Diplomarbeit

Laser hardening of deep drawing tools for industrial usage

Fundamentals, geometrical considerations and guidelines for successful hardening

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs

unter Anleitung von:

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I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

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Summary

In this thesis the wear mechanisms of sheet metal processing tools and the prevention of these problems are studied. The typical wear behavior of plate bending and cutting tools can be derived from the surface hardness of the tools. By laser transformation hardening the tools' surface hardness is measured, the microstructure is observed and than a comparison is made between conventional heat treatment methods (induction hardening, oven hardening), coating methods (including nitriding) and the laser transformation hardening. The experiments are made on three different steels, C45 (DIN 1.1730), 1.2312 (M200, hot work tool steel) and 1.2379 (K110, cold work tool steel). The two simplest geometry features (bending radius and 90°cutting edge) are chosen to determine the possible laser hardening strategies. First the bending radii are investigated. The aim was to find an optimal laser hardening method by taking the wear behavior into account. By this means the so called "three times hardening" is introduced, by hardening the bending radii from 3 angles (top, side and 45°). The result shows that the overall reachable hardness is definitely high (60-62 HRC) and the back tempering effect of the overlapping zones is relative small and it can be neglected. Than the laser hardening of cutting edges from different inclination angles is investigated. Three different angles are chosen (45°, 70° and 90° respect to the cutting direction of the tool) to select the right hardening angle. The results show that the 90° is the best to prevent the melting of the tool's edge and to reach a constant layer thickness. This investigation also shows that the cutting tool can be resharpened several times so tooling costs can be spared. Taking together, these results are useful to increase the efficiency of the laser hardening technology and to decrease the tooling and maintaining costs of companies.

Kurzfassung

In dieser Diplomarbeit werden die verschiedenen Verschleißmechanismen von Tiefziehwerkzeuge bzw. die Prävention dieser Probleme durch Laserhärten untersucht. Die Abnutzung der Werkzeuge kann bei der Verarbeitung von Metallblechen in vieler Fällen von der inadäquaten Oberflächenhärte abgeleitet werden. Aufgrund der niedrigen Härte des Werkzeugs entstehen Kratzer auf der Tiefziehradien und an den Schnittkanten, die später auf das zuverformende Blech übertragen werden. Die erarbeitete Laserhärtestrategie ist daher von großer Bedeutung zur Vermeidung solcher Oberflächenbeschädigungen für industrielle Anwendungen. Im ersten Teil wird der theoretische Hintergrund und der Stand der Technik von Laser dargestellt. Danach gibt es ein kleiner Umweg, wobei die möglichen Härtemessungsmethoden untersucht werden bzw. das passende Verfahren für Härtemessung von Dünnschichten ausgewählt wird. In der Experimente werden die zwei einfachste Geometrielemente von Tiefzieh- und Presswerkzeuge tiefgreifend analysiert, nämlich die Tiefziehradien und Schneidkanten. Zuerste wird die übliche Härtestrategie von Radien mit Hilfe von mikroskopische Aufnahmen erläutert und nachher wird eine verbesserte Methode, sie sogenannte „dreimaliges Härten“ (engl. „three times hardening) vorgeschlagen. Die neue und erweiterte Methode verringert die Rate der Abnutzung und erhöht damit das Lebensdauer der Werkzeuge bis zu 500 %. Für die Experimente werden Proben aus drei gewöhnlichen Werkzeugstähle hergestellt, nämlich 1.2312 (Warmarbeitsstahl - Böhler M200), 1.2379 (Kaltarbeitsstahl - Böhler K110) und 1.1730 (Karbonstahl - C45). Die Geometrie der Proben wurde so eingestellt, dass die Größenänderung von der Radien mitberücksichtigt werden kann. Nach dem ”Einmal-” und ”Dreimalhärten” werden die Proben geschnitten und für Ätzen vorbereitet, um mikroskopische Aufnahmen zu machen bzw. um die Unterschiede der Methoden untersuchen zu können. Beim Härten von Schneidecken werden die gleiche Stähle verwendet. Hier wird die Funktionalität und Schneidrichtung ebenfalls mitberücksichtigt, um den besten Einfallswinkel des Laserstrahls zu finden. Die Ergebnisse werden durch realen Werkzeuge validiert und ferner wird auch die Effizienz des Laserhärtens von Kostenseite her geprüft.

Danksagung

Recht herzlich möchte ich mich bei den Personen bedanken, die bei der Erstellung dieser Arbeit mich unterstützt haben. Im erstens möchte ich einen großen Danke mein Betreuer Prof. Liedl aussprechen. Ich habe wirklich sehr viel von Ihm über Laserbearbeitung gelernt und ohne diese Kenntnisse wäre diese Arbeit nicht möglich gewesen. Ich möchte natürlich bedanken an meiner Frau Ildikó und meiner Tochter Lilla, dass Sie mir so viel geholfen haben, speziell wenn der Abgabetermin war schon zu nah. Vielen Danke an meiner Eltern, die mir dieses Studium ermöglichten und mir ganzer Zeit seelisch ermutigten.

Contents

Abstract

Today laser technology is the essential and inevitable part of the general industrial manufacturing and machine building. Cutting plates from aluminium, steel and plastic or welding different materials are widely used technologies all over the world. Lasers have arrived to this state on a long route, since the first solid state laser (the Ruby laser) was invented in 1960 by Maiman. As the first semiconductor lasers appeared on the market R&D in laser technology became a very important niche in the industry. The cooperation between universities and companies led to different types of lasers. They are usually classified by the source of the laser radiation and the emitted wavelength. Even though experts have discovered a lot of laser materials the general industry uses only a few types and the main cause for that is their quite low plug-in wall efficiency. Hopefully the research continues and sooner or later we will meet a lot of different machines specialized in different fields. Recently the most widespread lasers are solid state and CO2 lasers, because diode lasers cannot reach the same beam quality as the others and it is a crucial problem when cutting. The other cause of not using diode lasers is the price. Although the cost of diode and excimer lasers decreasing year by year, they are still expensive compared to other laser sources especially if one compares the same throughput and beam quality between different types of lasers.

So the main topic of this work is to give a brief and dense introduction to laser hardening, to show the latest developments in the laser hardening of deep drawing and cutting tools in the automotive industry. After describing the state-of-art laser types this work will show the current state of the laser hardening technology. The principles of laser transformation hardening will be described to understand the differences compared to conventional methods. Later the economical aspects are discussed, whether the laser hardening is beneficial or not. Before the first experiments the hardness measuring method has to be controlled, because the relative thin layer of the hardened track cannot be directly measured with conventional methods, such as Rockwell C or Brinell. At this part two typical geometric features will be deeper examined: Bending radii and cutting edges. First the typical failures of deep drawing tools are investigated to understand why is the hardness of the surface important. After declaring the backdraw of using multiple track on a surface, a better hardening method of bending radii is introduced. This means the radius has to be hardened from three sides to ensure a higher surface hardness on the areas where the blank constantly scratches the surface. With the help of micrographs and hardness measurement the impact of overlapping zones is investigated. In the next part the best irradiation angle of cutting edges will be experimentally

found. After several samples the result are validated by real life parts from the automotive industry. The results show the best ways to harden deep drawing and cutting tools by minimizing the chances of burning and by maximizing the overall hardness of the functional surfaces.

Chapter 1

Introduction

1.1 The motivation of this thesis

The aim of hardening is not only to use the tools more so the company can reduce to maintenance costs but also to lower downtimes. The price of raw material is increasing and the cost of human resources too. This results in the need for special high end tooling which can withstand the everyday struggles and it can work perfectly until the newer model comes. Which problems can occur on these? Mainly the different types of wear not to mention the human failure. This thesis aims to investigate the state of art laser hardening techniques of sheet metal bending and cutting tools and to develop these to a higher state to improve the lifetime of tools and to decrease costs of maintenance and tooling.

1.2 The goal of this thesis

Firstly this thesis aims to introduce the laser transformation hardening. Than it will be compared to other state of art technologies, such as nitriding, induction harden or vacuum harden. To make this, some measurements had to be taken, because the conventional hardness measuring method cannot be always used. This means the smaller layer thickness compared to other methods doesn't allow to use high forces during measuring, because it can break through the hardened layer and the measurement fails. Therefore other measuring tools are used during the experiments. Last but not least, specific the geometries and features on the tools are have to be found where the highest stresses occur and the state of art hardening techniques has to be developed to a stage where the functionality of the tools is also taken into account. As later mentioned these can be reduced to two main geometrical features: radiuses and cutting edges. As a result I aim to get a more sophisticated and efficient method of laser hardening to reach higher value tools.

1.3 The main goals of the experiments

For the radii the currently available simplest method is taken the so called “one time hardening” (see figure 3.24) and some investigation was made to understand what happens if more hardened tracks on one radius are created and how affects this the overall pricing and the lifetime. The hardness along the radius is measured and compared to the simple one time hardening. The influence of the radius size and the material is also investigated. This will be measured with three kind of materials Böhler K110 (1.2379), M200 (1.2312) and C45 (1.0503) and they will be compared to each other to decide which would be the best to create a bending insert. Unfortunately due to the lack time it wasn’t possible to get a good sample for cast iron which is a very popular material for bending tools, but some simple measurements were taken on a smaller sample and so some results are derived from that information.

In case of cutting edges the best way of hardening respect to the functionality of the tools are found. By taking the cutting direction and the possible re-sharpening direction of the cutting tools the different angles of incident are compared to reach the best solution. The measurements will be taken by three different materials (Böhler K110 (1.2379), M200 (1.2312) and C45 (1.0503)) to understand the differences and to find the best for cutting.

1.4 The structure of the thesis

The thesis has five chapters, starting with the introduction. In the intro the main problem of the tooling and the end users (the sheet metal processing companies) stated than the goals of the work. After defining the goals the first approach is described, including the materials used, the problematic of the hardness measurement etc. In the second chapter the theoretical background will be detailed. By starting with the definition of laser transformation hardening, the effects of laser radiation on steels will be presented including the parameters influencing the hardening process. After this part the macroscopic changes of the material will be shown after hardening including the deformations and the oxide layer. Some micrographs will be presented to see what happens inside the material. In the next section the different types of wear and their cause will be declared, than the currently available possible solutions for these problems will be shown. Here the different technologies will be compared to each other which are used for tool’s lifetime improvement in terms of cost, lead time, post treatments (deformations) and the presence of foreign material in/on the surface. Than in the next chapter the experimental setup will be shown, including the peripheral devices, the materials, the hardness testing methods.Then there will be smaller section to show the effect of choosing the right testing method which can result in a huge difference in the measured values. After this part the preparation of samples and the different geometrical features will be presented which were used for this thesis. Than in the following chapter the results are explained and through real life examples some lifetime improvements and cost reduction are exposed after using this technology. In the following chapter the company is presented which made the whole master thesis possible. This is followed by the summary of this work with the experimental results and some future benefits and further possibilities of development in this field.

Chapter 2

The theoretical background

The application of laser hardening of steels can be dated back to the first lasers [39]. After discovering the possibilities, the researchers in this field had to face many problems. The commercially used CO2 lasers' wavelength cannot be absorbed very well by steels, this means about 10 % of the total incoming laser power is absorbed. That is why these systems could be only applied by laboratories or in highly automated circumstances by car manufacturers and OEM-s.The second one is the high price of such laser systems. Fortunately the rapid development in the last 10-15 years led to an abrupt decrease of the investment and the maintain costs of lasers, so such applications are already possible in so called “job-shop” manufacturing systems. Today the typically used laser sources for hardening are solid state lasers and diode lasers. Both have their advantages and disadvantages, for example solid state lasers are usually very precise regarding beam quality, so it can be focused to very small spot sizes and the intensity profile is very close to the Gaussian. This is very beneficial for cutting but not for hardening. In this case the beam quality should be rather low since the intensity distribution vertical to the track line has to be at least top-hat or an optimized top hat distribution, the so called armchair profile (first calculated by Burger [1]). In the following sections I will characterize some of the most important principles and experienced attributes of laser hardening, so the reader will get an impression about the phenomena of the laser heat treatment process.

2.1 The LASER

The LASER word is an acronym of Light Amplification by Stimulated Emission of Radiation. The lasers can be classified by the type of the laser active medium. In this medium takes place the population inversion, the most important event in the laser technology. The population inversion describes a pheomena which was

first assumed by Einstein.
The commonly used laser sources are

- Solid state lasers
- Gas lasers
- Diode or semiconductor lasers

2.1.1 Solid state lasers

The functionality of solid state lasers is based on the active medium which has special (rare earth) ions embedded into a host crystal e.g. Nd:YAG. The doping element determines the wavelength of the source, this can be for example Ytterbium (Yb:YAG - 1030 nm), Neodymium (Nd:YAG - 1064 nm) or even dislocations in the crystal. The typical amount of the doping element in the host crystal is about 0,1-1 %. In the case of Neodymium ions the pumping lamps add the energy for the population inversion and the YAG crystal (Y3Al5O12) has an optimized refractive index and thermal conductivity to withstand the high power laser light traveling through the laser active medium. This type of laser is optically pumped with flash lamps or with diode lasers depending on the design and construction as seen in figure 2.1.

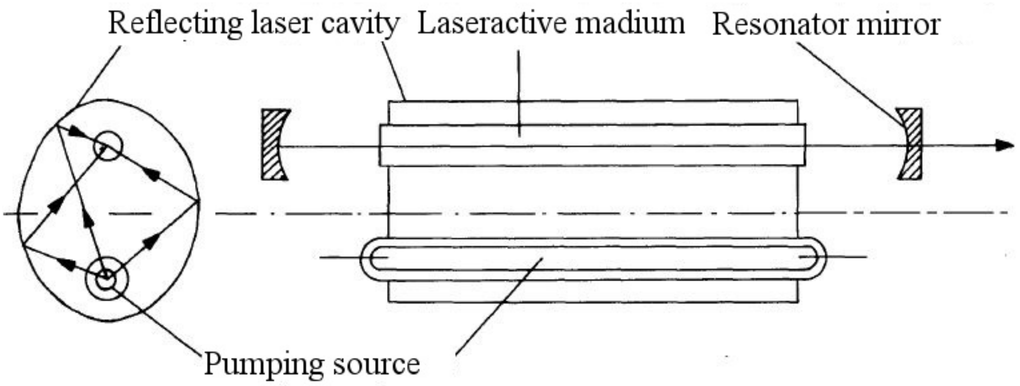


Figure 2.1: Nd:YAG laser basic structure. The laser cavity reflects the lamp's emission. Instead of lamps diode lasers are also commonly used. Source: [2]

The most common construction types are slab-laser, fiber laser and disc laser. Thanks to the good absorption in this wavelength in steels the Nd:YAG lasers are widely used in the everyday material processing of metals. The applications including cutting, welding and wire cladding, where the beam quality plays an important role. The overall efficiency, which goes up to 20% enable these types to be used in industrial applications even by smaller companies. Note there are smaller firms who are specified to laser welding, using 2-5 machines to satisfy even very big partners from the automotive industry. In the following figure 2.2 we can observe a commercially available Nd:YAG manual laser welding machine and a aluminium mold repair (figure 2.3)which is a typical use of such machines. The small lines are manually welded with ⌀0,8 mm welding wire made of 1.2344 steel.

Figure 2.2: Alphalaser ALM for laser welding. Source: [6]

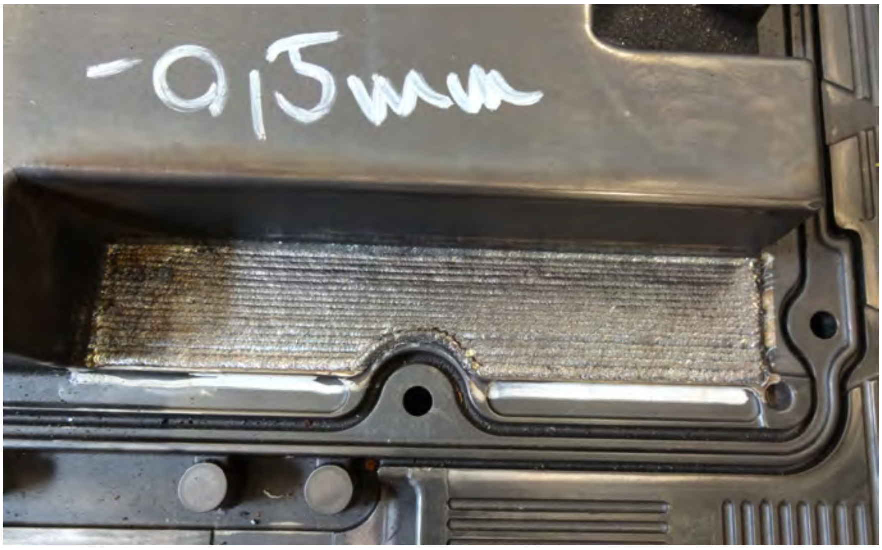


Figure 2.3: Typical application of solid state lasers: repairing of worn molds. Source: [5]

2.1.2 Gas lasers

Gas lasers were the first commercially applicable laser sources. They usually contain a mixture of different atoms or molecules. The most common types are Excimer, He-Ne lasers and CO2 lasers. The Eximer Laser is a special type of lasers, the word “excimer” is an artificial word made of “excited dimer” since the laser active medium in these systems are diatomic molecules which are only existing for short period of time [2]. These molecules in commercial systems confine to inert gas-halogen gas connection such as ArF or KrF. In the laser cavity the atoms of the gases are get into an excited state until they create molecule together for a short time. After this short period the molecule falls apart and the residual energy will be irradiated on a certain wavelength according to the energy level of the molecules (KrF - 248 nm, ArF - 193 nm). Since these art of lasers have a very small efficiency (1%) they aren’t utilizable for laser hardening.

The He-Ne lasers are in the same situation as the excimer lasers. Even though they offer a better coherence, beam quality and even shorter wavelengths the advantages of solid state lasers and semiconductor lasers are overwhelming [3]. The laser gas is a mixture made of two gases Helium and Neon. The Helium gas atoms’ excitation is achieved by electrical discharge. The kinetic energy of the He atoms will be transferred to the Ne atoms. After leaving their excited state the Ne sends out electromagnetic waves in certain wavelengths depending on the shell of the electrons. Even though the wavelength of these lasers would be better regarding the absorption coefficient, the maximum energy in continuous mode is about 10-50 mW which makes laser hardening with them impossible.

CO2 gas lasers containing three gases, Nitrogen (which will be excited through electrical discharge or radio frequency), CO2 (which is the laser medium) and Helium for efficient cooling. The light emission is achieved by the”jumping” between the different vibrational states of the CO2 molecules (see figure 2.4). The emitted wavelengths are 9,6 and 10,6 µm, but the probability of emitting 10,6 µm wavelength is higher so the literature is referring to the CO2 laser with a nominal 10 600 nm wavelength.

Even though its plug in wall efficiency goes up to 10-20 % the CO2 lasers are rarely used in laser hardening applications. The main problem is the low absorption coefficient of metals, especially steels and iron to the CO2 laser’s radiation. The absorption of the emitted wavelength of the solid state lasers or the semiconductor lasers is almost 3 times bigger than the CO2 (see figure 2.5). Accordingly the CO2 is well suited for laser hardening but the huge demand for high power supplanted them with solid state lasers and semiconductors. The only place where the CO2 remains inevitable in the material processing is the laser cutting. The high reflectivity and near Gaussian beam allows the laser radiation to enter the molten material (the keyhole) as deep as possible so a deeper cut is achievable.

