Dynamics of the heat affected zone and induced strains in laser machining below ablation threshold

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Abstract. The Heat Affected Zone - HAZ of a laser irradiated AISI H-13 steel workpiece, is investigated via numerical simulations and experimental measurements. A three-dimensional transient thermo-structural finite element model is developed to simulate the machining process. A Gaussian laser beam is employed as the heat source. The developed finite element material model considers the effects of plastic strain, strain rate and temperature, along with a fracture model. The experiments are carried out with a laser of 1-4 W power and with a scanning speed of 100 mm/min. Thermocouple sensors are used for the temperature measurements, while the surface roughness is measured using white light interferometry and related experimental diagnostics. A parametric numerical analysis regarding the average absorptivity of the workpiece is performed and is compared to the experimental findings. The depth and width of HAZ and the induced strains are studied for the plastic and melting regimes. The influence of the surface roughness of the metal workpiece on the dynamics of HAZ is also experimentally demonstrated. The findings of this study highlight the role of the absorption coefficient and the surface roughness on the HAZ below the ablation threshold and can be applied to related laser machining processes.

1. Introduction
The technological advancements and emerging industrial applications of the last decades in fields such as engineering, electronics and heavy industry applications, have led to the utilization of high-strength and high-temperature resistant materials, such as steel, titanium-based alloys and others. The dynamic changes of the material properties, when these metals are exposed to extreme conditions, like large applied stresses or high temperatures, have been the subject of many studies [1-3]. Such extreme conditions arise when it comes to cutting and machining of the workpieces, resulting in possible damages due to the very large strains developed.

Among the cutting methods applied on hard materials, laser assisted machining (LAM) is of high impact; LAM exploits the laser-induced increase of temperature for softening the material, and therefore reduces the forces required for processing and cutting of the workpiece within conventional contact machining techniques [4-6]. In micro-cutting with laser assisted micromachining (LAMM) the laser beam is focused in front of a miniature grooving tool on the workpiece, with the effect of a high...
rise in temperature in the vicinity of the focus and the generation of a corresponding heat affected zone (HAZ). However, the HAZ often constitutes a critical issue in LAMM, as it may induce severe damages in the area of interest [7,8]. The extension of the HAZ is dependent on the amount of heat applied, the duration of exposure to heat and the properties of the material itself. When a material is exposed to greater amounts of energy and for longer periods, the geometrical characteristics of HAZ increase. The computational results of the laser heating simulations are of great importance, since their use may monitor, optimize and secure the machining process [9].

The current research focuses on the characterization of the produced HAZ when laser irradiates to heat AISI H-13 steel workpiece of medium machinability. A transient thermal-structural FEM approach is used [9-13] to simulate the laser heating process and predict the induced thermomechanical effects. The model is capable to highlight the induced thermoelastic and thermoelastoplastic effects and include the phase change from the solid to the melting phase. An elastoplastic Johnson-Cook material model that takes into account the effects of plastic strain, strain rate and temperature, as well as damage initiation criteria is adopted. Experiments are conducted at 1-4 W laser power and for a scanning speed of 100 mm/min. Thermocouple sensors are used for the temperature measurements, while the surface roughness is measured using white light interferometry and conventional experimental diagnostics. A parametric numerical analysis regarding the absorption coefficient of the metal material under study is performed and is further compared to the experimental findings. The depth and the width of HAZ and the induced strains are studied for the plastic and the melting regimes. The influence of the surface roughness of the metal workpiece on the dynamics of the heat affected zone is also experimentally demonstrated.

2. Finite element modeling

3D thermal-structural transient simulations are performed using the LS-DYNA FEM software [14]. The workpiece is defined as a deformable body, while the laser beam is modeled as a Gaussian moving heat source. The \( q(x,z) \) absorbed laser heat flux that follows Gaussian distribution is:

\[
q(x,z) = \frac{2\eta P_{inc}}{\pi r_b^2} e^{-\frac{(z-v_t t)^2 + x^2}{r_b^2}}
\]  

