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Laser hardening of thin walled parts with cryogenic cooling

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Abstract

The surface properties of functional components have a significant influence on the wear resistance or fatigue behavior and therefore on the lifetime of the part. To improve these surface properties, one common industrial process is laser hardening. The aim of the process is to heat the material locally over the Ac_3 temperature staying below the melting temperature and to get martensite by self-quenching.

However, in case of thin walled parts, the volume of the material is not large enough to transport the heat fast enough out of the process zone for self-quenching. To realize a sufficient cooling and to get simultaneous a high depth of hardening, the approach of using an active cryogenic cooling for laser hardening of thin walled parts was investigated. As a result of the cryogenic cooling with liquid CO_2, the temperature decreased fast enough under the martensite start temperature that the microstructure changed to martensite. Due to the position of the localized cooling point in relation to the position and feed rate of the laser spot, parts with a thickness of 1 mm and 3 mm have been hardened. As a consequence of the process parameters and the cryogenic cooling, the achieved depth of hardening of the thin walled parts are in range between 0.2 mm and 1 mm. This paper will present in detail this innovative approach and the results.

Keywords: Macro Processing; Surface Treatment; Laser Hardening; Cryogenic Cooling

1. Introduction

To reduce increasing requirements to save fuel and reduce the emission of CO_2, many lightweight components have been designed. Lightweight components allows to increase the efficiency e.g. of cars or planes and therefore to save resources during practice (Siebenpfeiffer, 2014). The objective of lightweight construction is to create a reliable part under given boundary conditions with minimum weight (Klein, 2013). To reach these objectives, thin walled parts are often used (Klein, 2013). There are different approaches for

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lightweight components with sufficient mechanical properties. One approach is to laser harden the parts increasing wear resistance. For laser hardening, a sufficient thickness of the part is required to remove the induced heat fast enough to get a hard martensitic microstructure. This effect is called self-quenching. The necessary thickness of approximately 5 mm (Beyer and Wissenbach, 1998) might be missing in a lightweight design. Therefore, an external cooling technique will be investigated.

2. State of the Art

2.1. Laser hardening

Laser hardening is a transformation hardening process where a hard martensitic surface layer is generated. Fig. 1 shows the principle of laser hardening. A small part of the laser energy is absorbed at the part surface depending on its absorption coefficient and a larger amount is reflected (DIN 17022). Due to the absorbed energy, the material in the boundary layer heats up very fast to austenitising temperature (Zornhagen, 2009). After austenitising, the part needs to cool down to create martensitic microstructure. The martensitic transformation starts when the temperature decreases under martensite start temperature (M_s). The transformation finishes when the temperature is below the martensite finish temperature (M_f). The M_s and M_f temperature depend on the material composition. With increasing carbon amount, the M_s and M_f temperature will decrease (Bargel et al., 2008). The cooling rate depends on specific material and geometrical boundary conditions to realize a heat flow from the boundary layer to the core of the part (Schmitz-Justen, 1986). If the critical cooling rate is not reached, then the austenite will not change completely into martensite. The critical cooling rate depends on the carbon amount, the amount of other alloying elements, the austenitising temperature and the size of the grains (Laska, 1992).

Due to high temperature gradient in thick walled parts, the boundary layer cools down very fast. Therefore, the cooling is sufficient to reach the critical cooling temperature without external cooling, e.g. with water or oil (Zornhagen, 2009). In thin walled parts, there is not sufficient material volume in the hardened area for a steep temperature gradient to reach the critical cooling rate (Amende and Bödecker, 1985). If the wall thickness is less than 5 mm, heat accumulation is reported (Beyer and Wissenbach, 1998). To avoid the heat accumulation and reach the critical cooling rate, there are several possibilities. A material with a lower critical cooling rate (Müller, 1999) can replace the material if all other mechanical properties are justifiable. Furthermore, a temperature control can help to reduce heat accumulation and avoid overheating or melting at the surface (Zornhagen, 2009). Additionally, to increase the cooling speed, external cooling mechanism are possible (Müller, 1999 and Zornhagen, 2009).