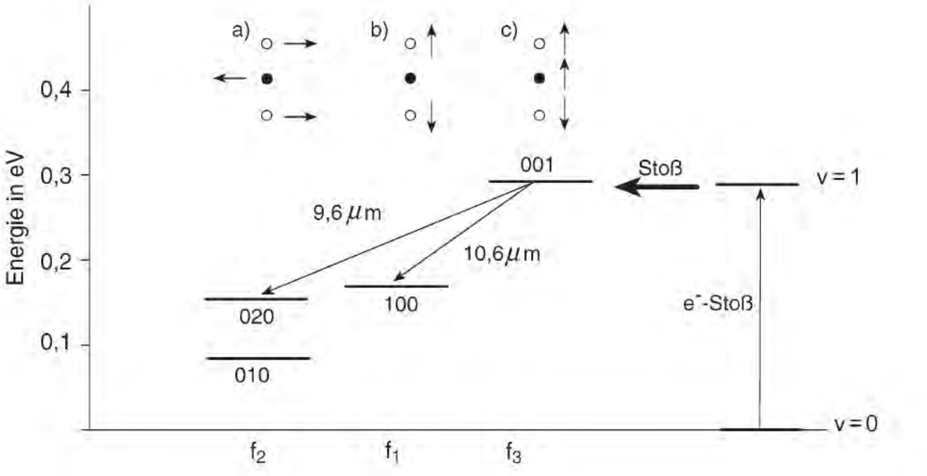


Figure 2.4: The vibrational states of the CO2 molecule and the emitted wavelengths. Source: [2]

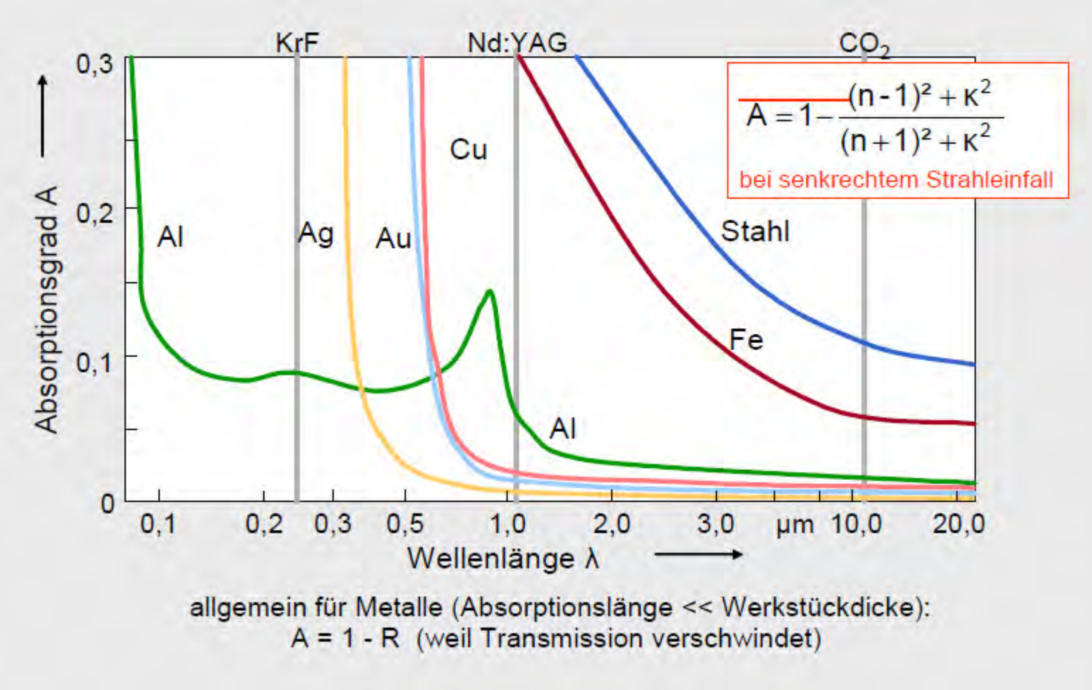


Figure 2.5: The absorption rates in different materials on different wavelengths. Source: [4]

2.1.3 Semiconductor lasers

Semiconductor lasers were first described right after the ruby laser in 1962. Nathan, Quist and Hall used GaAs, while Holonyak and Bevacqua tried GaAsP as medium for the population inversion. Unfortunately this had a quite low efficiency combined with a bad beam quality, so until the end of the 20th century the semiconductor lasers were only used by researchers for experimental purposes. As the technology evolved to a state where the throughput of these machines reached several hundred Watts the semiconductor lasers became an important equipment in material processing. The cutting and welding application are widely used not only with steels but also with polymers. The semiconductor lasers are based on the pn junction of diodes. The laser diode contains a p-doped and a n-doped semiconductor part separated from each other. As the current starts to flow between the two sides of the diode the recombination of holes with electrons results in light emission (see figure 2.6). On lower current flow this is spontaneous emission, so the diode works as a traditional LED. If the current density goes higher after a threshold the electron and hole density reaches a state where population inversion occurs. This leads to the emission of laser light on the specific wavelengths of the material.

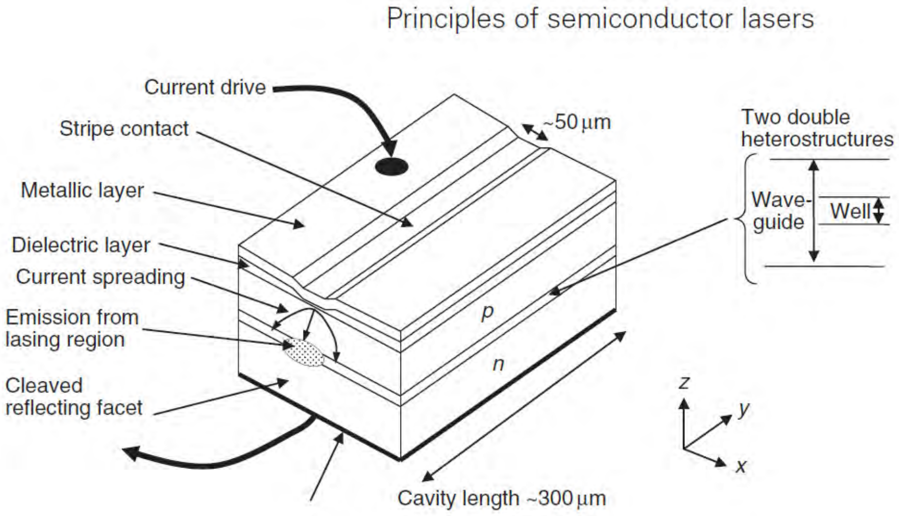


Figure 2.6: The operation principles of laser diodes. Source: [29]

The average throughput such diodes is 1-20 W each so to reach several kW one need to multiply and arrange the single diodes such way that the power of each diodes can be combined. Using passive micro-optics the diodes are arranged in -so called- bars. The bars can be further arranged into stacks until these units can radiate several hundred Watts continuously. Using wavelength multiplexing or Bragg grating (see figure 2.7), the output can be scaled to more than 10 kW. By this means the laser source will be powerful with a relative bad beam quality and coherence. In the field of macro metal processing such as welding, cutting, cladding or hardening power densities of $10^4 - 10^5 W/cm^{-2}$ are enough, so even cutting is viable.

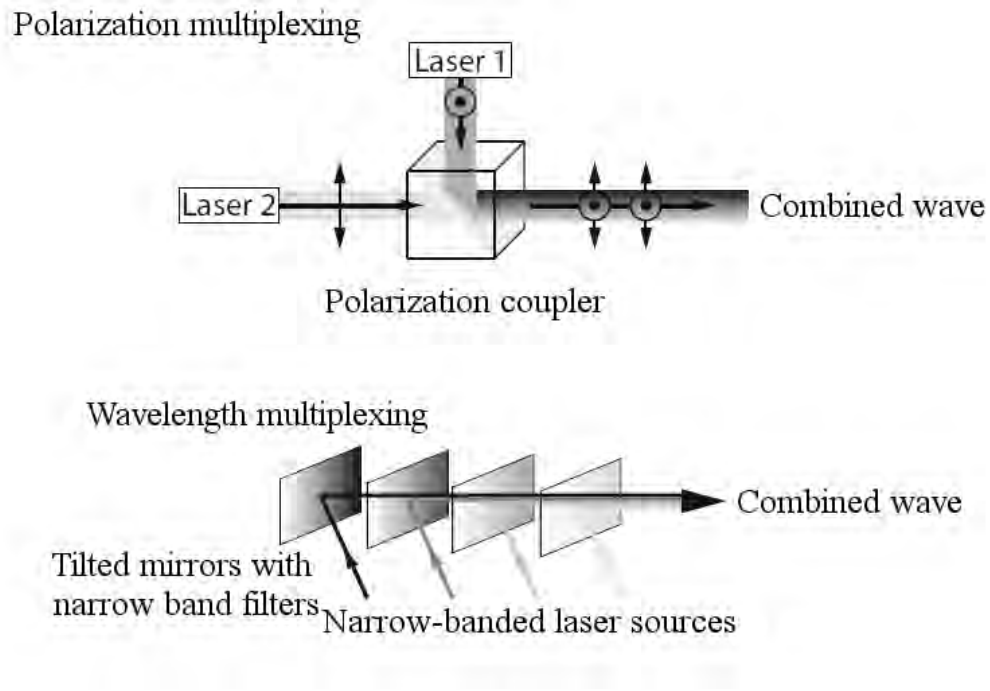


Figure 2.7: Polarization and wavelength multiplexing. Source: [2]

2.2 The principles of laser transformation hardening

The laser hardening technology is based on several physical effects including material heat conduction, beam-material interaction and other metallurgical issues which need to be considered. The surface of the metal will be irradiated with a certain amount of power to warm up the surface up to 1000-1200°C. As the surface reaches 400-500°C an oxide layer forms which affects the absorption on the surface significantly. The heat conduction transfers the heat to deeper layers of the material where perlite transforms into austenite due to the very high temperature. As the laser spot leaves the interaction zone the so called self quenching occurs (this could mean even 6000 K/s [7] cooling speed) which is enough to transform the material into fine grained martensite or even (depending on the material of course) leave a lot of retained austenit behind (see figure 2.8). This means also that the laser transformation hardening is only applicable if the steel has enough carbon to form martensite. This condition automatically decrease thee number of hardenable steels to a certain group of materials.

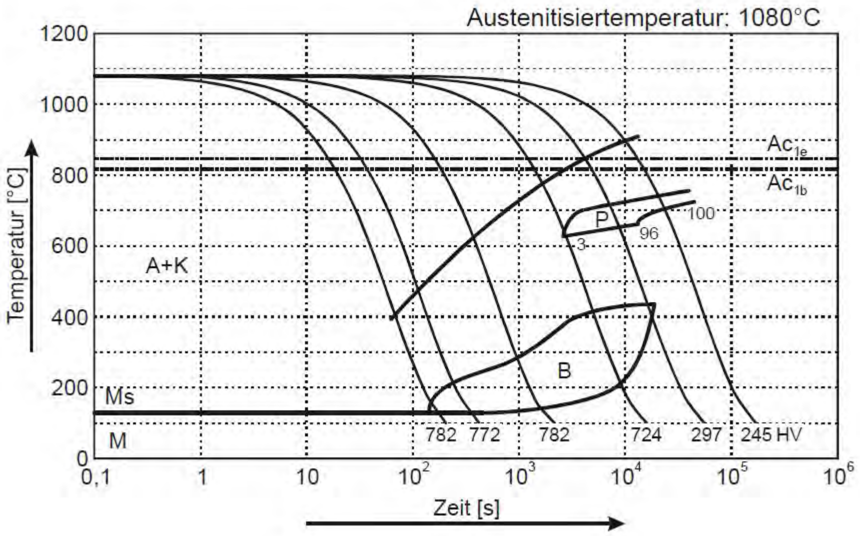


Figure 2.8: The continuous cooling transformation diagram (CCT) of Böhler K110 steel (1.2379), Source: [36]

There are several beneficial behaviors of the martensite "coated" steels. Ingelgem et al. observed the higher corrosion resistance which occurs due to the existence of retained austenite. The high ratio of austenite combined with nitrides in special alloy steels could improve the resistance against NaCl solutions [7]. The high hardness of the martensite layer on a soft bulk material results a high resistance against abrasive wear without pitting and cracks in the material or the surface. In normal volume hardening a tempering right after the quenching is usually necessary. If the highest hardness needs to be reached on the surface without losing the toughness of the base material (e.g.: knives, pressing/punching tools, forging dies etc.) the laser hardening is an optimal solution. There's no need to use cooling but we need to be careful when one tries to harden low alloyed carbon steels. In the case of C45 for example, the steel can be hardened up to 60 HRC but only if there's enough bulk material which can transfer the heat away from the processing zone. If the thickness of the material is lower than 10 mm one might need to use cooling material such as water or oil. The reason is the cooling speed:

It might not high enough to transform to material into martensite or (which is usually expected, see figure 2.9) the low cooling speed induces a back-tempering of the surface (for c45 the drop of the hardness starts at 100 °C !). On the TTT diagram is clear if the part's cooling rate is lower than 1000 K/s it will be rather perlitic or bainitic.

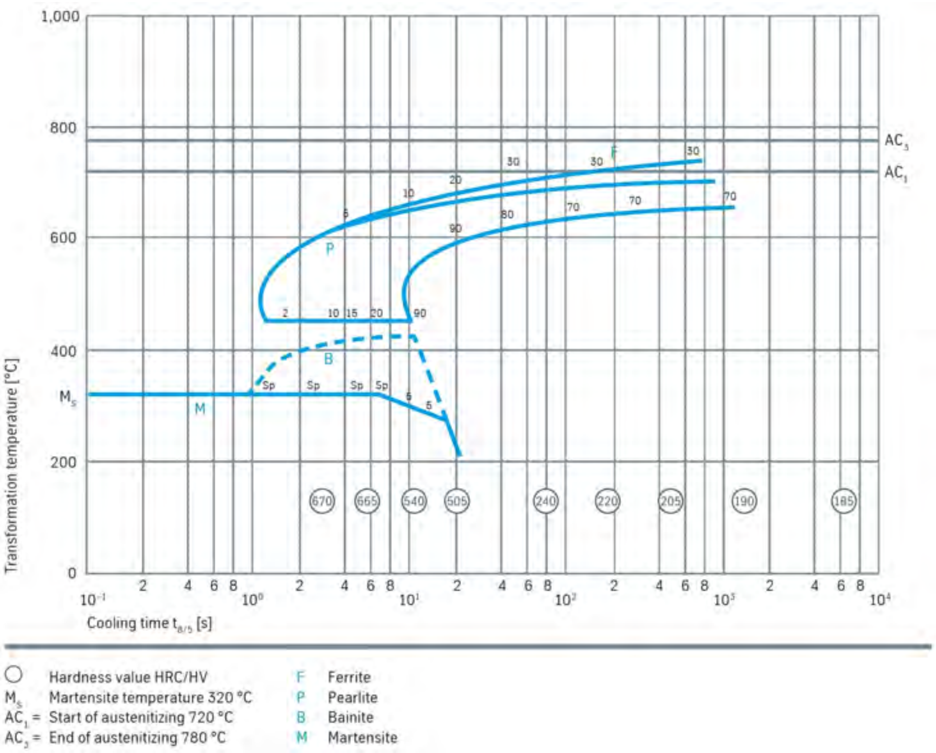


Figure 2.9: The Time-Temperature-Transformation diagram (TTT) of 1.1730 carbon steel. Austenitizing temperature 870 °C, holding time 15 minutes Source: [37]

There is one more important phenomena which needs to be mentioned to understand the results of the heat treatment. It's vital to understand the fact that the process of laser hardening causes volume and structural changes of the material. During hardening the perlite turns into austenite and the material expands due to the heat. The high temperature causes a rapid fall of the yield strength and this creates stresses in the surface layer. As the stresses step over the yield strength of the material (which is lower due the high temperature) the material experiences a plastic deformation (see figure 2.18). This creates a hump on the hardened track so the hardened material will deform. This effect is similar the laser assisted bending as seen in figure 2.10.

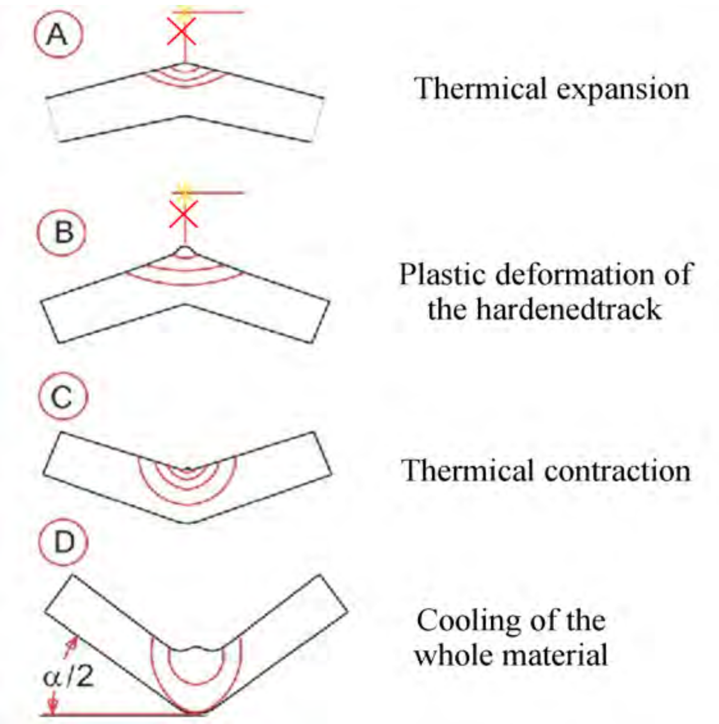


Figure 2.10: The principles of laser assisted bending. Source: [4]

2.2.1 Laser hardenable materials

The hardenability of steels is mostly related to the carbon content. The other very important factor of the hardenability is the amount and type of the alloying elements, since they can decrease the critical cooling speed rate to form martensite. The solubility of the carbon in austenite is much higher than in perlite and ferrite so the carbon atoms of the material diffuses into the austenite lattice (see figure 2.11). As the rapid cooling occurs the austenite transforms into martensite which leads to a torsion in the microstructure. The torsion or the deformation of the lattice creates a stress in the microstructure which shows a drastic increase of the hardness. The main element for a laser hardening is carbon, that means every steel which contains at least 0,2 % carbon can be heat treated with conventional methods. The rapid cooling during laser hardening allows smaller carbon content, so with laser some structural steels are still hardenable. Typical examples for structural steels are S235 and S355, they are low alloyed and contain maximum 0,23 % C. They still can be hardened between 40-50 HRC depending on the material source. Unfortunately the uniformity of the material makes the hardness profile of the surface very inhomogeneous, so the industrial applications are limited, but still there are some companies who prefer such low cost materials.

