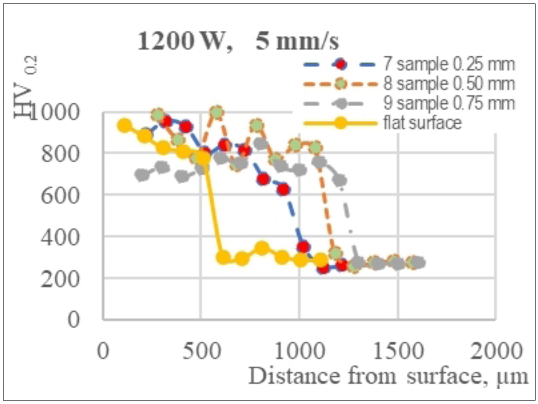


Fig. 9. *Hardness plots as a function of distance from the surfaces in case of 240 W s/ mm specific laser heat input.*

4. Conclusions

In case of pre-hardened 42CrMo4 steel increasing the specific laser energy input during laser beam surface hardening increases the depth of hardened surface layer.

The change in the angle of incidence results in a change in the surface area of the laser beam on the material surface, which affects the power density and the energy input along the path. The angle of incidence of the laser beam at 45° increased the depth of laser hardened layer versus flat surface.

The surface hardened layers in zone of deeper grooves were deeper at the same laser power. When flat surfaces were hardened by laser beam hardening, the depth of hardening was the smallest.

The grooved surfaces formed with 0.25 mm, 0.5 mm and 0.75 mm milling depths were hardened to full depth even at 150 Ws/mm specific heat impute.

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