2.2. External cooling

External cooling can be done either with solid, liquid or gaseous media (DIN 17022; Müller, 1999; Weißbach et al., 2015; Spur and Zoch, 2011 and Bartz and Blanke, 2000). For solid cooling elements, material with high thermal conductivity as cupper or aluminium are used (Müller, 1999 and Zornhagen, 2009). Kim et al., 2015 and Ki et al., 2014 show that hardening of thin walled parts with cupper heat sink is possible. Their results show that distortion is reduced and the microstructure is better if external cooling with solid cupper plates is used than without external cooling. One disadvantage of solid cooling components is that it is not flexible for other geometries and you have to be sure that you have a good contact between your part and the cooling component.

Water with or without additions or oil are commonly used liquid cooling media (DIN 17022). While the liquid easily can be applied on complex geometries it has to be assured that the processing area is not contaminated. Contamination might lead to process errors due to cooling, lower absorptions and interference of vapor with the laser.

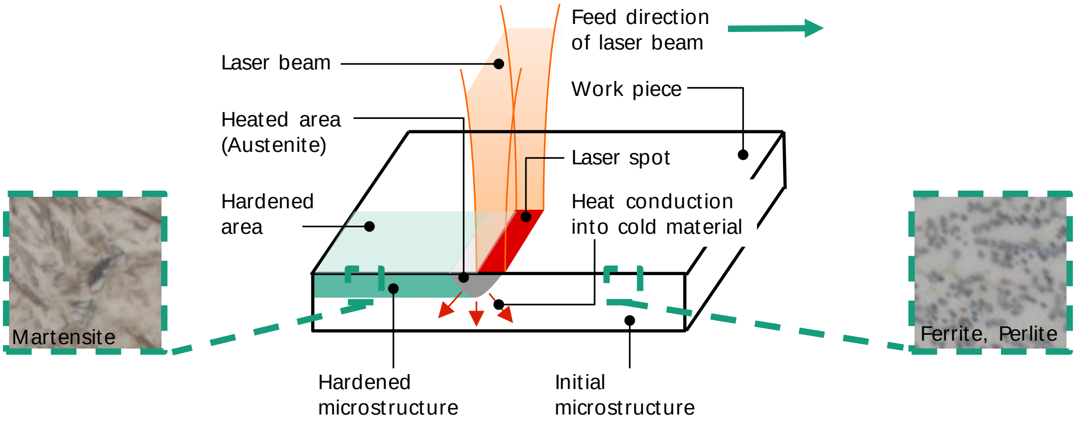

Fig. 1. Principle of Laser hardening

Compressed air is gaseous cooling media. The cooling effect is normally less than for liquid cooling media (DIN 17022), but it increases with increasing pressure. If a shielding gas is used for cooling, it can also protect the surface form oxidation (Polzin et al., 2007). The advantage of gaseous cooling medium is, that it will not cause the process errors due to contamination of the process zone. It is also possible to use it on complex geometries.

To combine the advantages of liquid and gaseous media – high cooling rate, localized cooling for complex geometries, no interruption of the laser beam and no contamination – cryogenic media can be used. As cryogenic liquids, liquid N_2 or liquid CO_2 are often used (Abrahams, 2013; Böhm and Kroh, 2014). Investigations show that the realized cooling rates of liquid N_2 and liquid CO_2 are comparable (Biermann, 2016) due to the Leidenfrost effect. To avoid the high safety instruction and complex handling for liquid nitrogen (Böhm and Kroh, 2014), only liquid CO_2 was used for the presented experiments. At room temperature and normal pressure CO_2 is an incombustible, nontoxic and inodorous gas. The liquid CO_2 is under high pressure in a gas container with riser pipe (dip-tube bottle). Due to decrease in pressure caused by expansion of the liquid CO_2 when it comes out of the gas container, it changes into solid particles and gaseous CO_2. At room temperature, the solid CO_2 particles sublimate residue-free. By the phase changing enthalpy, the temperature can reach -78 °C. Therefore, liquid CO_2 is used for the investigations.

3. Experimental Set-up

For the experiments, a Laserline LDF 5000-40 high power diode laser from Laserline GmbH, Mühlheim-Kärlich was used. The laser combines four different wavelength of 910 nm, 940 nm, 980 nm and 1040 nm. The maximum laser power is 5000 W and the beam parameter product is 40 mm·mrad. A laser light cable with a core diameter of 1000 µm was used. The used laser optic is also from Laserline GmbH. It has a homogenizing optical element and a focal length of 250 mm. With this optical set-up, the laser spot is rectangular with a size of 16 mm x 4 mm and a top hat intensity profile. To create a defined temperature at the part surface, a quotient pyrometer "Type 2" form Dr. Mergenthaler GmbH & Co. KG, Neu-Ulm was used. The pyrometer measured the temperature in the middle of the laser spot and controlled the laser power to hold the temperature constant. Fig. 2 shows the optical set-up and the experimental set-up.