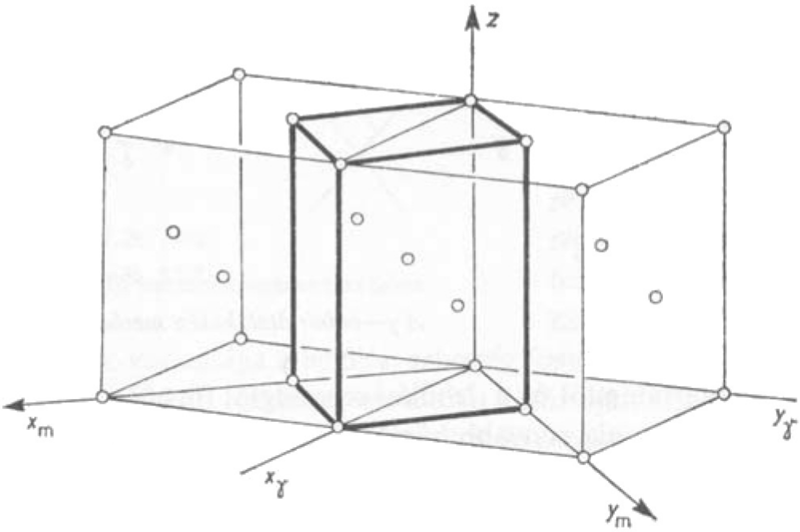


Figure 2.11: The change of austenite structure into martensite by trapping the carbon in the lattice. The body centered cubic lattice (bcc) is already included in the face centered cubic lattice (fcc) [8]

The low alloyed carbon steels such as C45 (1.1730) are excellent examples for laser heat treatment. These materials need a very high cooling speed and during conventional volume hardening they become brittle, so their hardness is usually balancing somewhere between 48-52 HRC to avoid cracks in the material. Fortunately in the laser hardening this phenomenon won't occur since the material will be hardened only on the surface and the bulk won't be brittle. If the cooling rate is high enough excellent hardness is achievable, even 60 HRC (see figure 2.9). Other high alloyed steels, cold work steels, hot work steels react perfectly to laser hardening especially if they contain some Mo, V and Cr. Stainless steels are different in this case. The very high content of Cr and V build carbides so if the Cr content is very high and C content is low, the achievable hardness reduces to 40-55 HRC which is the usual hardness of martensitic stainless steels. The austenitic stainless steels with even more Chromium a lower carbon content, such as 316L can not be hardened with lasers, because the material micro-structure doesn't make this possible. High speed steels (HSS) are also laser treatable but the hardenability is limited. These materials can reach their working strength through 2 or 3 steps annealing which creates a structure with different carbides. The whole process is diffusion controlled which is not possible during laser hardening since to achieve such carbides an annealing on 400-500 °C needed. The achievable hardness varies between 60-65 HRC, which is quite low if one compares it with a volume hardened and several times annealed HSS. There's one frequently used material which needs to be mentioned separately: The cast iron. A lot of manufacturers create their tools from spheroidal graphite cast iron to lower the tooling costs. The laser hardening of lamellar graphite iron is not very effective, the reachable maximum hardness is significantly lower compared to spheroidal cast iron. Due to microstructural purposes the hardness is increasing with the quality (the tensile strength and the chemical composition) of the material. By this means the hardening of GGG 40 (EN-GJS-400) is not possible, but from GGG 60 (EN-GJS-600) an elevated surface hardness can be achieved. The best results were made by the GGG70L (EN-GJS-HB 265) material which is very popular among the automotive companies, where even 64-67 HRC was also possible (Source: experience at BuBenLaser). Laser hardening or better named *laser transformation hardening* is also limited to steels mainly. As known some aluminium and other materials (such as copper alloys) are also heat treatable and hardenable but mostly not with laser rather in ovens with special heat treatments such as aging. By this means the laser hardening of Al alloys or pure Al is not possible due to the lack of a similar transformation like the austenite-martensite transformation.

2.2.2 Limits of laser hardening

There are a lot of phenomena which are limiting the reachable hardness as mentioned in the chapter before, but if one takes only the hardenable steels there are still problems to face to reach a specified hardness and layer thickness combination. The most important limitation of laser hardening results from the geometrical dimensions of the components to be hardened. Since a certain minimal cooling rate is required, the component thickness shouldn't go below 10 mm (for materials which are tending to be backtempered e.g. C45), but for high alloy steels this minimal thickness can be even lower, around 5 mm. This experience corresponds with other studies such as the study of Sangwoo So and Hyungson Ki about modeling the hardenability for different thicknesses of AISI 1020 steel[17]. Under this size without artificial cooling, there is not enough heat capacity to reach the highest hardness of the material. Therefore the whole material will heats up to 300-500 °C and the critical cooling rate won't be reached. In special cases some might use heat sink to improve the speed of cooling to reach the demanded hardness and to decrease deformation but this requires a lot of peripheral equipment and it's only possible for flat metal sheets [18]. Despite these disadvantages in special circumstances further improvement is possible.

It has to be mentioned the maximal hardness reachable for steels differs according to its carbon and alloying element content and it's also varies with the source of the metal [5] (the manufacturer of the material). The usual hardnesses reachable can be observed in the following figure 2.1.

Material	Hardness [HRC] ±3
1.2379 (K110)	58
1.2343	60
1.2358	60
Toolox44	55
1.2842	60
S335	38-40
1.4057 (KO16)	40-45
1.7225 (42CrMo4)	58
1.0511(C40)	58
1.2085	53
1.7131	45
1.2842	60
1.2162	47
1.2316	54
1.2363	60
1.1730 (C45)	60
1.2312	60
1.2714	64
1.2311	60
1.2083	47
1.2767	59
Cast iron (GGG70L)	64

Table 2.1: The possible maximum hardness values on different steel types after laser hardening, Steel grades according to EN-ISO

2.2.3 About the thickness of the hardened layer

The thickness of the hardened layer depends on several parameters:

- The wavelength of the laser
- The laser head type (scanner or process head)
- The scanning speed (track velocity of the robot)
- The target temperature
- The hardenability of the material (which is mainly depends on the chemical composition)

The wavelength of the laser has a very important role in the laser hardening. As mentioned in the former chapters the absorption coefficient has a strong influence on the possible thickness of the layer. That means the shorter the emitted wavelength of the laser the higher the absorption: e.g. the appr. absorption for CO2 (10,6 μm) is about 10%, for diode lasers and Nd:YAG (between 800 - 1064 nm) is about 30% and for ArF lasers (193 nm) is about 80%. Nowadays the economically feasible lasers are diode and Nd:YAG lasers in relation to laser heat treatment. Beer's law for the absorption of light in material can give some further information about this effect:

$$I(z) = I_0 e^{-\alpha z}$$

$$\text{where}$$

$$\alpha = (4 * \pi * \kappa)/\lambda$$

The $I(z)$ is the power in the material along z axis, I_0 is the emitted overall power of the laser, α is the absorption coefficient and the reciprocal value of α is the so called absorption length. The α is a function of κ and λ, so the absorption length is indirectly proportional with λ (the wavelength) and proportional with κ - which is the extinction coefficient of the material. If we take the same material the only difference will be the wavelength so the absorption coeff. for radiation with a wavelength of 10,6 μm is 10x smaller compared to radiation with a wavelength 1,06 μm. By this means on longer wavelength more energy is needed to heat up the surface.

The laser head type is a crucial part of the laser hardening. There are two commonly used types of heads for laser hardening: The scanner head with moving optics or the one called processing head with(partially) passive optics. The scanner head contains a movable mirror which can move the focused spot with a velocity up to 1000 m/s. With such equipment the power distribution of the processing zone can be optimized. On the following figure 2.12 an optimized chair-like distribution can observed, which is a good option for flat surface hardening. The downside of this is the small working envelope and the need of high repetition accuracy. There are several examples where such heads are applied to laser hardening and they are very useful if the temperature control along the beam is precise, so the power distribution can be continuously altered in such way that the temperature everywhere in the processing zone stays the same. The processing head which contains "passive" optics are easier to obtain but the power distribution is of course is limited due to the focusing lenses. The processing heads are economical option for very complex 3D surfaces where the hardened track can't be programmed "offline" only "online". This means we cannot create a robot program on PC (offline programming), we have to create the program directly next to the hardened part (online programming).

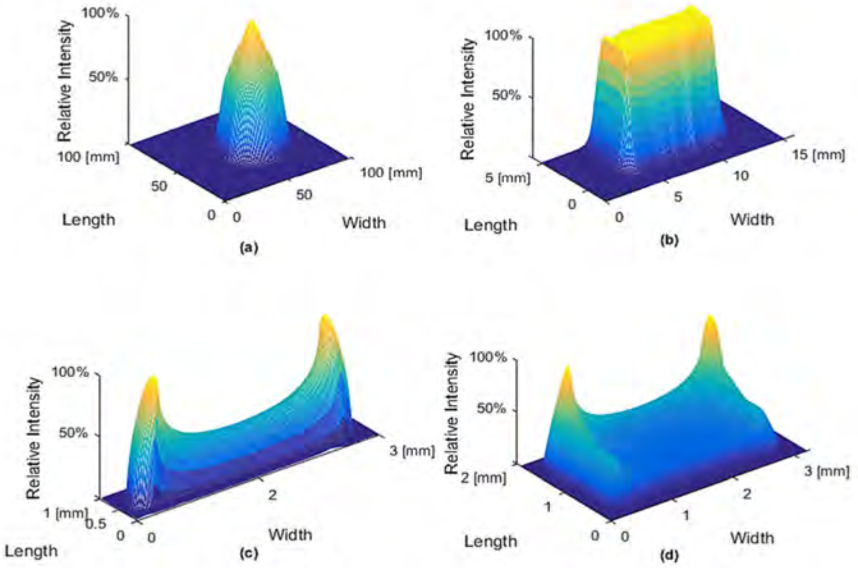
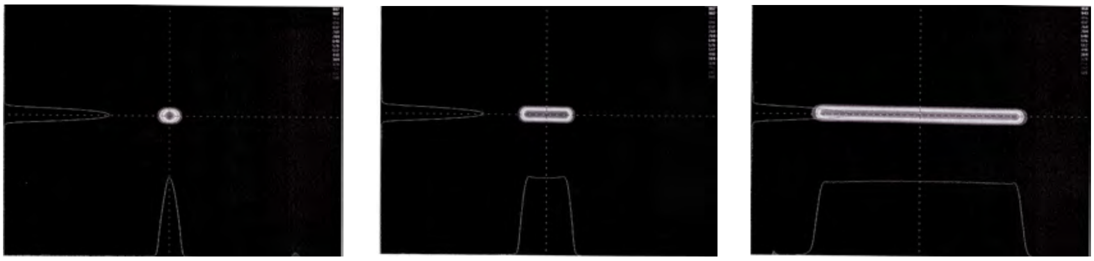


Figure 2.12: The intensity distributions, a) Gaussian, b) top-hat, c) harmonic oscillation of scanning mirror, d) optimized Burger intensity profile [1]

Combined with a so called "Zoom-optic" the width of the laser beam/track can be varied between few millimeters and several tenth of millimeters. The zoom optics allow the user to change the size of the spot during laser process or between the tracks according to the hardened surface size. The zoom optics however cannot make the power distribution of HPDL-s in small diameters perfect (see figure 2.13). The optics used at BuBenLaser made by Laserline show that the distribution at the smallest adjustable spot in the focus is rather Gaussian, but at 15 mm wide spot size is almost perfect top-hat. Therefore this has to be taken into account, that smaller surfaces (under 10 mm typically) will have bigger heat affected zone compared to the hardened zone.



(a) 6,5 mm (b) 20 mm (c) 40 mm

Figure 2.13: Power distributions for the different diameters of a LaserLine Zoom optic. Source [5]

However, with respect to the power distribution the cross section of the laser hardened track shows a lens like profile, where the hardened layer reaches its maximum depth at the center. Towards the end of the hardened track the thickness of the layer decreases continuously (as seen on figure 2.14). This happens due to the different heat flow conditions at the center of the beam and at the periphery. Therefore if a bigger surface had to be hardened the only option is to use overlap between multiple tracks with the problem of back tempering. This phenomenon will be described later in this thesis. The overlap is in this case a crucial factor, to find a good overlap percent, to minimize the size and the amount of overlaps where the hardness can fall down. The thickness in the case of top hat distribution is not perfectly constant across the track as seen in the following picture.

Figure 2.14: Cross section of 1.2379 steel after laser hardening, Source [5]

The scanning speed determines the amount of heat transferred into the material. The slower the tracking velocity the more power is absorbed and the more volume is heated up to the desired temperature. A lot of literature refer to this as a line energy which is the ratio of power and velocity. The velocity is constant during the hardening but the power has to be always changed according to the surface conditions (temperature feedback). Therefore the line energy is constantly changing during the hardening process. By this means the line energy is not a good parameter for the characterization of the process. If the surface temperature is held constant (e.g.: 1200 °C) according to the following simplified model the hardening process can be divided into two parts. First there's the heating process, which means the beam continuously heating the surface temperature on e.g.: 1200°C. If the temperature can't go over this limit, by 0 m/s tracking speed the heating process arrives to an equilibrium when the heat conduction and radiation losses become equal to the absorbed laser power. This is the case where the best results can be achieved regarding to the layer thickness if we're assuming a semi infinite bulk material. Of course during a normal process the tracking speed isn't 0 and the bulk is also not infinite, so there's a certain amount of energy which creates a certain temperature gradient in the material. The second part is the cooling of the heated volume. As the laser beam proceeds there's no absorbed light only a temperature gradient and a heat loss by heat conduction and radiation. If a bigger volume is heated up the temperature gradient inside the processing zone will be small and the cooling speed decreases under the critical cooling ratio (for example for c45 is 1000 K/s, see figure 2.9).

This results in a smaller hardness of the heat treated material because it turns back from austenite into perlitic structure. The desired temperature of the process is also very important. Because of the high heating rate (about $10^3 - 10^5$ K/s) the austenitizing temperature shifts to higher grades and it also needs some time to transform the lattice into austenite. The optimal is the highest temperature closest to the melting. The higher operating temperature is vital to achieve good cooling speed (depending on material but usually over 800 K/s) and of course to have a big temperature difference so the heat can be transferred faster into the material:

$$q_x = -k * dT/dx$$

The one dimensional heat transfer equation clearly shows if the heat conduction stays the same, the higher temperature difference leads to a higher heat flow, so for the same interaction time the heat will be transferred deeper and the critical temperature drop (under the martensite start temperature Ms, see figure 2.9) can be achieved also in deeper section of the bulk material. The melting temperature of steel is about 1300 °C and 1000 °C for cast iron depending on the chemical composition and homogeneity. Since a lot of steels and cast irons have not only a high tolerance regarding carbon and other alloying elements but also regarding homogeneity, a safety offset from the melting temperature has to be implemented. This offset is about 50-100 °C depending on the geometry and material. Not holding this offset can cause melting of the surface.

The hardenability of materials is purely chemical composition dependent. Under the definition of hardenability the literature mostly refer to the Jominy end quench test (see figure 2.15). First the part with a predefined geometry (100 mm long, 25 mm in diameter) has to be normalized to eliminate the microstructure of forging, than it will be austenitised. After that water is sprayed on to the end of the cylinder which leads to rapid cooling on the end. As the part cools down the hardness of the part decreases lengthwise regarding to its critical cooling rate. This test shows the influence of alloying elements on the hardenability as well. The crucial elements for increased hardenability are C, Cr, Mo, Mg, Si, Ni, and V. A good hardenability helps to reach the maximal possible layer thickness which is about 2 mm for special tool steels. The hardness distribution of the laser hardened layer has some similarities to the Jominy test.

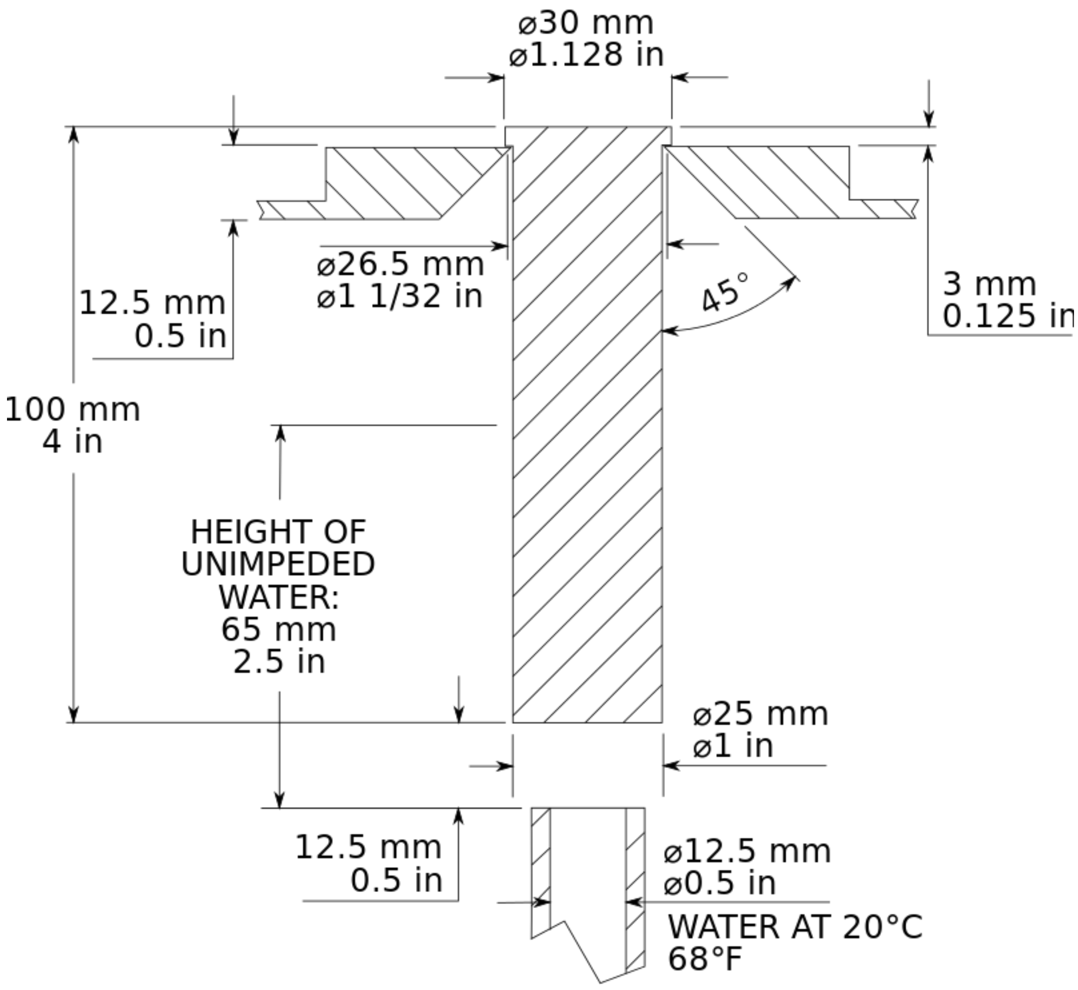


Figure 2.15: The Jominy end quench test. Geometrical properties of the testing equipment. Source: [16]

During the measuring the surface hardness of the layer a slight decrease of the hardness is observable until the border of the martensitic layer is reached. This is where the cooling rate is already smaller than the critical cooling velocity which means the part is not heated long enough (=tracking velocity is high) so the conduction can't transfer the energy into deeper sections of the bulk material or the maximum thickness is reached. The hardness of the material drastically drops as the martensitic layer removed (see figure 2.16), which corresponds with the border of the hardened layer on the micrographs. The overall thickness of the hardened layer varies between 0,1-2 mm respect to the formerly listed variants, where the key parameters are in this order: track velocity, temperature, chemical composition of the steel, power distribution of the laser source.