(1)

where \( \eta \) is the average absorptivity of the workpiece, \( P_{inc} \) is the incident laser power, material \( t \) is the time, \( r_b \) the laser beam radius and \( v_t \) is the laser scanning speed along the x-direction. The laser heat flux is applied on the top surface of the workpiece. The boundary condition on the top laser irradiated surface considers the heat flux, convection and radiation is:

\[
-k \frac{\partial T}{\partial y} = q(x,z) - h(T - T_0) - \sigma \varepsilon (T^4 - T_0^4)
\]

(2)

where \( k \) is the thermal conductivity, \( h \) is the convective heat transfer coefficient, \( T_0 \) the ambient temperature, \( \sigma \) is the Stefan–Boltzmann constant (5.67 \times 10^8 W/m^2K^4) and \( \varepsilon \) is the emissivity. Moreover, the heat flux is normal to the laser irradiated surface.

The dimensions of the workpiece are 8.0 \times 1.0 \times 1.0 mm (length \times height \times width). The length of the laser scanning along the x-direction is 6 mm and is consistent to the experimental measurements, while the total simulation time for the scanning speed of 100 mm/min is 4.8 sec. The workpiece is uniformly modelled with approximately 8 million cubic solid finite elements of size 10 \times 10 \times 10 \mu m. The ambient temperature is set to 21°C, while a constant temperature of 25°C is considered for all sides, except from the symmetry and top surfaces. The Johnson-Cook (J-C) material model [15] that considers the effect of plastic strain, strain rate and temperature and also includes the effect of fracture by defining the equivalent plastic strain at the onset of damage, is adopted. The half-symmetric model in Z-direction and the laser workpiece interaction are shown in figure 1.
3. Experimental methodology

The experimental set-up employed for the current measurements on the AISI H-13 workpiece (W) is presented in figure 2(a) and described briefly in the following: The output of a continuous-wave (CW) laser source, of maximum power of 4 W at 532 nm, is directed by metallic mirrors (M) and focused by a converging lens (f=15 cm) onto the sample surface. The power of the laser beam reaching the sample is controlled by a power meter and varied in the range 1-4 W. The focusing lens (FL) is placed on translation stages in order to finely control its distance from the sample, the exact beam size and the intensity of the laser beam. The beam profile at the desired distance can be determined prior to the sample irradiation by the CCD camera (C1), shown in figure 2(a). The bases of the camera and the workpiece are mounted on a long metallic rail, which allows for exchanging their positions in front of the static laser beam.

For the temperature measurements through the temperature sensor, a special channel-type geometry was engraved on the surface of the workpiece, as shown in the section view of figure 2(b) (light grey). The sensor head (SHe) is then firmly attached inside and at the edge of this channel and the measured temperature values are recorded by our data acquisition software. It is worth noticing that the thermocouple’s head is not attached directly onto the sample surface, but at a depth d, so that false temperature readings due to the scattered light coming from the reflection of the beam on the metallic surface can be avoided. The workpiece and sensor holders (WH and SHo) are mounted on a motorized translation stage, driven by a motion-control software. This way the whole system is able to move along a line relative to the laser beam and the temperature can be measured while the “scanning” laser irradiates the sample, passing over the sensor head at a distance r (figure 2(b)).
Figure 2. (a) Experimental set-up for the laser micromachining measurements, (b) zoomed view of the sample in the vicinity of the temperature sensor and (c) profilometry set-up.

The workpieces are characterized by a surface roughness, determined before and after laser irradiation and heat processing of the sample. Figure 2(c) shows the optical profilometry set-up used for this purpose [13]: The set-up is based on a Michelson interferometry configuration and a white-light source (WLS) is used; a beam splitter (BS) and a moving metallic mirror placed on a linear piezoelectric transducer (PZT) are used for introducing the relative optical path difference between the two beams of the interferometer, the reference and the object beam, the latter reflected by the surface sample as shown in figure 2(c). The two beams are combined on a CCD camera, after passing through an objective lens (OL). A series of acquired interferograms for the different positions of the moving mirror allows for the determination of the surface topology with high resolution [13].

