Development of a flexible laser hardening & machining center and proof of concept on C-45 steel

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Abstract

The production of hardened precision parts is conventionally done in 3 steps. Rough machining of a workpiece in soft stage is followed by a hardening step, usually a batch process, and finalized by a hard machining finishing step. To omit the inevitable time delay and loss of accuracy because of part re-clamping, these steps should be incorporated within one flexible machining center. This paper describes the development of this machining center which allows machining and laser hardening in one setup, followed by a proof of concept for hardening C45 steel on this setup.

Keywords: Laser hardening; Machining; 5-Axis milling center; Nd:Yag Laser; Optical Design

1. Introduction

Today the production of a hardened precision part is conventionally done in 3 steps. After soft machining, the workpiece is unclamped to be transported to the hardening department. When hardened, the workpiece is transported back to the machining shop, to be re-clamped and aligned for finishing. This conventional procedure (illustrated in

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Fig. 1) not only introduces loss of accuracy (because of re-clamping), but also time delay because of the logistics and the time consuming alignment.

Hardening on the machining center itself would allow for both an increased final part accuracy and significant reduction in production time, resulting in lower costs of workpiece handling/aligning and logistics. Fig. 2 illustrates the simplified process chain when hardening is done within the machining center. The three different steps are now performed on one machine.

As a result of recent developments for new tool materials, stiffer machines and high speed spindles; the machining of hardened steels is evolving from classical grinding operations to hard milling and turning operations using carbide or CBN tools, or hybrid processes such as ultrasonic assisted grinding. For hardmilling, surface finish values below $R_a = 0.1 \, \mu m$ for hardened steels above 60 HRC are reported (Dewes et al., 1996). Integrating a hardening step within the same platform as soft and hard machining enables all operations to be performed without the need for re-clamping. This research investigates only one part of the proposed new process flow; the integrated hardening step. In this paper, the development of an integrated laser hardening setup is described. A conventional 5-axis milling machine has been adapted and equipped for laser hardening. Using this setup, C45 steel samples have been hardened as a proof of concept. Hardness, depth of hardened layer, surface temperature and ‘melted or not’ (possible occurrence of undesirable melting) are described and evaluated. A simulation was performed and correlated with the test results.

2. Current production methods for hardened precision components

Carbon steel is composed of a mixture of cementite ($\text{Fe}_3\text{C}$) and ferrite (BCC), which can dissolve a maximum of up to 0.006% carbon. When heated up to the $A_c_3$ temperature, an austenitic structure is formed (FCC) (Komanduri et al., 2001), which can dissolve up to 2% carbon. When the material is then cooled quickly to below the $M_s$ temperature, the carbon does not have the time to precipitate out and a non-equilibrium martensite phase is formed. Martensite is extremely hard, but also brittle. This behavior is desired at the surface of many components, because of its wear resistant properties. Nowadays surface transformation hardening is done using techniques such as induction hardening, flame hardening, case hardening and laser hardening. In case of surface treatment by laser, the material is heated up by a laser source. The surrounding material acts as a heatsink, leading to quenching through conduction resulting in hardening phase transformations. While for case hardening, the complete part needs to be heated; laser hardening, flame hardening and induction hardening allow for only heating up and transforming a selection of the workpiece surface. The first published industrial application of laser hardening was the hardening of the internal surface of an automobile steering column, back in 1973 (Ion, 2002). Laser hardening has been around for years, it was always applied outside the machining center, using a separate setup to handle the laser. In many cases, a robot, holding the collimator which is connected through a fiber to the laser source, is used because of its relatively low cost and high flexibility. Today new developments are being introduced: Bin et al. (2013) proposed an integrated turning–laser hardening setup combined with laser assisted turning. Monforts, a machine tool manufacturer, is also moving towards integrated turning and laser hardening. However, the geometric flexibility of
these platforms is limited compared to the robotic platforms, therefore the added value of a laser hardening setup on a flexible 5-axis machining center.

One of the main advantages of laser hardening is the fact that very little distortion is introduced into the workpiece compared to conventional case hardening, since the laser treatment takes place on localized surface areas. This omits in many cases the need for a hard finishing step, thus eliminating the final step in Fig. 2. However, for the production of highly accurate hardened parts, a hard finishing step is required. For low quality gears (below accuracy class DIN6), the distortion introduced in the gear by laser treatment is small enough not to influence the accuracy class of the gear (Zhang et al., 2003). However, for higher accuracy gears, a hard finishing step will be required. The soft machining of a high accuracy gear on a 5-axis milling machine was investigated by Bouquet et al. (2014). The development of integrated laser hardening, discussed in the next section, on the same 5-axis milling machine, will allow to harden these gears on the machine, as proposed in Fig. 2. The laser hardening and hard finishing of this gear is the topic of future research.