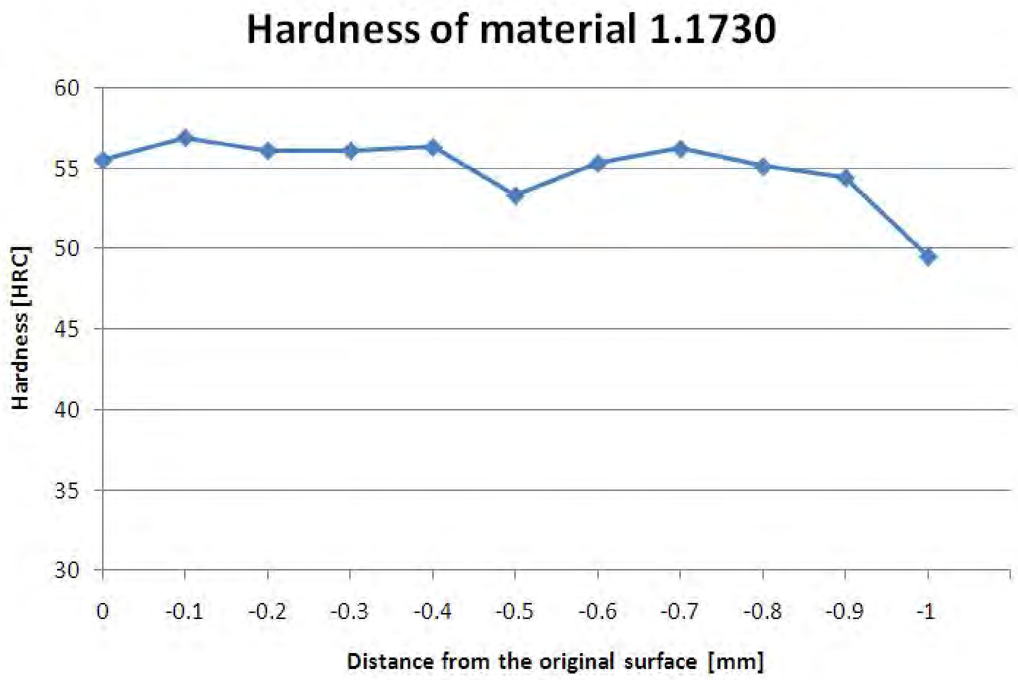
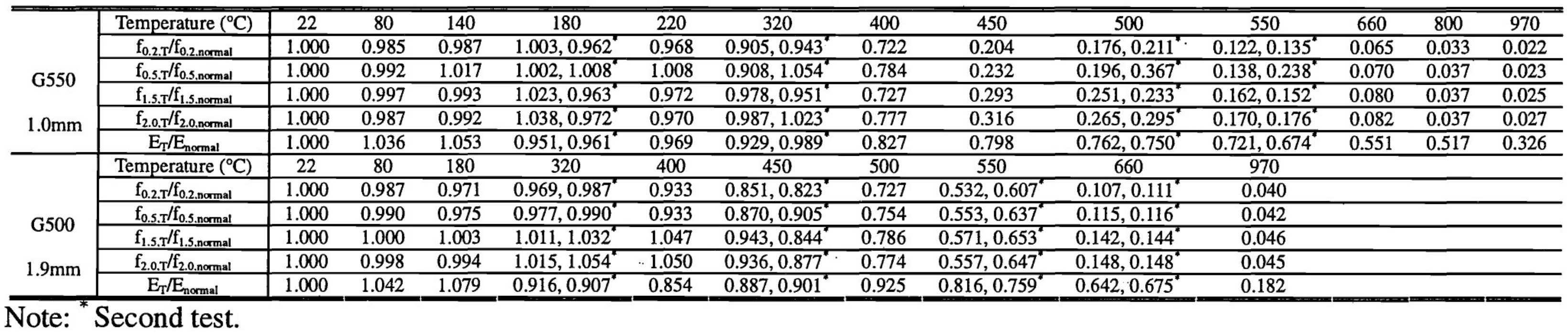


Figure 2.16: The hardened layer is removed by grinding layer by layer and then the surface hardness is measured by UCI testing. Base hardness is lower than 21 HRC. Source: [5]

2.2.4 Deformation, torsion and heat treatment allowance

In conventional volume hardening it's impossible to finish the machining before heat treatment because the deformation of the geometry is inevitable. That is the reason why the designer puts heat treatment allowance on the drawing. Sometimes this can be even several mm but even by induction hardening several tenth of millimeters are quite common. The laser hardening's one big benefit is the comparably smaller (or even none) deformation of the dimensions. This is of course tolerance and geometry dependent. The problem originates from the principles. As mentioned the heating up of the surface causes stresses on the top layer and also the drop of the strength in the processing zone. Several studies noted that the yield strength around 1000 °C may drop to 2% of the yield strength of the steel in room temperature [22]. As seen on the figure 2.17 the yield strength of G550 steel drops at 970 °C to 2,2 % of the yield strength on room temperature.



	Temperature (°C)	22	80	140	180	220	320	400	450	500	550	660	800	970
G550 1.0mm	$f_{0.2,T}/f_{0.2,\mathrm{normal}}$	1.000	0.985	0.987	1.003, 0.962*	0.968	0.905, 0.943*	0.722	0.204	0.176, 0.211*	0.122, 0.135*	0.065	0.033	0.022
	$f_{0.5,T}/f_{0.5,\mathrm{normal}}$	1.000	0.992	1.017	1.002, 1.008*	1.008	0.908, 1.054*	0.784	0.232	0.196, 0.367*	0.138, 0.238*	0.070	0.037	0.023
	$f_{1.5,T}/f_{1.5,\mathrm{normal}}$	1.000	0.997	0.993	1.023, 0.963*	0.972	0.978, 0.951*	0.727	0.293	0.251, 0.233*	0.162, 0.152*	0.080	0.037	0.025
	$f_{2.0,T}/f_{2.0,\mathrm{normal}}$	1.000	0.987	0.992	1.038, 0.972*	0.970	0.987, 1.023*	0.777	0.316	0.265, 0.295*	0.170, 0.176*	0.082	0.037	0.027
	E_T/E_{normal}	1.000	1.036	1.053	0.951, 0.961*	0.969	0.929, 0.989*	0.827	0.798	0.762, 0.750*	0.721, 0.674*	0.551	0.517	0.326
G500 1.9mm	Temperature (°C)	22	80	180	320	400	450	500	550	660	970			
	$f_{0.2,T}/f_{0.2,\mathrm{normal}}$	1.000	0.987	0.971	0.969, 0.987*	0.933	0.851, 0.823*	0.727	0.532, 0.607*	0.107, 0.111*	0.040			
	$f_{0.5,T}/f_{0.5,\mathrm{normal}}$	1.000	0.990	0.975	0.977, 0.990*	0.933	0.870, 0.905*	0.754	0.553, 0.637*	0.115, 0.116*	0.042			
	$f_{1.5,T}/f_{1.5,\mathrm{normal}}$	1.000	1.000	1.003	1.011, 1.032*	1.047	0.943, 0.844*	0.786	0.571, 0.653*	0.142, 0.144*	0.046			
	$f_{2.0,T}/f_{2.0,\mathrm{normal}}$	1.000	0.998	0.994	1.015, 1.054*	1.050	0.936, 0.877*	0.774	0.557, 0.647*	0.148, 0.148*	0.045			
	E_T/E_{normal}	1.000	1.042	1.079	0.916, 0.907*	0.854	0.887, 0.901*	0.925	0.816, 0.759*	0.642, 0.675*	0.182			

Note: * Second test.

Figure 2.17: Reduction factors of yield strength and elasticity modulus of cold formed steel G 550 and G 500. Source: [22]

The study of Poh [23] shows a 3D representation of the drop of the yield stress respect to the temperature up to 1000 °C. In the figure 2.18 the same results are observed: On elevated temperatures the strength of the material significantly drops.

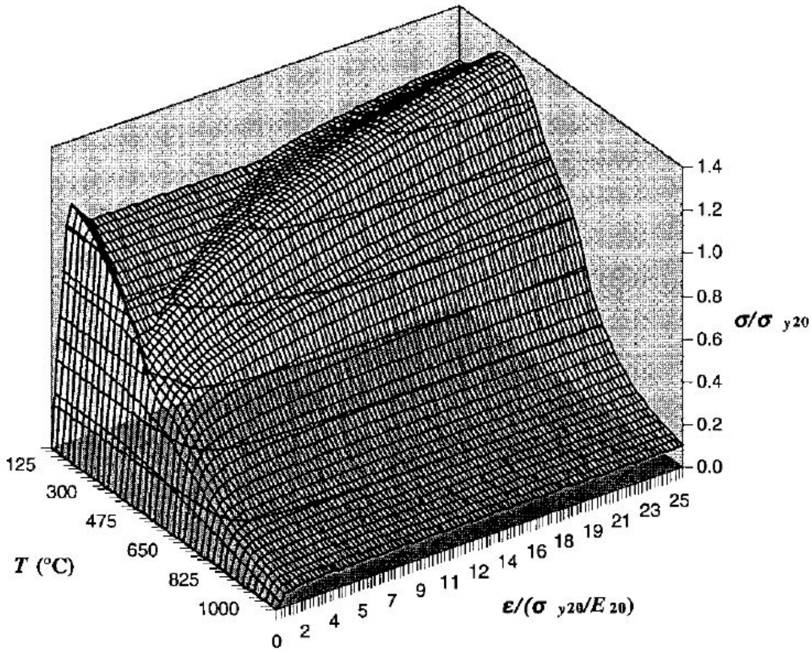


Figure 2.18: Perspective view of resulting stress-strain-temperature relationship [23]

If it's also noted that during laser hardening the stress on the hardened zone can be quite big (the residual stresses may go up to 300 MPa in some studies [24]) it's clear the deformation of the surface is inevitable. During the hardening the part is heated up until the austenite transformation temperature (A3 or AC3 see figure 2.9) and creates a tensile stress, while thermal expansion leads to strong pressure in the surface. After the phase transformation during the cooling there will be a large volume expansion caused by the different lattice sizes. This causes also a high compressive stress against the cold material and the transformed material behind the processing zone. Unless the cold material has a very low yield strength, the cold material and the already treated material try to push the hot material in the processing zone which will result in a piling up of the material permanently. The local heat treatment of sheet metals shows the same result. Only the heat treated part of the material is deformed, so the untreated part stays fully straight. Also need to be noted the fixing of the part cannot reduce this effect, since the inner stresses will be still there to deform the workpiece, so after removing the fixing the part immediately deforms. As the material cools down the top layer is a bit shorter than the bottom layer, so the material bends like a bimetal during heating. The thinner the base material and the longer is the part in one dimension, the higher can be the deformation. Without correct precautions this can be even millimeters. Fortunately it needs to be noted that these deformations can be avoided in come cases or at least it can be minimized by compensating with heat treatment on the other side. By hardening both sides of a part, the stresses partially equalize and the deformation will be smaller. The surface of tools also changes during and after hardening, this means the creation of an oxide layer and the increase of roughness. The oxide layer originates from the high temperature oxidation of the steel. The oxide is made from the bulk material, so if one removes it with sandpaper the dimensions of the workpiece will change. It is also possible to remove it with commercial rust remover fluids if the part is sensitive (e.g.: polished surfaces or cutting edges). This means about 1-5 μm layer which cannot be observed on stainless steels. This shell also have another important attribute: the darker color ensures a higher absorption during the heat treatment process. The chemical composition of the oxide is dependent from the bulk material. It contains usually Fe_3O_4 and Fe_2O_3 which are the common forms of oxidation on carbon steels (exception is stainless steel, very high chromium content might cause forming of Cr_2O_3 scales). As a result a very small enrichment in carbon of the surface layer might be observed [21]. This effect was not verified but it might be an idea for further investigation of laser hardening. As mentioned above the repetition of heat treatment is fully allowed if some problems occurred during the hardening process and the hardened layer is not homogeneous enough. That means the laser heating and cooling process always "overwrites" the current structure of the steel. The state of the oxidation layer can also give us some hint about the temperature we use . As getting close to the melting temperature the part will be heated up so close to the melting point that the under the scale CO gas bubbles try to exit. As seen in the following picture (figure 2.19) as the temperature rises some small blistering occurs. This is only the blistering of the oxide layer and can be easily removed by sandpaper. This is an optical forewarn of the high temperature for carbon steels and it should be taken into consideration. The controlled temperature should be lowered because in case of pyrometer the feedback and control uses average values, so if the part melts the monitoring system might still think the power is not too high.

Figure 2.19: C45 hardened with different temperatures. From left to right: 1150, 1200, 1250, 1300°C. Source: [5]

In everyday use of laser hardening the oxide layers can be very annoying especially when treating 3D profiles. These have to be carefully cleaned because some oxide particles can ruin the whole track so the process have to be repeated all over again. The benefit of the oxides is the preventive scaling against rust and of course it's an optical proof of the existence of the hardened layer. Usually it's not removed before shipping back to the partner so the customer can observe the hardened tracks. If a polished surface is demanded, the customer need to know that after laser hardening the surface roughness slightly increases. This effect was investigated during the laser hardening of polished injection moulding tools. In the following picture (figure 2.20) we can see the original polished surface roughness and after laser hardening it was polished back until almost everything disappeared. The change is quite small but it can be still problematic in some cases.

Figure 2.20: There was one laser hardened track on the surface. After polishing there's still a small difference between the original and the hardened. Source: [5]

This picture gives an important hint: if highly polished surface needed, the part should be hardened before polishing than milled or grinded with NC machine and at least polished with diamond. So the part won't be affected with effect of piling up. The next two pictures (figures 2.21 and 2.22) show the result of the surface roughness measurement of the laser hardened and the original surface. Fortunately this effect didn't have any influence on the structured surface and they remain intact. However the laser hardening of polished surface is a subject of ongoing experiments at the company, to achieve at least a partially hardened layer without harming the polished surfaces.

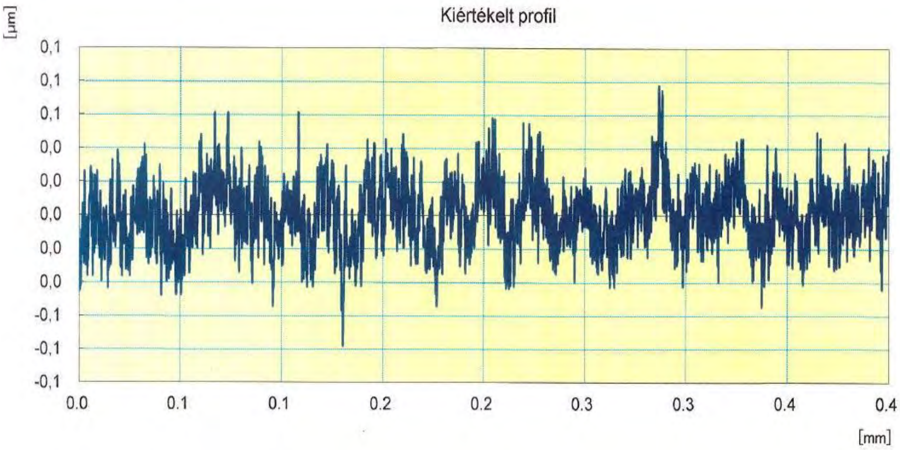


Figure 2.21: Original surface without hardening. Surface roughness Ra=0,015 µm. Measured with Mitutoyo SJ-210. Source: [5]

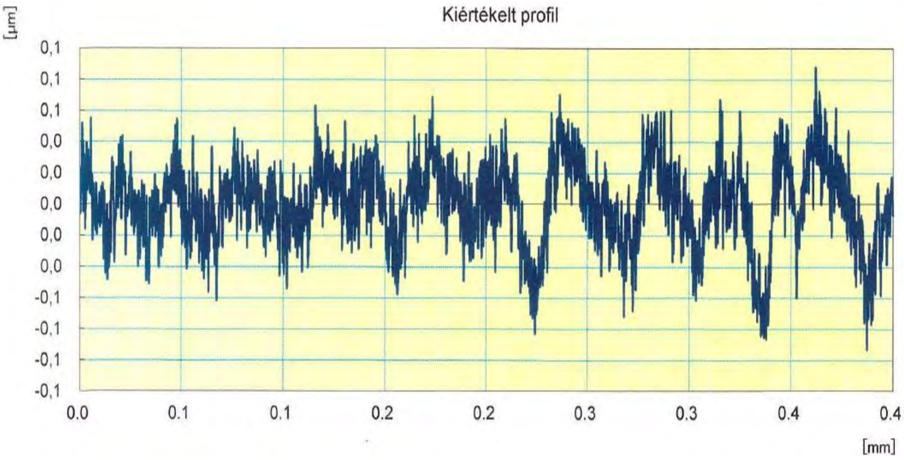


Figure 2.22: Laser hardened surface after polishing. The surface roughness could be adjusted to Ra=0,020 µm. Measured with Mitutoyo SJ-210. Source: [5]

2.2.5 Material microsturcture

The microstructure of the laser hardened materials is very beneficial since they contain usually fine grained martensite with some retained austenite. The fine grained martensite ensures a lower wear and the austenite improve the chemical resistance. The cross section of the hardened track shows also that the heat affected zone contains other structures as well, depending on the cooling speed (see figure 2.23). When the cooling speed is not enough to start the martensite forming the slow temperature drop induces grain growth and stress relief inside the material. This creates a layer where the hardness of the material can be even lower than the bulk material. This is also very thin and does not affect the overall hardness of the top layers, so it can be usually neglected [19]. These structures can be observed under an optical microscope after proper sample preparation. After cleaning the surface from oil and other pollutants (with acetone or pure alcohol) the part can be etched. A very common etchant for steels is Nital but for special stainless steels some stronger etchant are recommended e.g. ferric chloride, Kalling's or Vilella's reagent. The effect of etching differs from material to material, the aim is usually to make the hardened layer and the microstructure visible by making the softer material darker (because it's less resistant against acids).

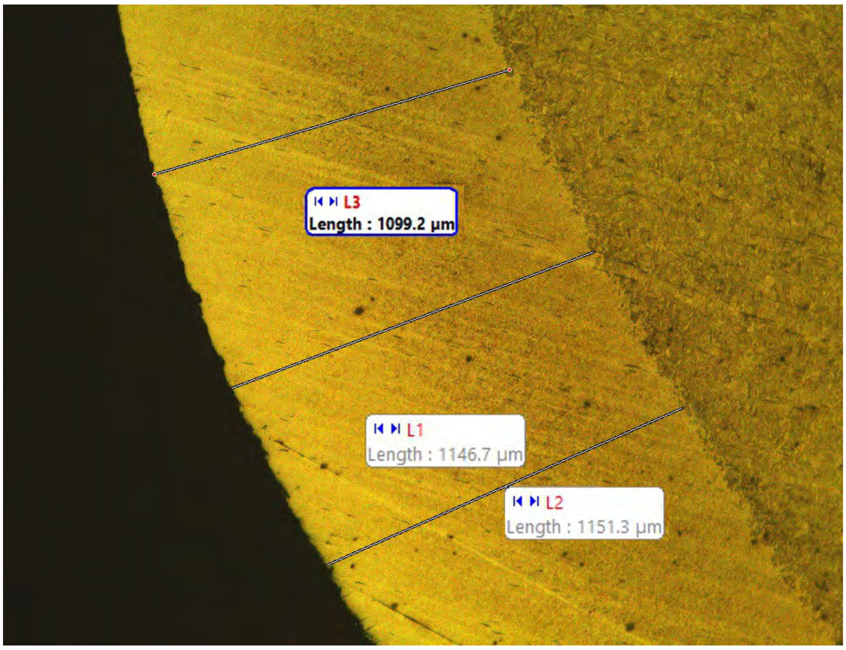


Figure 2.23: Microstructure after the etching with Nital (2%). On the border of the layer we can notice the difference between the fine grained martensite and the perlitic bulk material. Source: [5]

2.3 The economical aspects of the laser hardening

As stated in the abstract the one of the biggest problems in the industry is the profit. Before using a new/better technology for hardening the first question comes from the management: How much will it cost? The financial aspect can approached from several ways. First of all what is the point of using a different heat treatment method?