Table 1. Thermomechanical properties of AISI H-13 in room temperature and Johnson-Cook material model and failure parameters [11,16].

| Property                        | Workpiece | Material Model Parameters | Values   | Failure Parameters | Values |
|---------------------------------|-----------|---------------------------|----------|--------------------|--------|
| Density (kg/m³)                 | 7800      | A (MPa)                   | 674.8    | D1 (-)             | -0.8   |
| Elastic modulus (GPa)           | 211       | B (MPa)                   | 239.2    | D2 (-)             | 2.1    |
| Shear modulus (GPa)             | 80        | n (-)                     | 0.28     | D3 (-)             | -0.5   |
| Poisson’s ratio (-)             | 0.28      | C (-)                     | 0.027    | D4 (-)             | 0.0002 |
| Specific heat (J/kg °C)         | 460       | m (-)                     | 1.3      | D5 (-)             | 2.7    |
| Thermal conductivity (W/m °C)   | 17.6      |                           |          |                    |        |
| Thermal expansion (10^-6°C)     | 10.4      |                           |          |                    |        |
| Melting point (°C)              | 1427      |                           |          |                    |        |
| Latent heat of melting (kJ/kg)  | [20]      |                           |          |                    | 280    |

4. Results and discussion
The thermomechanical properties of the steel workpiece are set for the simulations according to the values presented in table 1, accompanied with the J-C material model and failure parameters of the workpiece [11,16] while thermal conductivity, specific heat and thermal expansion are temperature-
dependent [17,18]. A mean value of emissivity $\varepsilon=0.5$ is considered [5]. The heat transfer coefficient used for the convectional heat transfer to the surrounding air is $h=50 \text{ W/m}^2\text{K}$ [19].

The average absorptivity $\eta$ of each workpiece material was determined by the comparison of the computed temperature values against the experimentally measured at a reference specific workpiece point with common laser power of 2 W and speed of 100 mm/min. In figure 3 the temperature distribution in relation to distance from the laser spot is shown for three different values of average absorptivity ($\eta=0.55$, 0.7, 0.9) for the model “Bound” where constant temperature of 25°C is considered for all sides, except from the symmetry, while for the top surface the ambient temperature of 21°C is assumed. Moreover, for $\eta=0.7$ and for the model “Nobound” where initial ambient temperature of 21°C is everywhere assumed, the temperature distribution is demonstrated. These numerical results are compared to the experimental measurements from the reference specific workpiece points. It is determined that the average value of $\eta=0.7$ of the model “Bound”, agrees with the experimental findings, while the “Nobound” model underestimates the corresponding temperatures.

![Figure 3](image-url)

**Figure 3.** Temperature distribution in relation to the distance from the laser spot for the laser power of 2 W in the plastic regime.

Figure 4 presents typical results of the temperature and the plastic strain distributions at the time of 2.6 sec of the simulated “Bound” model, in the plastic regime for the laser power of 2.4 W and in the melting regime, for the laser power of 4 W. The laser scanning speed is 100 mm/min. In both regimes, elements that have been fractured can be observed. Since they overcome the fracture threshold of the failure criteria of the Johnson-Cook damage material model, their contribution on the stiffness matrix is eliminated. The maximum surface temperature values in the plastic regime is 980°C (figure 4(a)) and 1476°C in the melting regime (figure 4(b)). The width and depth of the plastic strain for laser power of 2.4 W (figure 4(c)) is 120 and 50 μm respectively, while it is 170 and 70 μm for laser power of 4 W (figure 4(d)).
Figure 4. HAZ dynamics. Temperature and plastic strain distributions in the plastic regime (a, c) for the laser power of 2.4 W and in the melting regime (b, d) for the laser power of 4 W.

Figure 5 shows a representative result of the surface roughness for the AISI H13 workpiece, as measured with the white-light interferometry technique, described in the previous section [13]. From the plotted profile for the selected lineout of the presented image the max. peak to min. peak (micro Rt) and corresponding changes on the metal surface could be determined, with resolution in the nanoscale. Results of the surface roughness for the AISI H13 workpiece for two reference channels, before and after laser irradiation, are presented in table 2. It is worth mentioning that these values were also confirmed using a roughness meter (Roughness gauge TESA Rugosurf 20), which indicated the same results for Rt. The laser power with which the samples were irradiated was 2.4 W, i.e. within the plastic regime, as indicated by the simulations. As one can notice, after laser irradiation the surface roughness reduces for the examined case.