3. Development of integrated laser hardening on a 5-axis milling machine

3.1. Introduction

A 5-axis milling machine is well suited to use for an integrated laser hardening setup because of its high flexibility. Since both hardening and machining processes are required, no changes to the machine, compromising the machining capabilities, are allowed. Therefore, an optical path was developed, transporting the laser energy from source to the desired location on the workpiece. To make use of the flexibility of the 5-axis machine, the laser head is designed to be mounted in the machine spindle. Since no commercial laser head exists based on a HSK-63 tool holder, one was designed in house (Fig. 3). A 500W Nd:Yag Lumonics MW500 laser (wavelength 1064 nm) equipped with fiber and collimator was integrated into the 5-axis milling machine (Sauer 70-5 Ultrasonic / DMG 70 eVo), using a HSK-63 tool holder system. This machine is also capable of Ultrasonic Assisted Grinding, which allows to machine very hard materials, ideal for hard finishing (hardened steels, glass and ceramics), as described by Lauwers et al. (2010).

3.2. Optical path

The provided collimator has a focus lens with focal length \( f = 68 \text{ mm} \). Since optical components limit the allowed laser diameter to 25.4 mm (1 inch optics), when entering the mirror holder, a minimum distance between collimator and the 45° mirror holder is necessary. Correct position and alignment of the collimator in respect to the mirror
holder is ensured by a cylindrical sleeve. The mirror holder allows small alignment corrections. The laser beam is reflected downwards by the mirror and guided through a plano-convex focus lens. For the used wavelength, the reflectivity of the mirror and the transmittance of the lens are above 99%. The focus lens of the laser head (not the collimator) is easily interchangeable, allowing an easy change of focus distance. In case a focus lens with \( f = 25 \) mm is used, the focus distance for this focus lens can be calculated by the Gaussian thin lens equation, resulting in 99.4 mm. In case of a \( f = 30 \) mm focus lens, the focus distance becomes 294.7 mm. Depending on the workpiece size and shape, an appropriate lens for a required focus distance can be selected. This is of course the ideal case, with a perfect focus point. The principle of Fermat allows to calculate the distance to the desired spotsize, taking into account the real minimal spotsize (0.52 mm) of the laser beam.

3.3. Additional features

Since a 5-axis milling machine is not equipped for laser purposes, some changes to the machine are necessary to guarantee the safety of the operator. All transparent panels have been replaced by 2 mm thick aluminum sheets, which have been softly sanded in order to reflect the light in a diffuse manner. To be able to still monitor the milling or hardening process, a safety glass was added as well as a camera, protected by an optical filter. When the 5-axis milling machine is used for milling, the work area is polluted by chips and cooling liquid. Therefore it is important to store the laser head in a separate container, closed off from the workspace, during milling. Since the laser head cannot be positioned in the conventional tool magazine (too big and connected with fiber), an additional storage unit was added next to the machine. This unit is sealed from the workspace by an electric roll-down shutter, depicted in Fig. 4.

Since debris and cooling liquid can still be in the machine area, it is important to keep the optical path clean in order to guarantee a good reflectivity of the mirror and transmittance of the lenses. Therefore positive pressure is applied to the optical path area, to make sure no debris can enter this space. This small positive pressure is applied using pneumatic connection °1, marked in Fig. 3 (b). To make sure no debris or liquid falls on top of the focus lens, a shielding gas ring is mounted around this focus lens. The center of this ring has an array of small holes, which create a radial air screen, protecting the focus lens of possible pollution. The gas is provided using pneumatic connection °2.

3.4. Control system

In order to be able to control the laser shutter, the electric roll down shutter of the container and the air supplies (2 different pressures) to the laser head, a control system had to be build. Fig. 5 gives an overview of this control system. An Arduino microcontroller is connected with a standard NC controllable PLC output of the 5-axis milling machine. In this way, it is possible to control the laser shutter, using NC code, since the open-source computer platform (Arduino board), is connected to the laser through a PC. This computer communicates through serial data communication with the laser source. Since the pneumatic valves and electric roll down shutter need to be
controlled, they are as well connected to the Arduino board. A pyrometer (2 colour pyrometer, Dr. Mergenthaler)
outputs a voltage (analog communication) depending on the measured temperature. This voltage is read by the
Arduino board, and can be set as input for a PI(D) controller on the PC, regulating the laser power.