- I have an unsolved problem such as: the currently used heat treatment caused brittleness and the part/machine is destroyed
- I'm willing to increase lifetime of my current equipment e.g. cutting or bending tools
- I'm looking for a cheaper/faster method to replace case hardening/induction hardening.

In the first case there's a pressure on the customer to find a solution to the problem and since there's no other way they will make the hardening without concerning the price offer. In the second case the management of companies decides if an additional hardening or coating method is affordable or not. Unfortunately there are only a few predictions and experiences about the efficiency of laser hardening and therefore they are hard to convince. The third type of customer is the hardest issue because they usually seeing the laser hardening as a similar method to induction or case harden so they simply ask for a price and compare it with others. This happens because the CNC machining companies usually get a drawing and they are ordered to produce a part 100 % according to the model. If there's no continuous communication between the customer and the manufacturer it's complicated to convince them to try the laser hardening. As a result we get a highly sophisticated environment where a lot of viewpoints need to be considered. I will compare the most popular methods namely: case harden, nitriding, coatings (generally), volume hardening, induction hardening

- 1. Price of the hardened part
- 2. The lead time of the hardening
- 3. Complexity of the part including the tolerances
- 4. The expected lifetime and wear process
- 5. The amount of parts

1. This is a very complex topic because the price is derived for example from the bulk material price, price of machining including surface polishing and structuring, complexity of the part (cost of design) and the (predictable and unpredictable) maintenance costs, the price of preventing actions (hardening, coatings), etc. It's vital to see as the price of the materials and human resources going up one needs to find the optimal solution and so the price of heat treatment is getting lower and lower compared to the cost the other elements. This is also true by high end tools such as plastic/silicone injection moulding, bigger pressing tools and high precision parts made from special tool steels. Typical example: plastic injection mold made from EN ISO 1.2312 is about 500 kg/side (see figure 2.24). The average costs of volume hardening can go up to 2-3 EUR/kg in 2018 in Hungary. The costs of laser heat treatment is highly surface dependent, but depending on complexity the price of hardening is 1,2-1,5 EUR/cm.

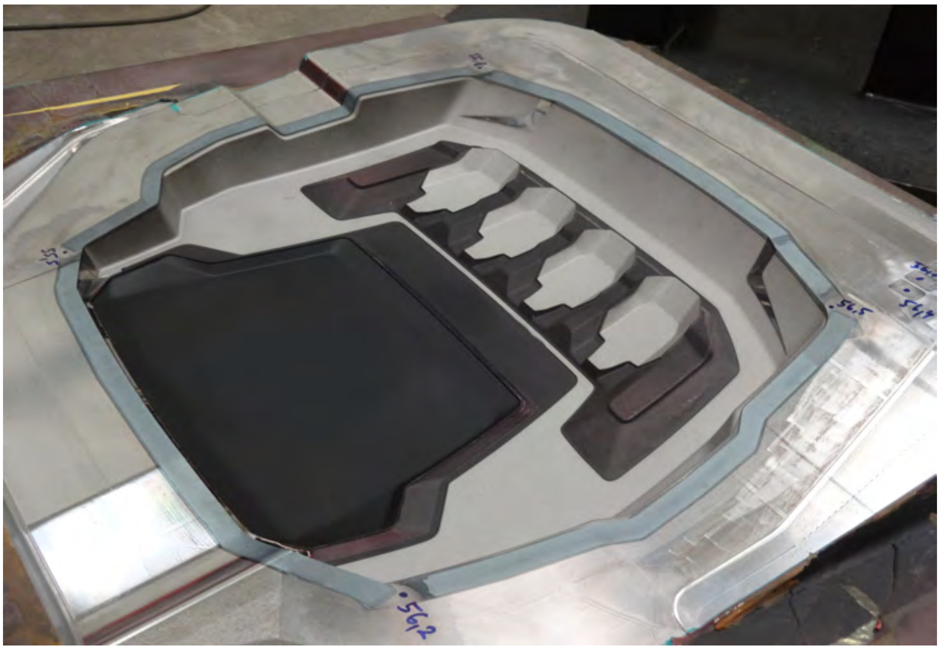
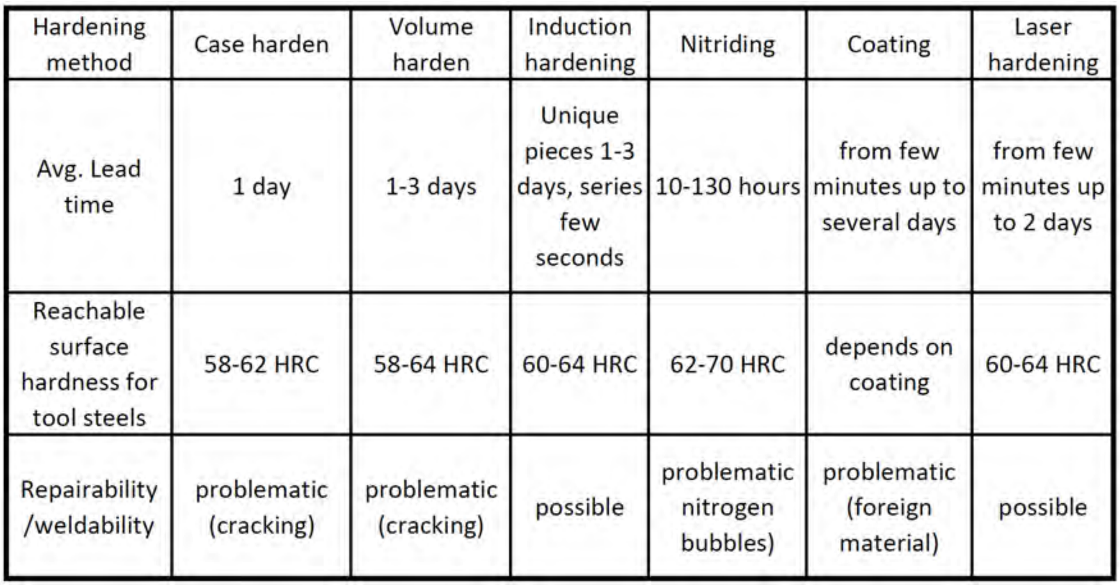


Figure 2.24: Plastic injection moulding tool after laser hardening of the parting line (gray track). Source [5]

If only the parting lines are hardened the cost of laser heat treatment can balance anywhere between 300-1000 EUR (depending on the amount of surface which needs to be heat treated. See figure 2.24). Compared to that the volume harden begins at 1000 EUR without concerning the dimensional changes, the need of hard material machining, etc. (both are usually less than 10 % of the cost of the new tool). But if the part has a mass appr. 1 kg made from C45 (1.1730) and just a simple pin with the dimensions ⌀20 mm x 200 mm and it needs to be hardened everywhere then it costs for laser min 60 EUR compared to the volume or case harden which is appr. max 3 EUR each. The figure 2.25 shows how can be the laser beneficially implemented. These parts are quite cheap (appr. 10 EUR each), but if one considers the machining after oven heat treatment the laser hardening becomes relevant. As only one diameter is functional and the others can remain soft the laser offers a cheap solution. It's also important if the part costs less than the hardening process itself. In this case it needs to be discussed whether the changing of the machine element is problematic. If the downtime costs are high (in automotive industry this goes up to several thousand euros per minute) one should consider the using of a hardened piece.

Figure 2.25: Smaller series made of C45 (1.1730) after laser hardening ready for shipping. Only the biggest diameter was hardened, around the circumference. Source: [5]

2. The lead time differs from one method to another but it can be quite easily compared. As written the in the following table (figure 2.26), the processing times vary from few minutes to few days. The processing times by coating, nitriding, case and volume harden goes up with the part size and weight. Over some size (appr. 6 m length of a shaft or if a tool's one dimension is bigger than 2 m) it's very hard to find a furnace and of course these heat treatments are usually extremely expensive. The induction hardening can be sometimes far cheaper because the processing times are depending on the piece quantity. From mid sized series - 1000 piece a year by smaller parts - the induction harden is a low cost solution especially by simple geometries where the conductor design is not challenging (e.g. pins, shafts, sprockets, gears).



Hardening method	Case harden	Volume harden	Induction hardening	Nitriding	Coating	Laser hardening
Avg. Lead time	1 day	1-3 days	Unique pieces 1-3 days, series few seconds	10-130 hours	from few minutes up to several days	from few minutes up to 2 days
Reachable surface hardness for tool steels	58-62 HRC	58-64 HRC	60-64 HRC	62-70 HRC	depends on coating	60-64 HRC
Repairability /weldability	problematic (cracking)	problematic (cracking)	possible	problematic nitrogen bubbles)	problematic (foreign material)	possible

Figure 2.26: Comparison between different hardening methods according to lead time, reachable hardness and repairability. Source: [5], nearby heat treating and machining companies

There is also an opportunity to use a manual induction hardening machine where the worker moves by hand the carefully designed conductors over the surface of the tool (see figure 2.27). The drawback is the precision: even though the price of this technology not high, to reach a homogeneous hardness profile the operator must have a lot of experience.

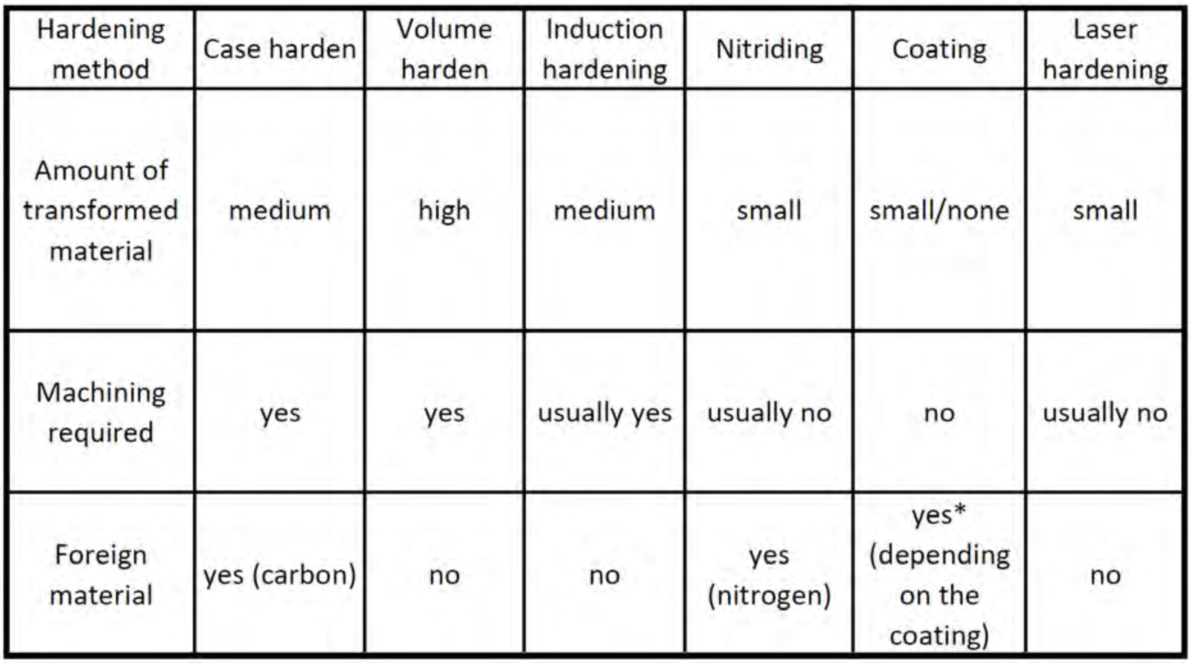
Figure 2.27: A handheld induction hardening machine from Radyne. Source [38]

Pricing of laser hardening is surface area driven, so the smaller the surface compared to the whole, the cheaper it gets. Without automation only smaller series feasible (up to 1000 pcs a year). Even though the laser hardening is a good competitor of the induction hardening at larger series of identical parts, today the investment cost for laser hardening machines for such series (over 1000-2000 thousand pieces per year) are too high compared to induction so if there's no quality benefit it's not worth to change to laser. So in general the laser is beneficial and competitive from unique pieces up to 1000 pieces a year with the consideration of hardening only the functional surfaces.

3. Complexity and the tolerances are always very important. By coating one has a lot of different technologies, like PVD or CVD, each has its benefits and drawbacks. Usual problem is that the toolmakers have to count with not only the thickness of the layer but also with the dimensional changes by heat during the coating process. So if the tool gets out of the tolerances the few microns coating has to be removed and re-coated. This applies to the other applications too but fortunately the thicker layers allow the machining to readjust the dimensions. So in this case one should compare the machining costs after the heat treatment. This means, the higher the hardness the slower the machining so the machining allowance describes how much afterwork needs to be done. In general we can say the more the transformed material the bigger the deformation and if one put foreign material in the part (case hardening - carbon, nitriding - nitrogen) the overall dimensions will grow, so post carburizing and nitriding machining is almost always needed (see figure 2.28).

4. Expected lifetime of the part becomes more important with the price and the complexity of the process or the machine where the part works. Usually the maintenance costs, especially the downtime costs are far bigger than the cost of

using an additional hardening process. Example: Copper extrusion wheels are used for creating copper wire for transformers. There is tool holder continuously moving on the cylindrical surface of the wheel causing abrasive wear on the tool holder. The base hardness of the tool holder is 45-50 HRC, because if the hardness is higher the high pressure would break the wheel into pieces. Changing the wheel in a fully automated system "costs" 8 hours, a whole shift. With laser hardening it's possible to improve the lifetime of the wheel by 50% without changing the geometry for the 1/10th of the price of the new. With such a small investment the factory is able to increase the yearly productivity by 2,4 % (with 1 shift) if this wheel is the bottleneck of the production. Another example is a cutting tool made from EN ISO 1.2379 for cutting of plastic egg holders. The laser hardening improved the tool's lifetime by 5 times compared to the original, which was a huge success (Both examples were made at BuBenLaser, the result is a customer feedback).



Hardening method	Case harden	Volume harden	Induction hardening	Nitriding	Coating	Laser hardening
Amount of transformed material	medium	high	medium	small	small/none	small
Machining required	yes	yes	usually yes	usually no	no	usually no
Foreign material	yes (carbon)	no	no	yes (nitrogen)	yes* (depending on the coating)	no

Figure 2.28: Effect of the hardening methods on afterwork. Source: [5], heat treatment companies, machining companies

Some studies of laser hardening of turbine blades in industrial environment are available in the literature. This technology allows the manufacturers to double the lifetime of the blades without risking the brittleness of the parts [31]. With time these result will grow but unfortunately most of the big automotive companies are not willing to give detailed information about their R&D statistics.

5. The amount of the parts can also limit the feasibility of heat treatment by laser, since (especially in the automotive sector) the parts are usually made in huge batches from thousand to hundred thousands pieces yearly. As stated formerly the induction hardening with a forced cooling can be more beneficial in terms of cycle times, not to mention the smaller parts which can be hardened in oven, so even several hundred pieces can be treated daily. So over 1000 parts a year the laser hardening without a forced cooling is not really competitive against other methods but in case of single parts it mostly a better choice.

Chapter 3

The laser heat treatment of different geometries

In the following chapter I will try to clarify the importance of different geometries, typical applications and the possible heat treatment solutions with examples and customer feedback. If the aim is to create a high quality heat treated surface one needs to understand the possible failures of tools such as pitting caused by too high hardness or fatigue wear due to bad material composition. To find an optimal heat treatment method the user needs to know what is the purpose of the tool, does it need to be hardened according to the drawing or is it because the designer wanted to send it to induction hardening? Is the high hardness problematic because it might cause that another machine part will be worn (which can be much more problematic to change or to buy)? It's also important to understand the terminology of back tempering and the influence of this phenomena on the overall hardness of a flat surface. To see the main niche of laser hardening it's also very important to understand the costs of laser hardening. Which means the quality or the costs are dominant? Some examples will be shown with the most important cost factors with or without laser hardening. This investigation contains the preparation (the used machines and how the result evaluated), then the two dominant geometrical features will be hardened with a "simple" track and multiply tracks. I show how can be this further developed to increase quality and tool lifetime.

3.1 Preparing for the tests

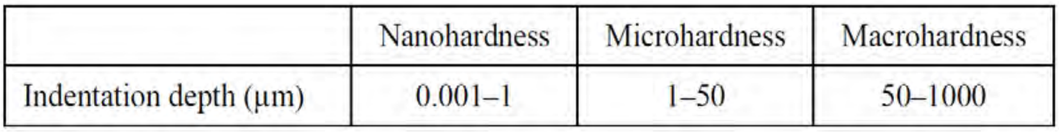
The Laser transformation hardening - as stated formerly - differs in several ways from the other heat treatment methods. Therefore some issues have to taken into account at the beginning. The hardness measurement for example. The same measuring method cannot be used for nitrided parts and for volume hardened part due to the difference of hardness in the bulk material. The same problem occurs by laser hardening. So at first glance some investigation was needed which measuring method is capable or acceptable for measuring the layers. Later the influence of the surface roughness and the cleanness of the surface to the hardening process had to be measured. After this the process control device is introduced, including the pyrometer. Last but not least the importance of laser safety is mentioned where the available safety tools in the chambers are presented.

3.1.1 Hardness measurement of laser heat treated materials

For the hardness measurement of hardened metals there are several options. Even by conventional hardening processes the choosing of the adequate hardness measuring method is crucial. In every way not only the shape and the material of the intender is specified but the affected zone of the measurement is also very important. If the sample dimensions are smaller than the minimum it can lead to false results. Therefore the measuring method needs to be picked carefully and in most cases frequently checked. This is generally the same by the measurement of laser hardened surfaces. The most important factor here is the sample (in this case the hardened layer) thickness. If the layer isn't hard enough the intender can break through the hardened layer and the measured surface hardness values are not correct. If the layer is too thin even though the surface hardness is high enough to withstand the abrasive wear the bulk material will bend/break under the pressure of the intender so the measured hardness will be faked by the soft material under the hardened layer. To understand the difference in this section some of the classical methods for hardness measurement will be examined if they are utilizable or not during checking laser heat treated layers. In industry typically used methodologies are:

- Brinell
- Rockwell
- Vickers
- Knoop
- and Leeb

Brinell hardness measurements are based on the indentation of a ball which makes the measurement very simple, because from the diameter of the impression the hardness can be easily calculated. The only thing one needs to consider is to create sufficient load on the surface so the elastic follow-up remains negligible [9]. In the standards there are tables which show the sufficient load to different hardness and ball diameters. However these are only applicable for volume hardened materials, because as the ball pushes the surface the bulk material under the hardened layer is too soft to withstand the force. Note the influence zone of the hardness test is at least 8 times the penetration depth. In macro-hardness measuring the penetration depth varies from 50-1000 micrometer (see figure 3.1) so the hardened layer must be at least 0,4 mm which is for laser hardening a mid sized layer thickness. If the testing forces are too low the elastic deformation of the bulk material may distort the measurement outcomes.