The parts of C45E steel were mounted on a test bench. The size of the parts is 100 mm x 120 mm. This size was calculated for sought temperature and speed to have no influence on the temperature field. Therefore, this part size can be seen as infinite in length and width.

For cryogenic cooling liquid CO_2 from Linde AG, Pullach was used. The liquid CO_2 was guided through a high-pressure pipe directly from the dip-tube bottle to the part. A gas nozzle was used which cover the whole width of hardened area. The position where the cooling liquid hits the surface was about 20 mm behind the laser spot.

Table 1 lists the used process parameters. The parameters were used in a full factorial design of experiments with three repetitions each. After the laser hardening process the specimen were analyzed metallographic and the micro hardness was measured.

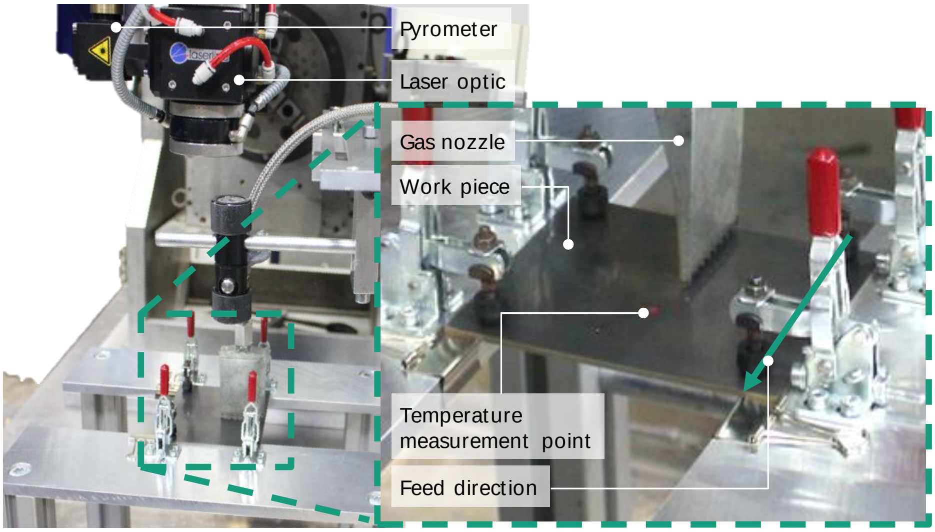

Fig. 2. Experimental set up

Table 1. Varied process parameters

Process parameters	Low	high
Temperature (°C)	1100	1400
Feed rate (mm/min)	300	3000
Part thickness (mm)	1	3
External Cooling	No	Liquid CO_2

4. Results and discussion

Fig. 3 shows the results of the micro hardness measurements and the microstructure. The first section shows the initial hardness of the part from C45E which is between 120 HV 0.3 and 160 HV 0.3. The hardness at the surface is reduced due to low carbon content there that comes from its manufacturing process. In addition, the grains crushed due to cold roll process.