Fig. 5. control system.

4. Integrated laser hardening of C45 steel

4.1. Introduction

Steen and Courtney conducted an investigation of the laser surface hardening of EN 8 steel (AISI 1036), using a
2 kW continuous wave CO2 laser. A full factorial design was conducted, by varying the parameters: power (P=1.2 to
2.0 kW), laser beam diameter (D=1.6 to 5.8 mm) and feed rate/traverse speed (v=25 to 400 mm/min). The depth of
the hardening was experimentally fit as a function of the parameter $P/\sqrt{Dv}$ and the onset of surface melting as a
function of the parameter $P/D^2v$. They presented operating charts of laser power versus traverse speed, for different
laser beam diameters. This experimental research initiated more fundamental research, different authors (Cline et al.,
Lax, Sanders, Mazumdar et al., Davis et al. and Komanduri et al.) performed analytical research, developing
thermal models, evolving from (quasi)-static 1D models, towards 3D models considering both transient as steady-
state and taking into account the boundary effects. The goal of this paper is not to develop new models or
fundamental research in the area of laser hardening, however the target is to apply this knowledge on an integrated
laser setup, and run a full factorial design as a proof of concept, in order to find correct hardening parameters for this
setup. Additionally, a transient heat transfer model was applied to simulate the laser hardening process. The finite
element modeling results are finally validated by hardness tests results indicating the surface hardness and hardness
along the workpiece thickness. Validated simulation results can be used to determine the minimum required
temperature for hardening of C45 steel.

4.2. DOE: full factorial design

Laser beam power (P), spotsize diameter (D), distribution of power across the beam (d), laser beam absorptivity
(a) into the work material and traverse speed (v) are the main processing parameters involved for laser surface heat
treatment. To reduce reflectivity, an absorbent coating is used in many cases. In this research, a graphite coating was
used, as a result the surface absorptivity can be assumed at about 60%. The intensity distribution across the beam is
fixed and cannot be changed in the current setup. Therefore this is not a variable in the full factorial design. Since
the laser light is transported using a common step-index fiber, the beam is expected to have a semi top-hat
distribution. The laser beam power (P) was held constant at maximum power (450W). Traverse speed (v) was varied
between 100 mm/min, 250 mm/min and 400 mm/min. The spotsize diameter (D) was varied between 2600, 2680,
2730 and 2780 µm. The investigated dependent variables are the depth of hardening, maximum hardness, average
measured temperature during process and whether the surface is melted or not. An overview of varied process
parameters is illustrated in Table 1. The samples were prepared and analyzed in a randomized order. Every set of parameters was repeated (replicates) 3 times.

Table 1. Variable process parameters.

| Test | v [mm/min] | D [μm] | Test | v [mm/min] | D [μm] | Test | v [mm/min] | D [μm] |
|------|------------|--------|------|------------|--------|------|------------|--------|
| 1    | 100        | 2600   | 13   | 250        | 266    | 25   | 400        | 2730   |
| 2    | 100        | 2600   | 14   | 250        | 266    | 26   | 400        | 2730   |
| 3    | 100        | 2600   | 15   | 250        | 266    | 27   | 100        | 2780   |
| 4    | 250        | 2600   | 16   | 400        | 266    | 28   | 100        | 2780   |
| 5    | 250        | 2600   | 17   | 400        | 266    | 29   | 100        | 2780   |
| 6    | 250        | 2600   | 18   | 400        | 266    | 30   | 100        | 2780   |
| 7    | 400        | 2600   | 19   | 100        | 273    | 31   | 250        | 2780   |
| 8    | 400        | 2600   | 20   | 100        | 273    | 32   | 250        | 2780   |
| 9    | 400        | 2600   | 21   | 100        | 273    | 33   | 250        | 2780   |
| 10   | 100        | 2665   | 22   | 250        | 273    | 34   | 400        | 2780   |
| 11   | 100        | 2665   | 23   | 250        | 273    | 35   | 400        | 2780   |
| 12   | 100        | 2665   | 24   | 250        | 273    | 36   | 400        | 2780   |
| 13   | 250        | 2730   | 25   | 400        | 2780   |
| 14   | 250        | 2730   | 26   | 400        | 2780   |
| 15   | 250        | 2730   | 27   | 400        | 2780   |
| 16   | 250        | 2730   | 28   | 400        | 2780   |
| 17   | 250        | 2730   | 29   | 400        | 2780   |
| 18   | 250        | 2730   | 30   | 400        | 2780   |
| 19   | 250        | 2730   | 31   | 400        | 2780   |
| 20   | 250        | 2730   | 32   | 400        | 2780   |
| 21   | 250        | 2730   | 33   | 400        | 2780   |
| 22   | 250        | 2730   | 34   | 400        | 2780   |
| 23   | 250        | 2730   | 35   | 400        | 2780   |