Figure 5. Representative result of roughness measurement using the white light interferometry.
For roughness greater than the laser wavelength, which is our case, enhanced absorption occurs due to multiple reflections [21]. Therefore, in order to properly simulate the interaction between the laser light and the material the measured roughness pattern from the samples will be further used as an input to develop the initial geometry of the workpiece in our future models.

Table 2. Effects of laser irradiation on surface roughness for the plastic regime.

| Before laser irradiation |  |
|--------------------------|--|
| Material                 | AISI H13 steel |
| Channel                  | I  II |
| microRt (μm)             | 2.27 3.33 |

| After laser irradiation  |  |
|--------------------------|--|
| Laser Power (W)          | 2.4 2.4 |
| Scanning speed (mm/min)  | 100 100 |
| microRt (μm)             | 1.90 2.76 |

5. Conclusions
This study characterizes the HAZ for a common steel, of medium machinability. An average absorptivity of the material under study is found compared to experimental findings. This study constitutes a preliminary effort to enlighten the role of absorption coefficient and surface roughness on the HAZ below the ablation threshold and can be further extended to various laser machining and micromachining applications. The nanoscale resolution of the white light interferometry technique along with future simulations that will consider the roughness from the experimental measurements will determine the relation of the measured surface roughness with absorptivity.

6. References
[1] Venkatesan K, Ramanujam R and Kuppan P 2014 Procedia Eng. 97 1626
[2] Venkatesan K 2014 Eng. Rev. 34 75
[3] Kaselouris E, Nikolos I K, Orphanos Y, Bakarezos E, Papadogiannis N A, Tatarakis M, and Dimitriou V 2013 J. Multiscal Model. 5 1330001
[4] Kim K-S, Kim J-H, Choi J-H, Lee C-M 2011 Int. J. Pr. Eng. Man. 12 753
[5] Singh R, Alberts M and Melkote S 2008 Int. J. Mach. Tool Manu. 48 994
[6] Singh R and Melkote S 2007 Int. J. Mach. Tool Manu. 47 139
[7] Dong X and Shin Y C 2017 Int. J. Adv. Manuf. Technol. 90 731
[8] Pan Z, Feng Y, Hung T-P, Jiang Y-C, Hsu F-C, Wu L-T, Lin C-F, Lu Y-C and Liang S Y 2017 J. Manuf. Process. 30 141
[9] Kaselouris E et al. 2020 Key Eng. Mater. 827 122
[10] Kaselouris E, Baroutos A, Papadoulis T, Papadogiannis N A, Tatarakis M, and Dimitriou V 2013 J. Multiscal Model. 5 1330001
[11] Kaselouris E, Papadoulis T, Variantza E, Baroutos A and Dimitriou V 2017 Solid State Phenom. 261 339
[12] Kaselouris E, Nikolos I K, Orphanos Y, Bakarezos M, Papadogiannis N A, Tatarakis M and Dimitriou V 2016 Int. J. Damage Mech. 25 42
[13] Dimitriou V, Kaselouris E, Orphanos Y, Bakarezos M, Vainos N, Nikolos I K, Tatarakis M, Papadogiannis N A 2015 Appl. Phys. A 118 739
[14] Hallquist J O 2006 LS-DYNA Theory Manual (California: Livermore Software Technology Corporation)
[15] Johnson G R and Cook W H 1985 Eng. Fract. Mech. 21 31
[16] Huang Y, Liang S Y 2003 Int. J. Mach. Tool Manu. 43 307
[17] Singh R. 2007 Laser Assisted Mechanical Micromachining of Hard-to-Machine Materials (Doctoral dissertation, Georgia Institute of Technology)

[18] Afazov S M, Ratechov S M and Segal J 2012 *Int. J. Adv. Manuf. Technol.* **62** 887

[19] Yang J, Sun S, Brandt M and Yan W 2010 *J. Mater. Process. Technol.* **210** 2215

[20] Woo Y, Hwang T, Oh I, Seo D and Moon Y 2019 *Adv. Mech. Eng.* **11** 1

[21] Ang L K, Lau Y Y, Gilgenbach R M and Spindler H L 1997 *Appl. Phys. Lett.* **70** 696

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