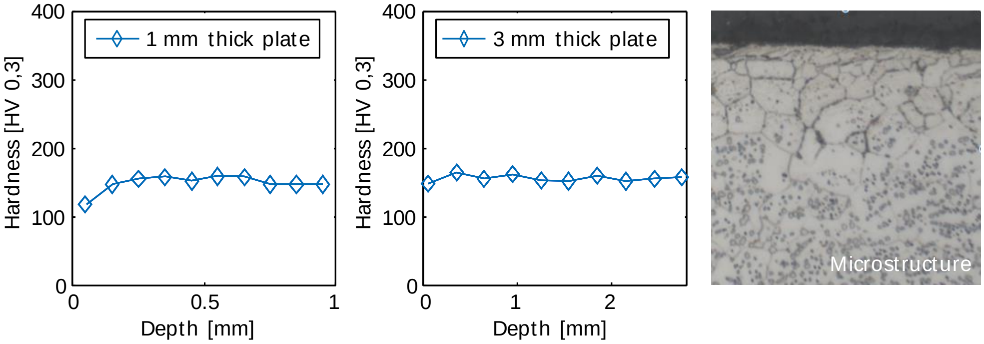

Fig. 3. Micro hardness and Microstructure of the initial C45E plates

4.1. Results for 1 mm thick plates

Fig. 4 shows the results for 1 mm thick C45E steel plate for the surface temperature 1100 °C and a feed rate of 300 mm/min. The critical cooling time to create martensitic microstructure for C45E between M_s and M_f-temperature (785 °C and 500 °C) is 1.5 s (Rudlaff, 1993). The results show that without any external cooling, the critical cooling time was not reached. There is no martensitic microstructure, only ferrite, perlite and bainite were detected. The hardness is a slightly higher than the initial hardness.

On the other hand, when cryogenic cooling is applied the part is completely hardened over the whole thickness. It has a hardness of around 600 HV 0.3. There is mostly martensitic microstructure in the hardened area.

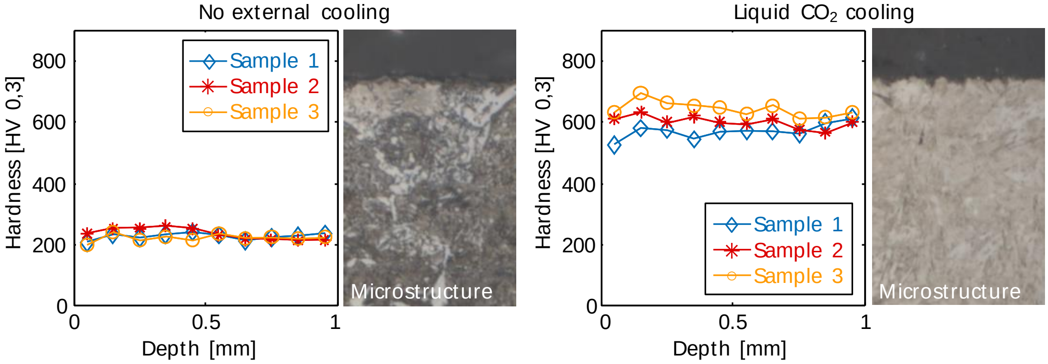

Fig. 4. Hardness and microstructure for 1 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1100 °C and a feed rate of 300 mm/min

For an increased feed rate of 3000 mm/min (see Fig. 5) there is also no hardening without external cooling. Withal the feed rate increases ten times, there is still a temperature accumulation that the M_f temperature could not be reached fast enough. The microstructure consists of ferrite, perlite and bainite. With cryogenic cooling, there is a hardening, but only at the surface with a hardening depth of approximately 0.2 mm. Due to the high feed rate in both cases independent from cooling, the temperature into the depth of the part is not high enough to austenitize the part in deeper regions. Therefore, the hard martensitic microstructure occurs only at the surface.

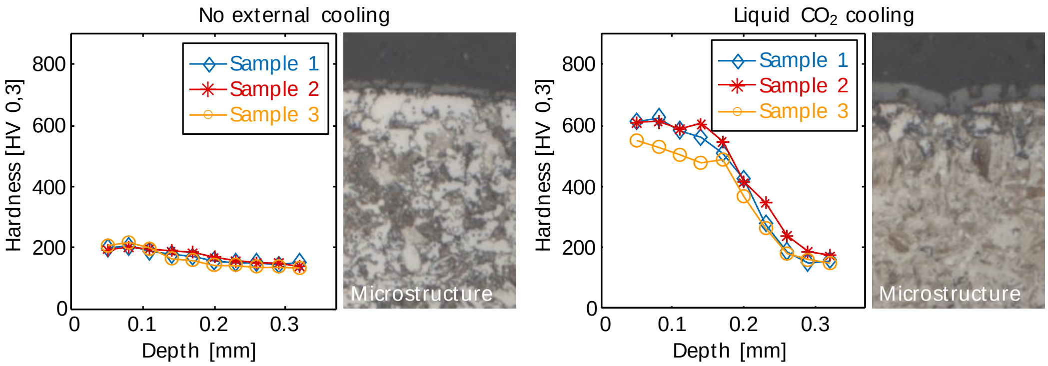

Fig. 5. Hardness and microstructure for 1 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1100 °C and a feed rate of 3000 mm/min