The 36 test samples out of C45 steel (1.0503, EN 10277 -2) are prepared as shown in Fig. 6. This steel is selected for a broad range of applications in the automotive (gears and shafts) and other sectors (wood working drills, axes and hammers, screws…). The base material has a hardness of 200 HV. The samples are divided in groups of 4. The scanning length is 30 mm. The C45 steel parts have a thickness of 8 mm. After the laser treatment, a wire-EDM machine was used to take out a small section out of the middle of the sample (indicated in red in Fig. 6). These sections were embedded in a polymer, ground, polished and etched, in order to be able to look at the microstructure and do micro-hardness tests.

The output parameters are listed below, as well as how they are interpreted:

- Depth of hardening: the samples are tested using a Vickers Micro Hardness tester, using a weight of 100g. The first measurement is done 50 μm below the surface, 80 μm of space is left between two successive measurements. 500 HV was considered as the limit, when the measured hardness falls below this value, the material is considered not satisfactorily hardened at this depth.

- Maximum hardness: every sample is tested until 2 successive hardness measurements fall below 300 HV, which means about 3 to 8 measurements are performed for every sample. The average of the 2 first measurements near the surface is considered as the maximum hardness of this sample.
Average measured temperature: a Dr. Mergenthaler pyrometer was used to measure the temperature during the laser surface treatment. The temperature was monitored and stored every 0.02 seconds. These values are averaged in time.

Melted or not: a Mahr Perthometer surface roughness measurement meter was used to inspect the surface roughness measurement of the samples, before and after heat treatment. The cutoff length was 2.5 mm, using 1 sample of 7.5 mm length to cover the full section of the scanned surface. Every piece of C45 steel, with 4 samples, was measured 3 times before hardening. After hardening, every sample was measured again 3 times across the scanning direction (see Fig. 6). The averages of the measurements after hardening were compared to the average of the measurements without hardening using a 2-sample t-test using 95% confidence level (H1 hypothesis: average after hardening > average before hardening). As soon as the P-value dropped below 10%, it was considered to accept the H1 hypothesis and to consider the surface to be melted.

4.3. Results

Table illustrates the ANOVA results. The significant factors (P value less than 0.05) are indicated.

| DF | MS    | F     | P-value |
|----|-------|-------|---------|
|    | ANOVA for depth of hardened layer | ANOVA for maximum hardness |
| A: v | 2 | 140144 | 51,22 | 2E-09 |
| B: D | 3 | 42885  | 15,67 | 7E-06 |
| AB | 6 | 1241   | 0,45  | 8E-01 |
|    | ANOVA for measured temperature | ANOVA for melt |
| A: v | 2 | 5384   | 0,63  | 5E-01 |
| B: D | 3 | 101556 | 11,80 | 6E-05 |
| AB | 6 | 24043  | 2,79  | 3E-02 |

Depth of hardening

The depth of the hardened layer is clearly influenced by the spotsize diameter (D) and the traverse speed (v). The P-value for both D and v is below 0.0001 and indicates that both are significant parameters concerning the depth of hardening. The combined factor shows to be insignificant. Fig. 7 (a) shows a higher traverse speed (v) and smaller spotsize diameter (D) clearly have a positive impact on the depth of the hardened layer.

Maximum hardness

The maximum hardness (average value of the two measured values close to the surface) is significantly influenced by v and D, as well as the combined factor. A smaller spotsize or slower traverse speed have a positive influence on the maximum hardness, comparable to the depth of hardening. As can be seen in Fig. 8 (a), for a high traverse speed and big spotsize diameter, the hardness drops dramatically, because at the combination of fast feed rate and big spotsize the material is not hardened properly. Thus the combination of these two factors is significant and they cannot be considered only independently of each other.