	Nanohardness	Microhardness	Macrohardness
Indentation depth (µm)	0.001–1	1–50	50–1000

Figure 3.1: The hardness types according to the depth of indentation. Source: [11]

Rockwell hardness measurement is very similar to the Brinell measurement. On figure 3.2 we can see a traditional Rockwell hardness testing device. A diamond cone will be pressed against the surface of the material with a pre-load. This eliminates the influence of the surface finish and breaks through the top layer. For laser harden this step might break through a part of the hardened layer as well. There are several loads for Rockwell hardness, but this documentation will only note two: Rockwell C and Rockwell A. For both the preliminary force is 98,07 N. The total applied force for Rockwell C is 1471 N and for Rockwell A is 588,4 N. As noted in the source [10] the Rockwell C hardness is only used for volume hardened materials because the minimum thickness of the material might be several times bigger than the layer thickness. The possible measurement solutions are using HRA (as used also sometimes and for checking at BuBenLaser) or the using of superficial Rockwell measuring devices. These methods are also used for measuring carburized materials. Note that the hardness of the layer varies as going deeper in the layer and at the edges of the tracks, where the layer can be several times thinner, these method can be also faked. Accordingly to these problems the Rockwell A scale or the superficial Rockwell scale can be used for hardness measurement with the consequence that the hardness measured will be an average hardness of the hardened layer.

Figure 3.2: The Rockwell hardness tester. Source: [5]

The Vickers hardness test is one of the most popular methods and widely used across the globe (figure 3.3).The intender in Vickers is a pyramid with a square base and with a side angle of 136°. The hardness of the material can be calculated by the impression of the intender. For harder and brittle materials it is possible to use different forces not to break the surface layer. The problems are similar to the Brinell test. The thickness of the probe has to be at least 1,5 times bigger then the diagonal of the impressions. The only way to use this method is the Micro-vickers testing of the material. This means the using of smaller forces but also a very expensive and sophisticated equipment with a quite long surface preparation.

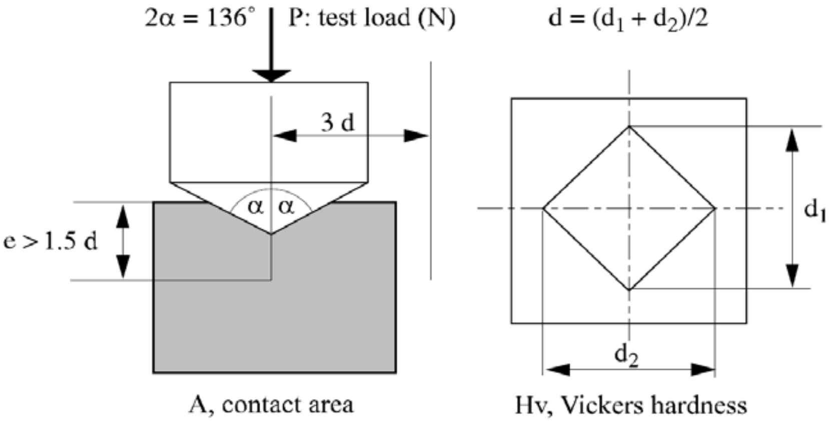


Figure 3.3: The Vickers hardness test. Source: [9]

Knoop test is mainly used for micro-hardness measuring so it's suitable for hardness testing of laser hardened layers. The intender body is a rhombus where one diagonal is 7,11 times bigger than the other. One benefit of using such device is the impression is much smaller compared to the normal Vickers pyramids, so even thinner films or hard metals are measurable. The downside of the method (which is the same for the Vickers micro-hardness) is the demand for very good quality surface, it needs to be clean, oil free and polished. This system is rarely used in steel industry rather in the machining of ceramics.

Leeb test is a special type of hardness tests since it's rather a dynamic process compared to the other 4 methods. On the figure 3.4 we can see a handheld Leeb hardness tester. This method uses a metal ball which will impact on the surface with a defined velocity than as it rebounds the velocity is measured again. The bigger the indentation of the surface, the more kinetic energy is transformed into plastic deformation, so the rebound velocity is smaller. The application is quite fast so in this case compared to the static tests the creep behavior of the material can be neglected. For Leeb the key is the speed: if one needs to check the hardness of the product immediately without taking it to a laboratory, then the portable Leeb testers are optimal for the job [12]. Unfortunately the material itself should be heavy, thick and dense enough to avoid measurement failures. This method is therefore not sufficient for the testing of laser hardened layers.

Figure 3.4: Portable Leeb tester from Sauter, Source: [5]

There are still a lot of other measuring systems and methods for thin layers such as Buckle's, Jonsson and Hogmark's or Burnett and Rickerby's model, etc. which can be used with traditional Vickers measuring devices. These models allow the influence of the substrate to be taken into account [11]. All of these methods have one thing in common, the need of extra work to calculate a surface hardness. Of course for a precise hardness measurement these methods need to be considered but in the everyday use they are hardly feasible. There are two more methods which are not so often used for laser hardened layers:

- From Vickers derived Ultrasound Contact Impedance measuring method (UCI)
- Scratch measuring

UCI measuring (UCI - Ultrasonic Contact Impedance) is a quite new method compared to the others because it's only about 50 years old. It was invented by Claus Kleesattel and this method is preferred when the parts to be measured are too heavy or hard to dismount and still need to be tested in place. The UCI uses the Vickers diamond as an intender with a predetermined force (see figure 3.5). The testing rod uses 78 kHz ultrasound and the contact impedance of the material to determine the Vickers hardness of the surface indirectly from the frequency shift. Using the same force the shift of the frequency is dependent from the mechanical attributes such as tensile strength. As a result the Vickers hardness of the sample is measured and this can be converted into other values such as HRC or other. A huge benefit of this technology is that the probe can be very small, even 0,3 kg and very thin layer can be measured [14]. This method always compares the result with a calibrated probe, so a former calibration of a known material and hardness is necessary. The measurement needs to be implemented in specified circumstances such as clean and (more or less) polished surface. This method is very useful in everyday job-shop work, since the parts usually hardened are too small/thin or too big to be measured in normal Rockwell or Vickers devices. According to the manufacturer the device has only 3% deviation, so further investigation is not always necessary. The drawback of this method is that it's not fully accepted (even though it's standardized - DIN 50159-1) in the industry and it's not widely known so some customers aren't satisfied with the results, because if they measure the same sample with a conventional method they get half or even less hardness. This is due to the lack of knowledge that the conventional methods are not usable for measuring hardened layers. This caused several times problems and in these cases the parts are usually accompanied with a hardness protocol to prove the hardness or they can be proved on place at the customer.

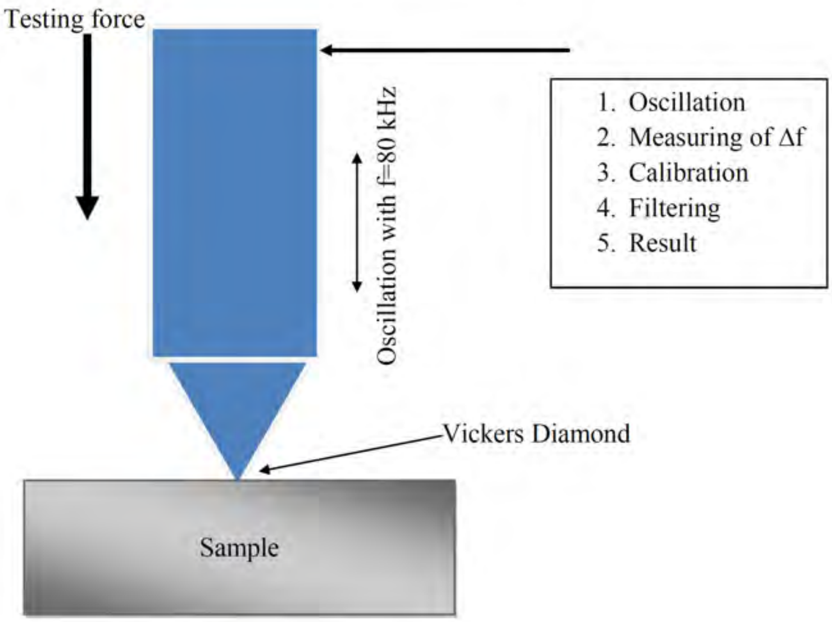


Figure 3.5: The UCI hardness test. Source: [13]

The last hardness measuring method is the oldest yet one of the best methods to determine rapidly the hardness of the surface. The scratching of the surface was the first known technique to distinguish the hardness of materials using different ores, stones and materials from diamond to talc (from hardest to the softest -Mohs scale). As it developed, it was considered as a subjective method, since the result is highly dependent on the user who measures. But still when someone wants to measure thin layers in the order of magnitude of several tenth of millimeters this an option to determine the surface hardness with a quite good accuracy. The principle is simple: there are several probes (with the same geometry) with predefined hardnesses and they are scratched against the surface. If it leaves a mark than the probe is harder, if it doesn't than the bulk material is harder. The scale of such testing sets can go from 40 to 65 HRC and can be used a lot of times when the conventional method are not applicable (see figure 3.6). The newest testers also have a spring to determine the preliminary force to be used so the hardness can be estimated with a precision of 2 HRC. It's a very important feature of this system is to always check the testers before testing whether they are sharp enough or they might slide simply on the surface cause they have a chamfer at the end.

Figure 3.6: Scratching hardness testing set from IBA. Source: [5]

At BuBenLaser the followings methods for hardness measuring are available: HRA, HRC, Leeb, UCI and scratching hardness testing devices. A simple test has been performed to determine the usability of the different methods. Annealed C45 carbon steel was used as a test material. The reference hardness of the measurements is the UCI hardness since it's the most applicable for measuring thin layers. After heat treating the steel with different tracking speeds (from 5-25 mm/s) and on different temperatures the result can be seen in the following table (see table 3.1):

Nr.	Temperature [°C]	Max layer thickness [mm]	Tracking speed [mm/s]	Hardness [HRC]	Hardness [HRA]	[HRA] converted to [HRC]	Leeb hardness [HRC]	UCI [HRC]	Scratching [HRC]
0	0	0	0	14.5	55.0	10.1	<20	23.1	<56
1	900	0.4	5	29.5	74.7	47.1	35.4	58.1	58-60
2	1000	0.7	5	51.8	81.2	59.3	49.2	61.1	60-62
3	1100	1	5	59.0	82.3	61.5	52.3	61.1	60-62
4	900	0.4	10	31.2	72.8	43.7	37.7	59.1	58-60
5	1000	0.6	10	47.3	79.0	55.3	45.7	60.8	60-62
6	1100	0.7	10	56.0	83.0	62.8	50	61.1	60-62
7	900	0.3	15	27.2	69.7	37.7	33.6	59.2	60-62
8	1000	0.4	15	41.8	76.8	51.2	43.3	60.3	60-62
9	1100	0.6	15	52.7	82.0	60.9	45.8	60.9	60-62
10	900	0.25	20	24.5	66.3	31.4	27.3	58.8	58-60
11	1000	0.4	20	37.2	74.3	46.5	41.1	61.3	58-60
12	1100	0.55	20	49.0	79.7	56.5	47.9	60.7	58-60
13	900	0.2	25	23.3	63.7	26.4	27.2	59.4	58-60
14	1000	0.35	25	34.5	74.2	46.2	37.6	61.5	60-62

Table 3.1: The measured data after heat treatment of C45, the deviance of the hardness for HRC ± 2 HRC and for HRA ± 2 HRA

From the data we can show the results of hardness test on different temperature levels and tracking speeds. The curves clearly describes that the HRC, HRA and Leeb methods are unable to measure the hardness correctly. The higher the temperature the bigger the layer thickness so at the highest temperature (1100°C) HRA showed good values especially at lower speed, see figures 3.7, 3.8 and 3.9.

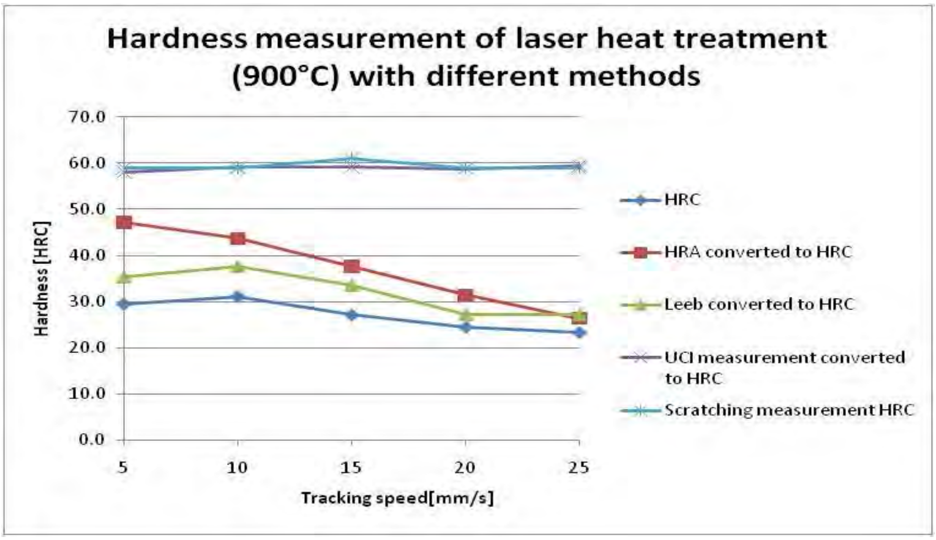


Figure 3.7: Hardness measurement results of C45 after hardening at 900°C. Source: [5]

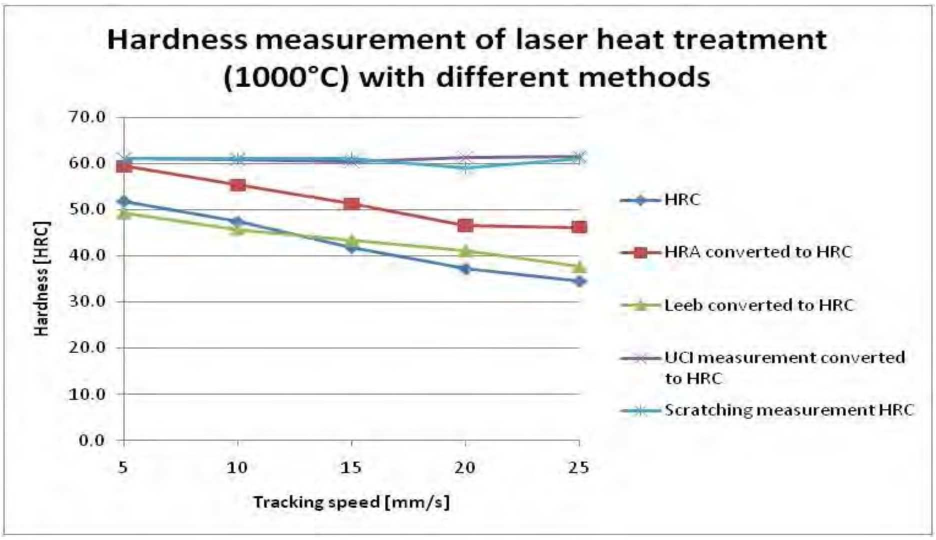


Figure 3.8: Hardness measurement results of C45 after hardening at 1000°C. Source: [5]

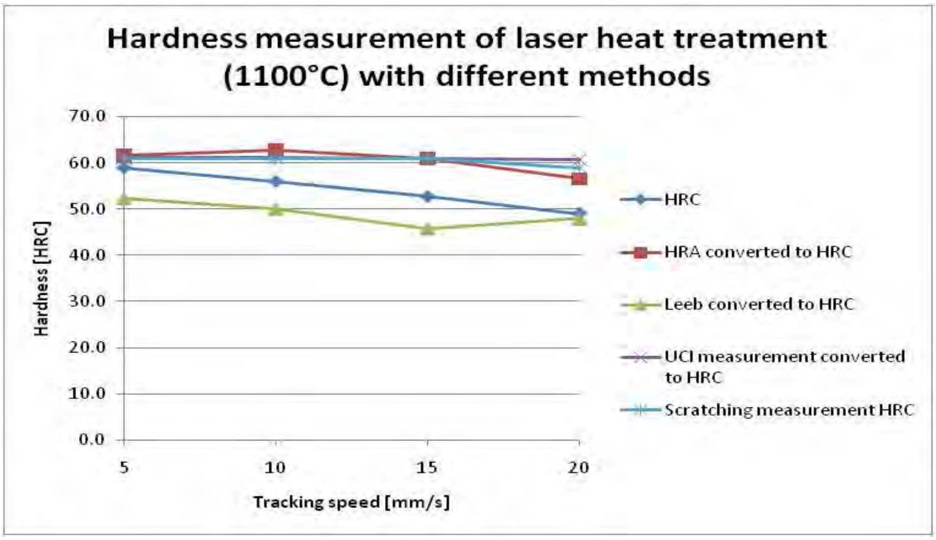


Figure 3.9: Hardness measurement results of C45 after hardening at 1100°C. Source: [5]

It's possible to determine the usability of the different methodologies regarding layer thickness. Since in normal circumstances the hardened layer thickness is unknown one needs a measuring method which is usable in this scale. If we define the UCI measurement as a base we can count the difference from the actual hardness between methods respectively to the layer thickness. As in the following diagram (figure 3.10) declared the conventional methods unable to measure the hardness only at 1 mm hardness or above.

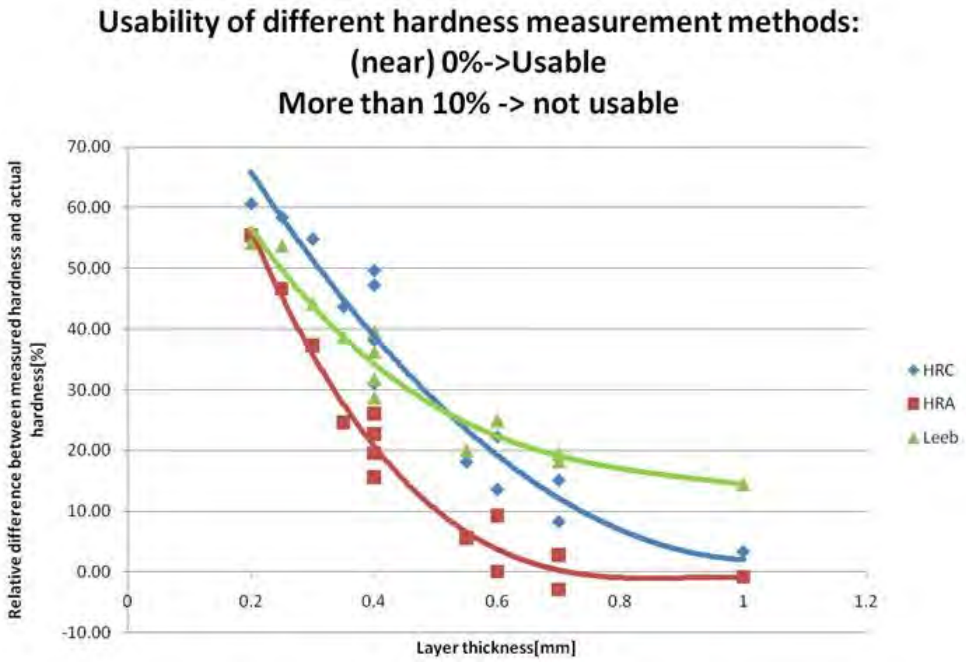


Figure 3.10: Usability: means how much the applied method differs from the actual hardness of the surface (UCI and scratch measurement used as a base) regarding the layer thickness. Source: [5]

Leeb hardness testing is absolutely inefficient in this case since the layer thickness rarely goes deeper than 2 mm. Unfortunately today there's no method to determine the layer thickness without cutting a segment out of the workpiece, but there are possible future methods right under development [25].With such technology it would be possible to measure the thickness and the hardness of the piece at the same time. As seen on figure 3.10, to measure the correct values the only way to use Superficial Rockwell, Microvickers, UCI or scratching.