Fig. 6 shows the results for a feed rate of 300 mm/min and a surface temperature of 1400 °C. There is a hardening of the plate without cryogenic cooling. The microstructure shows martensite, but needles are rough and the grain size is coarse. Due to high temperature and low feed rate, the possible germs for perlite formation are solved and therefore the critical cooling rate decreases. In some areas, there are perlite, ferrite and bainite in the microstructure, so the hardness is not constant. The cryogenic cooling helps to get a constant hardness through the whole part. The martenisitc needles are fine and therefore the part is more though.

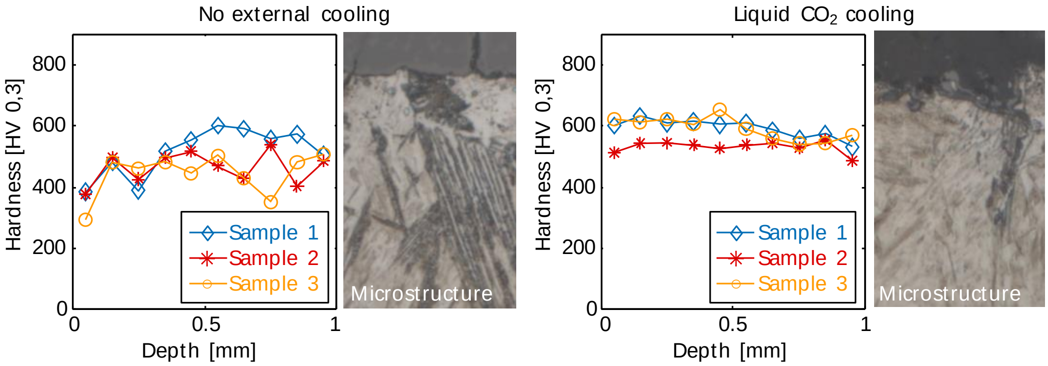

Fig. 6. Hardness and microstructure for 1 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1400 °C and a feed rate of 300 mm/min

Fig. 7 shows the results for feed rate of 3000 mm/min and temperature of 1400 °C. Due to the limited laser power, only 1200 °C was reached. Without cryogenic cooling, no martensite occurs and therefore the part is not hardened. With liquid CO_2 cooling, there is a martensitic microstructure at the surface. The hardening depth is up to 0.25 mm and therefore a little bit higher than in Fig. 5. Due to the increased surface temperature, the depth of austenitisation increases and therefore the hardening depth arise.

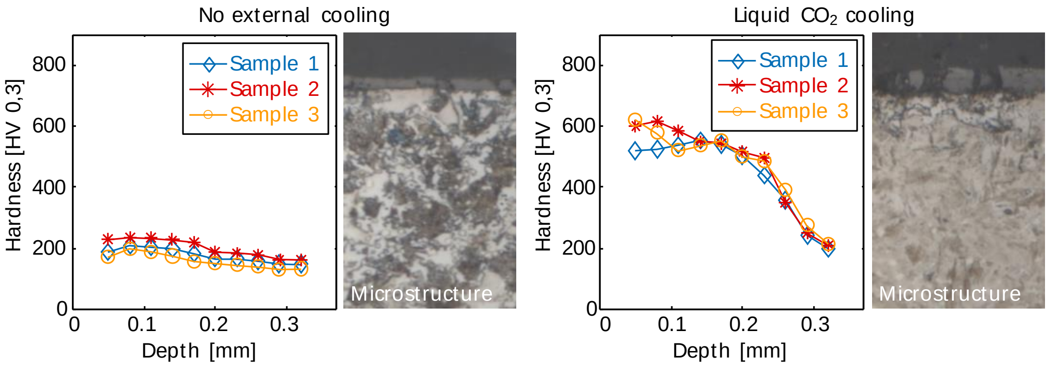

Fig. 7. Hardness and microstructure for 1 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1400 °C and a feed rate of 3000 mm/min

4.2. Results for 3 mm thick plates

Fig. 8 shows the results for 3 mm thick C45E steel plate for a feed rate of 300 mm/min and a temperature of 1100 °C. Without external cooling, there is no hardening. The microstructure consists of ferrite, perlite and bainite. The critical cooling rate was not reached. Also for cryogenic cooling, there is only a little hardness increase at the surface. The microstructure also shows ferrite, perlite and bainite. Due to higher amount of material in the hardened area, the temperature gradient for the low feed rate is very steep. Therefore, the area between M_s and M_f temperature is located closer to the laser spot. In the particular case, the cooling position is about 20 mm behind the end of the laser spot and seems to be too far away to have a significant effect.