Measured temperature

The spotsize diameter and the combined factor are both significant to the measured surface temperature. As can be seen Fig. 7 (c), a smaller spotsize has a positive influence on the measured temperature. The traverse speed as a single factor is not significant. This can be explained because the pyrometer only measures the top surface. Since the needed interaction time to heat up the upper surface is very small, the traverse speed has little to none influence to the temperature at the surface. However, the interaction time has a big impact to the depth of the heated zone. If the
temperature would be monitored using thermocouples on different depths below the surface, the traverse speed would have a significant impact. Fig. 8 (b) illustrates the combined factor influence.

- Melted or not

Fig. 7 (d) illustrates that the samples only melted when the spots size diameter was small and the traverse speed low. This is also mentioned in Table, indicating that the spots size, the traverse speed and the combination are significant. This hypothesis is confirmed when looking at Fig. 8 (c).
4.4. Correlation of results to simulation

A transient heat transfer model has been setup in ABAQUS to simulate the laser hardening process. Three-dimensional thermal solid elements with 8-nodes were selected for thermal analysis and in order to save computing time smaller meshes were used close to the laser scanning line. The laser beam has been modeled as a heat flux that changes its location in small identical time increments following an actual laser movement path. Each area segment of the workpiece is under influence of the heat load for a time step equal to the laser-workpiece interaction time which is determined by the laser movement velocity. Temperature dependent thermal properties of C45 steel were used based on the data provided in by Bennett et al (2013). Fig. 9 illustrates a schematic representation of the simulation.
Fig. 9. Schematic representation of simulation.

Fig. 10 (a) shows the thermal analysis results obtained from the simulation of laser hardening process with a spot size of 2780 µm at a speed of 100 mm/min. To find the minimum required temperature for hardening, the size of the hardened band obtained from experimental hardness measurements has been correlated to the thermal results both in X and Z directions. It has been observed that the isotherm of 877°C (shaded by dashed line in Fig. 10 (a)) has an approximate same size of the actual hardened zone (A: 1910 µm versus 1885 and B: 229 µm versus 210 µm). This temperature is well above the eutectoid temperature assuring martensite formation upon fast heating and high cooling rate achieved during the laser scanning process. In order to validate the simulation result, the simulation was repeated for the same spot size but a higher scanning speed of 400 mm/min in which no hardening effect was observed experimentally. It can be seen from Fig. 10 (b) that the maximum reached temperature is below the critical value (877°C) determined earlier, therefore material hardening is not expected. The experimental results confirm that the material is not surface hardened while the scanning speed increased to 400 mm/min (see Fig. 7 (a) and (b)). This thermal model can later be used to calculate optimum process parameters for laser hardening processes and reduce the amount of tests needed for DOE.

Fig. 10. Simulation results.

5. Conclusion

A 5-axis milling machine was converted to a machining center capable of laser hardening, 5-axis milling and ultrasonic assisted grinding. A full factorial design involving two parameters (traverse speed and spot size diameter) was conducted as a proof of concept. The influences of the two different factors as well as the interaction factors to the hardening depth, maximum hardness, measured temperature and ‘melted or not’, were investigated. It can be concluded it is well possible to harden C45 steel from 200 HV up to 800 HV, on the 5-axis machining center, using a Nd:Yag 500W laser. A transient heat transfer model was successfully applied to simulate the temperature
distribution in the workpiece during the laser hardening process and a critical temperature was deducted from this simulation.

6. Future work

This paper described the realization of integrated laser hardening and a first proof of concept. In future, this work will be extended towards the complete machining of complex shaped hardened components, focused on the production of gear prototypes. In order to have a stable hardening process for complex shapes, a temperature controlled power, or traverse speed, regulating system will have to be developed. However, evolving from the conventional process flow, illustrated in Fig. 1, to the proposed process flow illustrated in Fig. 2, requires additional research in the field of the soft machining step as well as in the field of the hard finishing step.

The new proposed workflow will be tested in the future on a high precision gear, made in C45 steel. The soft machining step by 5-axis milling was investigated by Bouquet et al. (2014). The laser hardening and hard finishing of this gear is the topic of future research. The possibility to manufacture a hardened gear, using only standard ball- and endmills or standard pin grinding tools (no design specific dedicated tools such as gear hobbing tools or profile grinding tools) on one machine setup would mean a substantial improvement to the production time and cost of functional gear prototypes. Using the conventional production process for gears, the production of a functional gear prototype has a lead time of up to 13 weeks (the need for dedicated tools). Soft machining, laser hardening and hard finishing on one setup, would make it possible to make a functional prototype within 24 hours.

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