3.1.2 Preparation of surfaces and the typical cycle of the process

The normal preparation of machined surfaces is quite simple. The material should be clean from oil, grease, burr and other particles. The leftover material from machining can heat up very quickly, because the volume is very small and if it reaches the control temperature the feedback system commands the laser to decrease the power. This leads usually to not uniformly hardened zones with blackened particles. This case the whole hardening process has to be repeated. The oxid layer needs to be removed by sandpaper or by grinding. Fortunately if once the leftover material is burnt there's no material which can confuse the pyrometer, the second hardening process is usually successful. Note that the hardening process can be repeated several times without harming the surface, because the material is always brought to the austenitizing temperature and than cooled back down to room temperature as described in section 2.2.4. If the surface is rusty it's suggested to clean the rust with sandpaper because the rust just like the oxide layer after the laser hardening confuses the control system. There's only one exception for cleaning is the intentional blackening of the surface for better absorption. It's possible to blacken the surface with black tint to improve the optical attributes (required power to reach the determined temperature is somewhat lower) but it does not affect the hardness or the layer thickness significantly and it might also release some toxic gases.

From the practical side the following steps of laser hardening can be observed and these are clearly seen on the curves of the monitoring software (see figure 3.11):

- Starting the laser (∼0,6s safety waiting time, checking the laser etc.), the part begins to warm up, the robot starts to move

- The desirable temperature reached, the control follows the temperature signal, the temporary dynamic equilibrium is reached

- As the part heats up globally, the power needed for the desired temperature is getting lower

- As the laser stops rapidly the measurement stops

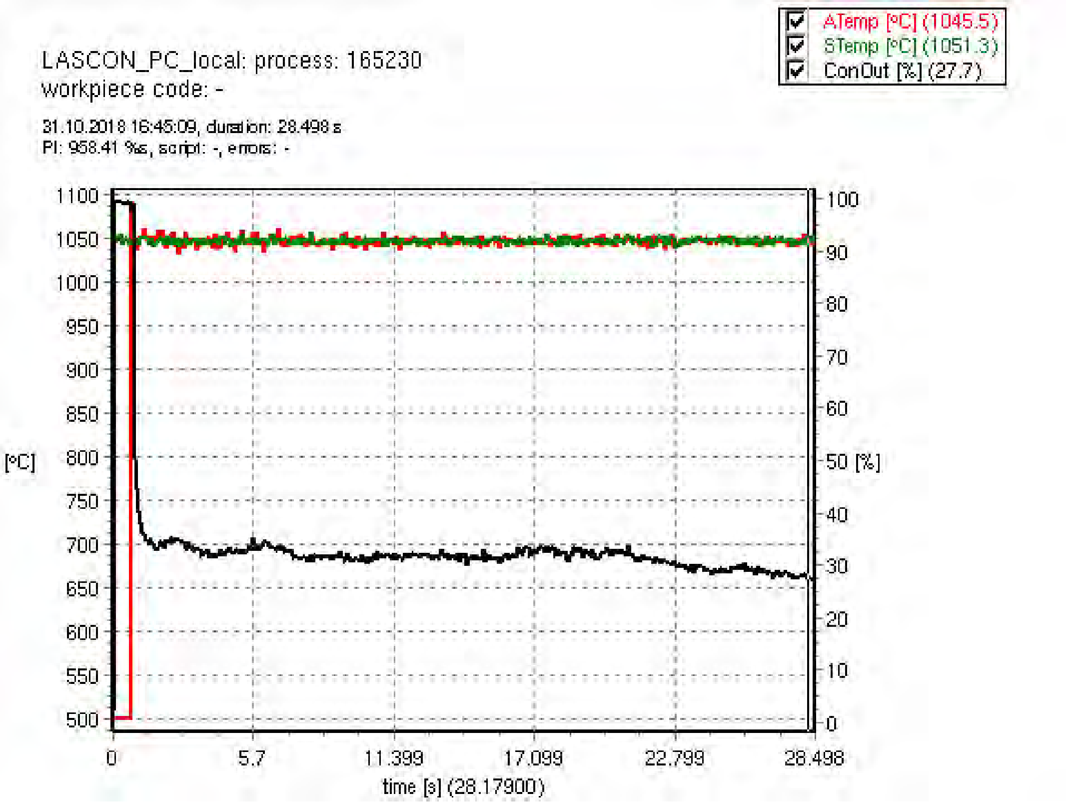


Figure 3.11: The monitoring curves: red - actual T; green - reference T; black - the controlled power. Source: [5]

3.1.3 Temperature control of the hardening process

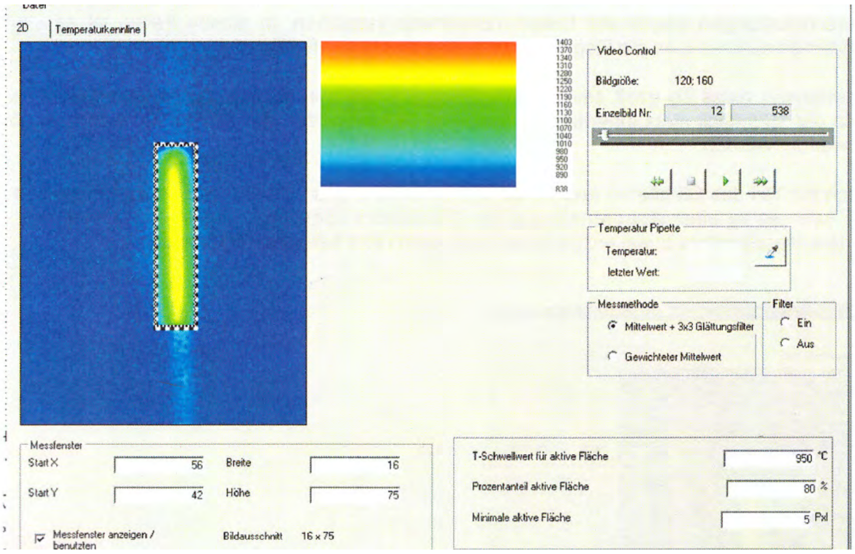
In the general heat treatment one of the most important parameters is the temperature control of the process, since if the temperature is not precisely adjusted the part might get tempered, recrystallized or even melt. The problem is even more complex in the case of laser hardening. As the speed of diffusion is temperature and time dependent, the hardening temperature has to be the closest to the melting point to reach a fully austenitized crystal structure in a very short period of time. The temperature of the surface can be measured in several ways, but in general the two options are commercially available:

- Thermographic camera
- One or two color pyrometers

The thermographic camera has basically the same function as a normal camera, except the pixels are infrared sensors, which can detect the changes in the near infrared spectrum of light. With this technology we can observe how the temperature changes along the spot width during the hardening process. Usually these cameras have due to the high price a smaller resolution (e.g.: 120x160 pixels) and their refresh rate is also low (6-9 Hz for example). This is absolutely not problematic during laser hardening, because the velocity of the laser spot hardly exceeds 15 mm/s so the operator sees almost every mm of the material. The very important is that the thermographic camera is a sensitive equipment and it's very hard to adjust it, not to lower the laser power after heating up some dust nearby the hardened tool. However it's necessary to have a thermographic camera if we want to apply this technology in mass production, since without this, it's nearly impossible to achieve a homogeneous temperature profile. The heat camera is usually adjusted to the laser head (figure 3.12) so you see the laser spot "from above".

Figure 3.12: The camera is mounted on the optics on the EOAT (End Of Arm Tool). The blue box is the thermographic camera module. Source [5]

For the correct using of the thermographic camera it needs to be well calibrated, some of the high end equipment can adjust the measuring window size (figure 3.13), the temperature characteristics and of course you have full control over the laser power.



Bildgröße: 120; 160
Einzelbild Nr: 12 538
Temperatur:
letzter Wert:
● Mittelwert + 3x3 Glättungsfilter
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○ Aus
Start X 56
Breite 16
Start Y 42
Höhe 75
☑ Messfenster anzeigen / benutzten
Bildausschnitt 16 x 75
T-Schwellwert für aktive Fläche 950 °C
Prozentanteil aktive Fläche 80 %
Minimale aktive Fläche 5 Pxl

Figure 3.13: The images of the thermographic camera as seen on the monitor screen during the hardening, with the legend of colours. Source: [5]

The pyrometer is a quite simply constructed sensory to measure the surface temperature with sampling time in the range of ms. The main parts of the pyrometer are the following:

- 1. Coupling to the laser head
- 2. Optical system
- 3. Sensor
- 4. Signal amplifier
- 5. Analyzer electronics with a display interface e.g.: a PC.

On the figure 3.14 we can see how it looks like in real life. Directly next to the aluminium housing of the optics there's the coupling to the optical fiber of the diode laser and after that there's the coupling to the sensory. The pyrometers are based on the emission of thermal infrared radiation of the treated bodies on different temperatures. NIR (Near Infra Red) emission is often used for measuring temperature because it's quite easy to detect especially at large surfaces. The calibration and the control of such equipment is generally easier but the capabilities are also limited. Due to its properties in some cases this simplified system can cause the destruction of some parts unintentionally. Unfortunately the emission of NIR radiation of steels is not only temperature and wavelength dependent but also very closely connected to the state of the surface for example oxides or the surface roughness. These problems can be minimized with two color pyrometers when the measurement is achieved parallel on two wavelength ranges. This solution originates from the emission of black and gray bodies. The temperature of the material can be calculated from the emitted radiation on a certain wavelength spectrum (=signal strength). The spectral radiance of black bodies was first calculated by Planck and he estimated the change of spectral radiance respect to the emitted wavelength [40] and [41].

$$L(\lambda)_{blackbody} = \frac{2 * \pi * h * c^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

Where L is the spectral radiance, c is the speed of light, k is the Boltzmann constant, λ is the wavelength, T is the absolute temperature in Kelvin. This works only for black bodies which has an emissivity of 1. In case of real materials the emissivity is need to take into account so the equation changes.

$$L(\lambda)_{graybody} = \epsilon(\lambda) * L(\lambda)_{blackbody}$$

Where the ϵ is the emissivity of the material. In case of so called “gray bodies” the emissivity of the material stays constant with the wavelength. Therefore if the emissivity of the gray body is unknown the body’s temperature can be estimated from the spectral radiance ratio by eliminating the emissivity of the material. In case of hot metals, the emissivity changes with the wavelength. Fortunately if one chooses the wavelength very close to each other, in this spectrum (e.g. around 1500 nm by hot steel) the change of emissivity is so small it can be considered as a gray body. Therefore the temperature of the material can be estimated from the integration of the spectral radiance between two certain wavelengths with a good precision. The problem is the small change of the radiation density, so the sensors have to be very sensitive to measure these small differences. Important to note that the measured surface has to be usually bigger than the measuring spot, so the temperature of the surrounding area won’t affect the measurement outcomes. This is, however, only important if the measurement is carried out in such environment where the surroundings have commensurable temperatures to the measured samples. In surface measurement of steel the temperature for heat treatment is at least 600 °C so the other parts in the room won’t affect the measured values. The measured signal according to the equation of intensity ($|I| = P/A$, where $|I|$ is the absolute value if the intensity, P is the overall irradiated power, A is the surface) is proportional with the surface, so if the measured steel part is tiny, the signal intensity can be so small, that the power control is difficult for the machine. This effect also reveals another problem, the inhomogeneous temperature field.

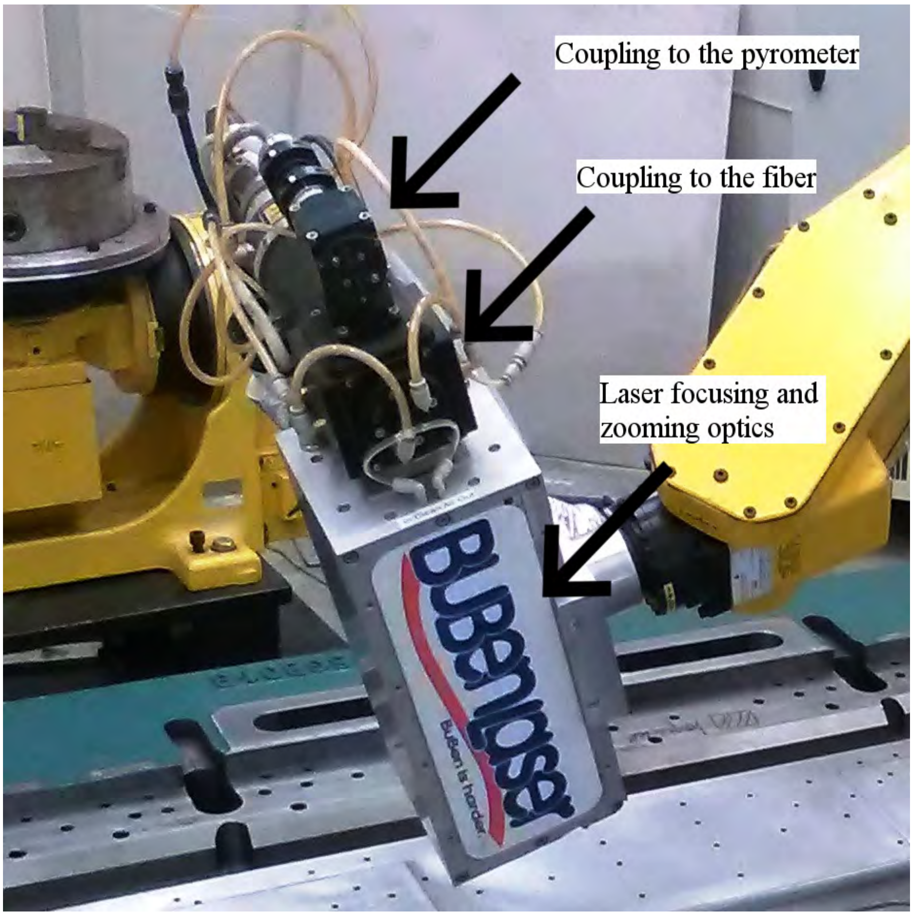


Figure 3.14: Two color pyrometer mounted on the laser head. Source [5]

If the part isn't irradiated perpendicular the temperature won't be constant across the process zone. Not perpendicular radiation is not the only possible failure. Since the measured temperature values of the pyrometer are average values, the local peaks of temperature (e.g. a thin edge) cannot be taken into account. If there's a small feature on the surface which haven't got the same heat conduction properties as the other segments of the workpiece (e.g.: edges), the temperature goes up to slightly higher values (50-100 °C). Even though the temperature of a geometric feature is locally high, the strongest signal comes from the rest of the process zone, so if the target temperature is around 1100-1200 °C the part can locally melt. This effect has to be taken into consideration during the hardening of edges and smaller parts or the workpiece might get damaged. The typical measurement wavelengths for pyrometers are 0,8;1,0;1,6;2,2 and 3,9 µm, but for diode lasers which work between 0,8-1,0 µm the higher wavelengths are favored [26].

3.1.4 Laser safety during laser hardening

The safety is a number one issue regarding laser technologies. The harms caused by lasers are usually permanent and are also very often eye damages. The multi kW lasers during operation, no matter if they are focused or not, are very dangerous level 4 laser sources. The diode lasers used for laser hardening are operating on wavelengths between 800-1000 nm so they aren't visible. The invisible laser light can cause even higher damages, because the blinking reflex won't try to stop the direct interaction and the receptors in the eyes will absorb the light directly. This can cause retina burn, cataract and permanent eye damages to the operator. The environment while working with such machines must include suitable walls, interlock, emergency stop buttons and other elements. Interlocks are the best way to avoid unwanted crossing of the laser beam (see figure 3.15).

Figure 3.15: Interlock on the doors to avoid the Level 4 class laser's direct meeting with human skin or eyes. Source [5]

If the operator tries to open the chamber door the interlock immediately shuts the laser down and sends an emergency stop signal to the robot. The robot and the laser together can be operated from the outside using a key switch to change between the manual and the automatic mode. The continuous camera monitoring helps the other operators and colleagues to ensure if there's somebody in the chamber. There are several emergency buttons placed in and outside the chamber and of course on the robot controlling device, on the so called teach pendant (see figures 3.16 and 3.17).

Figure 3.16: Teach pendant with the safety button. Source: [5]

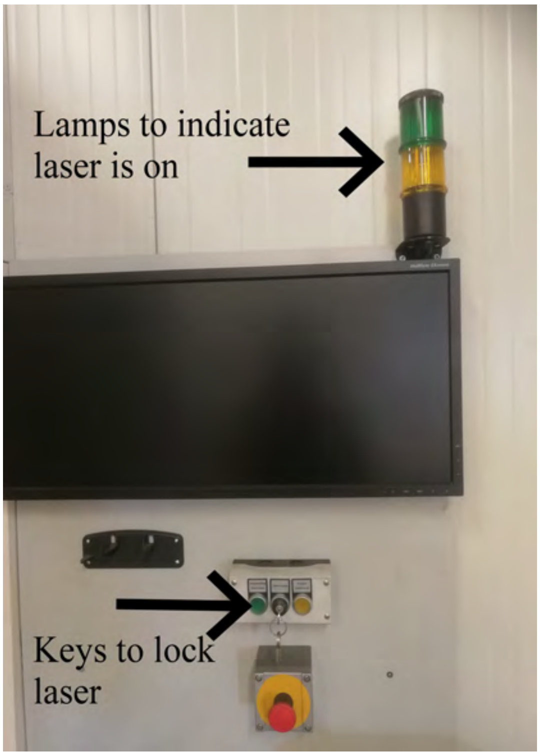


Figure 3.17: If the laser works a yellow lamp shows not to enter the chamber. Keys are also limiting the access of unauthorized persons. Source [5]

Beyond the laser there's another source of danger, the robotic arm itself. During the simulation of the hardening track the robot has to move on full speed which might reach 3 m/s in some cases. If the robot hits the operator at such speed the arm may accidentally kill the user. Therefore there is a torque sensor in the motors of the robot, so if the robot hits the walls, the workpiece or the operator with a certain force the robot immediately stops. The other way to ensure the operator's safety is to control the user's activity. The teach pendants have a special button on the backside which is called the "dead man switch". This 3 way switch has to be pushed with a moderate force by the operator during programming and the simulation to allow the robot moving along its track. If the operator gets hit by the robot she/he unintentionally releases the button so the robot stops moving. If the operator gets shocked by electrical discharge she/he might grab the pendant forcefully caused by a muscle cramp. This results in immediate stop of the robot and an emergency signal. However these actions can avoid the unintentional accidents during the everyday work, the intentional causing of dangerous situations need to be also avoided (e.g. hacking the interlock with metal parts). The main job here is the training to show the operators the possible losses (eyes, burns etc.) and the importance of their own life and health (see figure 3.18).