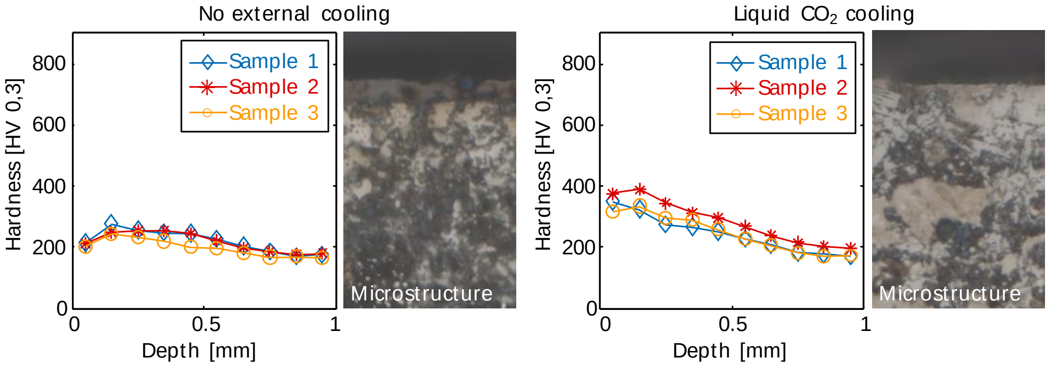

Fig. 8. Hardness and microstructure for 3 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1100 °C and a feed rate of 300 mm/min

With the increased feed rate of 3000 mm/min and temperature of 1100 °C, shown in Fig. 9, the material volume is high enough to reach the critical cooling rate. The cryogenic cooling increases the hardness slightly compared to self-quenching. This is caused by a reduced annealing effect, which can also be indicated by the brighter microstructure.

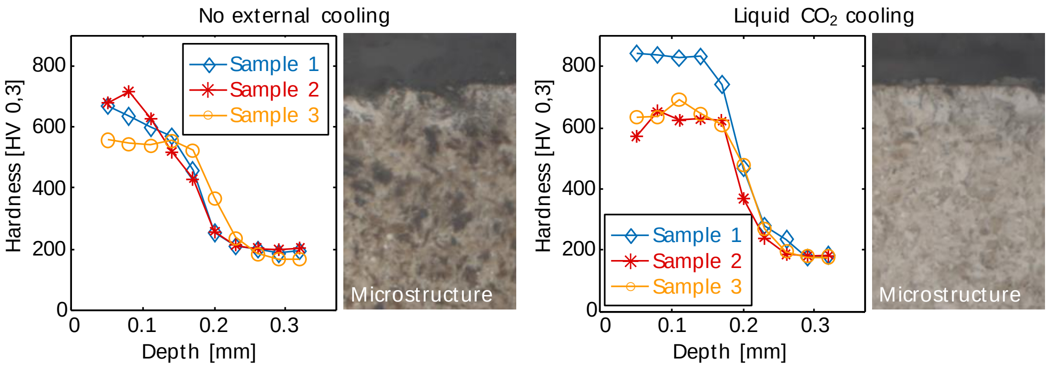

Fig. 9. Hardness and microstructure for 3 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1100 °C and a feed rate of 3000 mm/min

Fig. 10 shows the results for feed rate of 300 mm/min and a temperature of 1400 °C. Without cryogenic cooling, there is no sufficient hardening. The microstructure shows ferrite, perlite, bainite, and only less martensite. Due to the overheating, there is the same effect for germs for perlite like for the 1 mm plate. The cryogenic cooling helps to reach the critical cooling rate. To increase the hardening depth above the shown 0.5 mm, the cooling position has to be placed closer to the laser spot. The bainite microstructure in the deeper part region indicates that the critical cooling rate was only reached at the surface, not in the depth of the part.

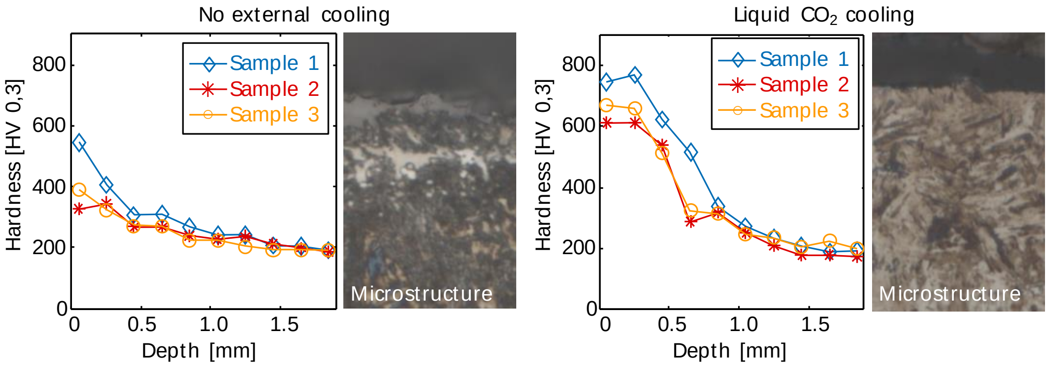

Fig. 10. Hardness and microstructure for 3 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1400 °C and a feed rate of 300 mm/min

The results for feed rate of 3000 mm/min and 1400 °C are shown in Fig. 11. Like for 1 mm thick plate, the laser power limits the surface temperature up to approximately 1200 °C. There is no significant difference, either in the microstructure than in the hardening depth for no external cooling or cryogenic cooling. Therefore, the critical cooling rate without external cooling is sufficient.

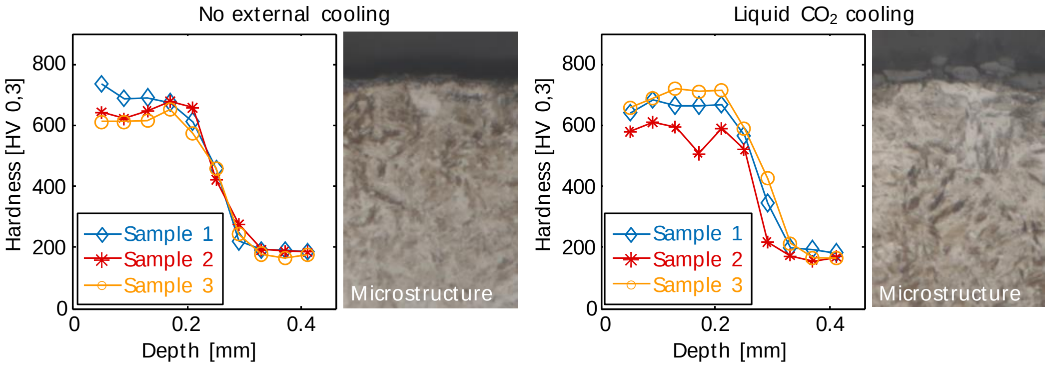

Fig. 11. Hardness and microstructure for 3 mm thick plate without (left side) and with cryogenic cooling (right side) for a surface temperature of 1400 °C and a feed rate of 3000 mm/min

5. Conclusion

Cryogenic cooling helps to harden thin walled parts. The critical cooling rate, which is necessary to gain hard martensitic microstructure can be reached with an insufficient material volume. Especially for components with a thickness of 1 mm, cryogenic cooling is necessary to get a hardened surface. Furthermore the cryogenic cooling helps to get a fine needled martensite. To get a suitable cooling, the position of cooling with respect to the temperature, feed rate and material thickness is important. The cooling must be located, where it can speed up the cooling rate between M_s and M_f temperature. A dislocation can at least have only an effect to avoid annealing effect. For the chosen process parameters for a plate thickness of 1 mm, the cooling position 20 mm behind the laser spot significantly influences the cooling rate of the part. For increasing part thickness, in particular case for 3 mm, the cooling position should come closer to the laser spot to increase the cooling rate between M_s and M_f temperature. To get a closer look at the process mechanisms and boundaries of laser hardening of thin walled parts, investigations with other materials and other cooling media occur. Furthermore, the cooling position will be adjusted.

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