Figure 3.18: Warning signs show not to enter the chamber without the permission of a technician. Source [5]

3.2 The importance of material thickness regarding layer thickness, hardness and melting

The question of hardenability was mentioned before but in this section it will be further detailed. The layer thickness was basically determined after the chemical composition = hardenability of the material and the scanning speed = the irradiated power on 1 cm^2/time. But this is only valid if the material is thick enough to transfer the heat to the colder parts of the piece, so the minimum cooling speed for martensite transformation is achieved. The bulk material needs to reach a critical thickness to be viewed as a “semi-infinite deep” material in heat treatment, so the workpiece is still hardenable. This thickness depends on material composition firstly. By comparing 1.1730 (C45) to an alloyed steel e.g.1.7225 (42CrMo4) the minimum material thickness can be 20% more if we want to reach the same hardness. Normally a satisfying thickness lays around 5-10 mm according to experience where the part can be hardened to its highest values [17], [27]. So very thin material e.g.: thin plates with 1-2 mm thickness used for automotive industry are practically not heat treatable in normal conditions. Still there are options to ensure enough cooling rate in these cases. As in BuBenLaser experienced, it’s possible to harden thin walled pipes made of carbon steel if there is a cooling medium on the inside e.g.: there’s water flowing through the sample. By this means in fully automated circumstances and big series by using a water cooled copper or aluminum heat sink the limits of heat treatment can be further pushed down to 1-2 mm. Unfortunately the referenced studies by So and Ki used Shore D hardness testing method which may caused high failures in the measurement outcomes. As written by Morgans, Lackovic and Cobbold [28] the thickness of the probe has to be at least 6 mm and in this case the layer thickness is less than 6 mm, so basically a Shore D hardness test isn’t suitable for laser hardened layers, not to mention the maximum penetration of the needle can be 2,5 mm which means the layer is not measured at all but the bulk material.

3.3 Laser hardening of plain surfaces

By the hardening of tools the hardening starts at the design. The design engineer needs to design whether the part will be hardened by laser or not. This is very good question, because the engineer needs to choose the right one from several other methods. So at the beginning usually the tool is hardened or at least it’s in a tempered state. Since the laser hardening “overwrites” the result of the former heat treatment on the surface, the original hardness of the tool is irrelevant.

3.3.1 Multiple tracks

The laser hardening of big surfaces is impossible without creating multiple tracks. The key here is the overlapping of the different tracks. By choosing the right overlap we can define an almost constant hardened layer on the surface. The only disadvantage is the so called back tempering effect. This is caused by the next track, as it goes through the already hardened layer. If one looks at the temperature distribution of the laser hardened track, it's clear that there will be a shell-like layer where the cooling rate assists a back tempering effect. An appr. 0.1-0.5 mm wide track in the overlapping zone becomes slightly (5-10 HRC) softer but it won't affect the average hardness of the surface. This effect is not material dependent it's speed dependent. The higher the speed (with constant overlapping ratio) the smaller the back tempering zone. By the amount of drop in the hardness is the material important. If we compare C45 (1.1730) and an alloyed steel like M200 (1.2312), by C45 the drop is appr. 10 HRC and by M200 it's only 5 HRC (Source: [5]). Some studies made by the west Bohemian University in the Czech Republic showed that the difference in the wear behavior between the hardened layer and the overlapped zone is 3% [32]. For big surfaces one needs to keep in mind: The heat treated surface/whole surface ration should be low as possible to achieve a deformation free good quality piece. For flat and long pieces (like bars or plates, see figure 3.19))the hardening of one side won't be the best choice since the material transformation can cause serious bending effect.

Figure 3.19: 40 mm thick guiding element, 4000 mm long after laser hardening. The material is c45, it had to be hardened both sides to equal the deformation. As a result the deformation could be pushed down under 0,1 mm/m. Source: [5]

In these cases it's advised to treat the opposite site as well to equalize the stress in the piece. Thin materials = sheets under 5mm thickness need to be force cooled by some good heat conducting material such as copper or aluminium from the other side or the low cooling rate won't allow the transformation of martensite, as in figure 3.20.

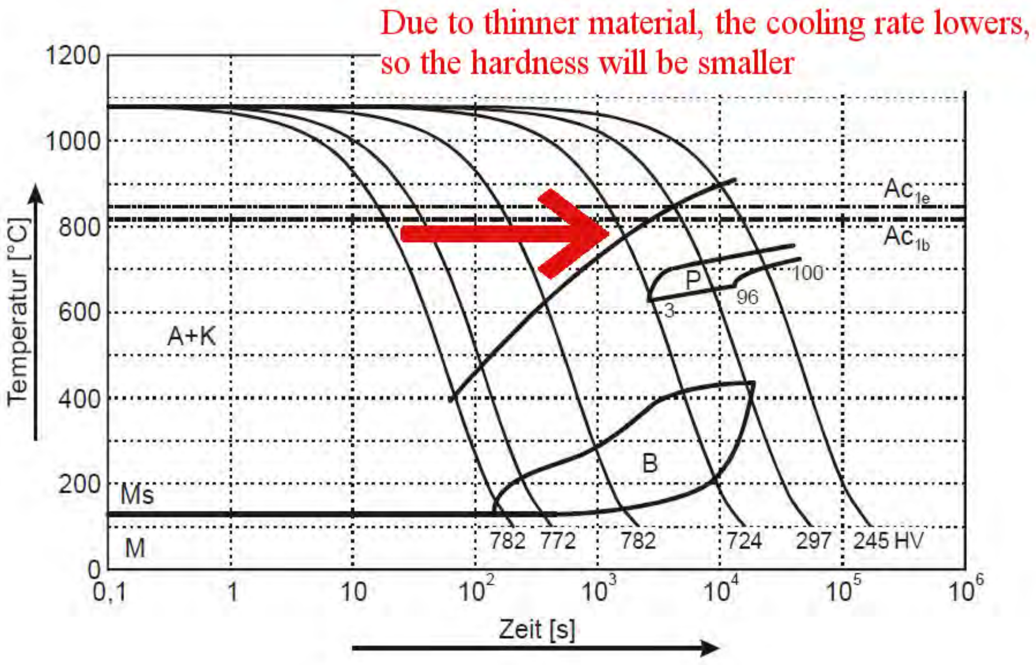

Due to thinner material, the cooling rate lowers, so the hardness will be smaller

Figure 3.20: Under 5 mm material thickness the cooling rate will be slower. As a result the overall hardness will be smaller. Source [36]

3.4 Radiuses

One of the first laser hardening applications is the surface treatment of big sheet metal forming tools. The biggest car manufacturers started to use this technology for increasing the lifetime by hardening the bending radii of the tools. This is mostly considerable where the part and die slip on each other during the forming process e.g. Deep drawing. In this technology there are three different tools, the die, the blank holder and the punch. As the die lowers it starts to form the sheet metal by pushing it with a force which is higher then the yield strength of the material (see figure 3.21. The blank holder's job is to avoid the wrinkling of the flange of the part. According to Böhler Uddeholm the typical failures of such tools are the following (source [35]):

- Wear - this mostly originates from the tool's properties, like hardness, volume, carbide type.
- Chipping - is mainly caused by the stresses in the process and the fatigue resistance of the tool material
- Plastic deformation - This happens if the process stresses overwhelm the yield strength of the tool
- Cracking - This happens if the tools tensile strength is smaller than the stresses occurring during the deep drawing
- Galling - Is a chemical/physical adhesion between the tool's surface and the work-piece. The amount of galling depends from the tool's and the product's chemical composition and the surface hardness.

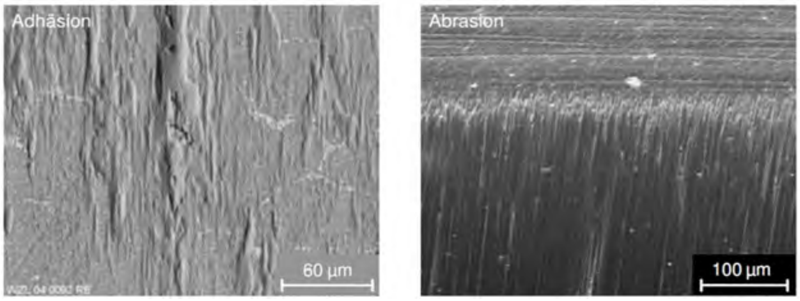


Figure 3.21: Typical failures on deep drawing tools. Source: [34]

Basically the most of typical tool failures can be derived from the tool's volume and surface hardness. Even galling can be caused by lower hardness of the tool is significantly higher than the workpiece, galling won't occur. So by hardening to a medium hardness can fix these issues partially by increasing the yield and tensile strength. But in some cases if the hardness is too high the die and the punch become brittle and begin to break. On the other hand there are some tools which have a huge volume (such as deep drawing tools of car body sides) and cannot be simply put into an oven. These are the reasons why the surface hardening is getting more significant in the tool design. Even big companies use laser hardening to improve the lifetime of off-the-shelf bending tools. The investigation of deep drawing tools allowed me to understand the key failures and to select the correct hardening process according to the working material and the shape of the tool. By the drawing of outer parts of cars such as hoods or roofs the appearance of the drawn plate is the highest priority. If the product has scratches on the surface usually the tool is defective. This means during the drawing process the particles of the plates create some small scratches on the tool which will be “printed” on product (see figure 3.22). It’s caused by the small hardness of the drawing radius. This can be cured by the post-hardening of the surfaces with laser and the polishing of the scratches. The other critical part is the blank holder. If the surface is not flat enough the part is unable to push the plate against the counterpart so some wrinkling can appear on the product. To avoid this issue the blank holder surfaces can be also hardened so with the time it remains unchanged so constant forces can be applied (figure 3.23).

Figure 3.22: Scratches on the drawn car part due to the bad tool surface - scratches appeared on the tool because of the low hardness. Source: [5]

Figure 3.23: Blank holder after laser heat treatment. Source: [5]

3.4.1 One time hardening by 45°

This method is only used by tools made for aluminum sheet bending. The hardening takes place only on the radius and robot moves perpendicular to bending radius' cross section place as on figure 3.24. Since the aluminum is far more softer than the steel tool being used, the only thing to care about is continuous scratching forces on the bending radii. These tools are getting more and more importance as the automotive industry slowly changes several structural parts from aluminium to steel. To see the changes of the hardened radius I investigated the microstructural changes of the bending geometry after hardening with three different materials (bought from Meusburger):

- 1. C45 (1.1730)
- 2. Böhler M200 (1.2312)
- 3. Böhler K110 (1.2379)

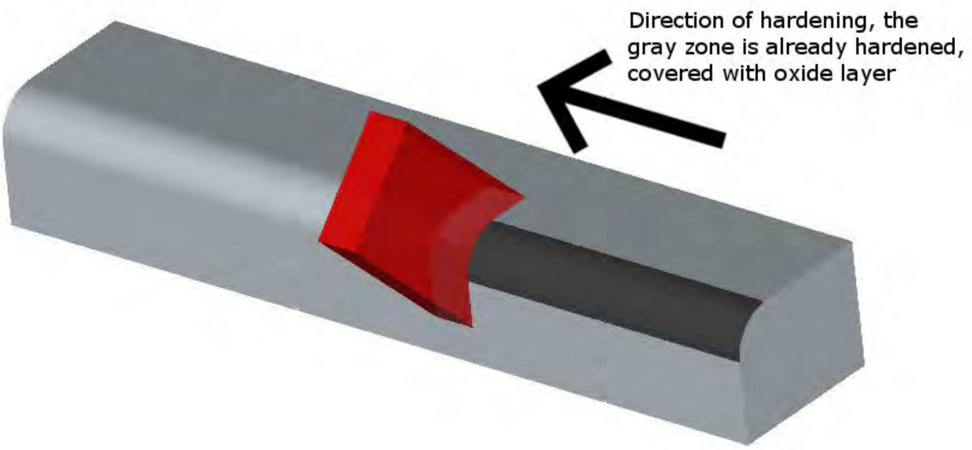


Figure 3.24: The “one time hardening” on a schematic picture. The gray zone is already hardened and covered by oxide layer. The red spot is the laser beam. Source: [5]

The first steel (1.1730) is a commonly used carbon steel for general usage, including tools, prisms, jigs etc. The second (1.2312) is a wide known tool steel in plastic injection moulding industry, but it’s also popular by hot forming of structural steel blanks for the automotive. The third one is a general cold forming tool steel used by the toolmakers to create cutting tools and high quality bending inserts. The aim of this experiment is to see how the different parameters and material composition affect the overall quality of the hardened tracks. 1100°C temperature was applied with different tracking velocities, namely 3,5,10 and 20 mm/s. The power control achieved by Lascon pyrometer which is designed by Dr. Mergenthaler GmbH .The size of the irradiated spot was 15 mm long (normal to the moving direction) and 5 mm wide (parallel to the moving direction). This also means the irradiated spot was definitely larger than the radius, which is 5 mm. The pictures were taken with an optical microscope (Optika metallurgical microscope, model XDS-3MET, serial nr.: SN 403055, mounted with a Moticam 10 documentation camera) at 50x magnification and a yellow filter used for metallurgical investigation. After taking several pictures they were combined with the Microsoft Image Composite Editor program to create a full view of the samples. This allows to see the change of the thickness of the hardened layer along the radii. Therefore in most cases the samples are not completely visible (mainly the bulk material) due to the demand of taking a lot of pictures. By hardening the tool’s surface at 45° the hardened layer gets the following pattern (see figures 3.25, 3.26 and 3.27).

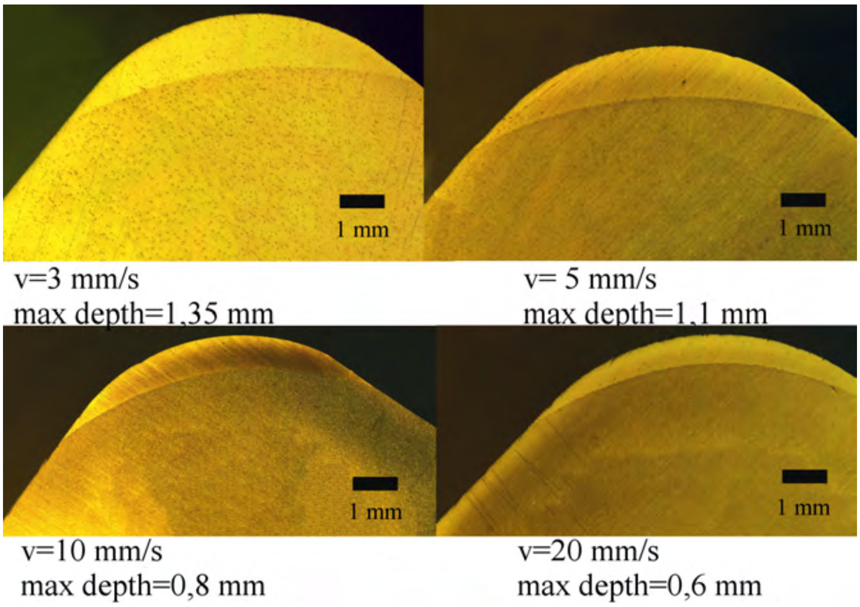


Figure 3.25: Specimen made from 1.2312, tracking velocity varies from 3 to 20 mm/s, etched with Nital 2%. Source: [5]

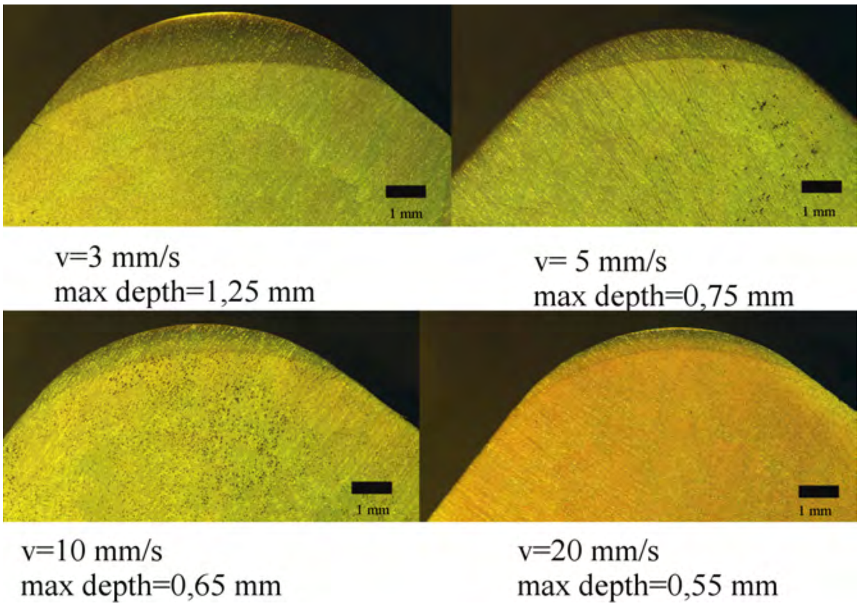


Figure 3.26: Specimen made from 1.2379, tracking velocity varies from 3 to 20 mm/s, etched with Nital 2%. Source: [5]

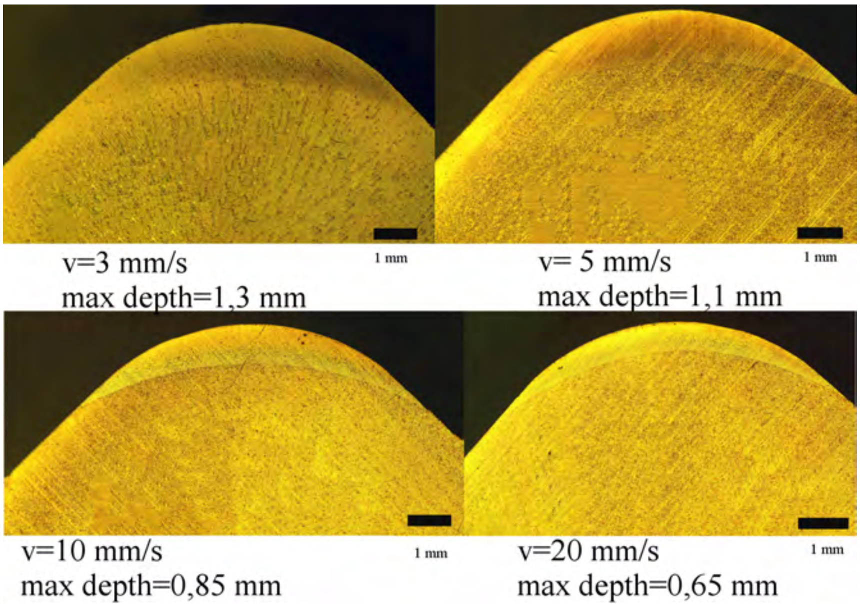


Figure 3.27: Specimen made from 1.1730, tracking velocity varies from 3 to 20 mm/s, etched with Nital 2%. Source: [5]

The hardness was measured after the process to see how affects the scanning speed the hardness values (table 3.2 and 3.3). Please note, we used a high quality source and therefore if the material is from unknown supplier (especially by C45) the reached hardness could be even 5 HRC lower than the expected (because of the tolerances of the chemical composition).

Material	v=3 mm/s	v=5mm/s	v=10 mm/s	v=20 mm/s
1.2379 (K110)	59,9	59,8	59,2	58,8
1.1730 (C45)	59,7	60,9	60,9	61,3
1.2312	60,6	60,9	62,9	62,8

Table 3.2: Hardness measurements of R=5 mm radius, scanning speed varies between 3-20 mm/s, in HRC, deviancy is less than 3 %. Source [5]

Material	v=3 mm/s	v=5mm/s	v=10 mm/s	v=20 mm/s
1.2379 (K110)	N/A	N/A	N/A	N/A
1.1730 (C45)	58,9	59,8	61,4	61,8
1.2312	62,2	62,3	62,7	62,9

Table 3.3: Hardness measurements of R=15 mm radius, scanning speed varies between 3-20 mm/s, in HRC, deviancy is less than 3 %. Source [5]

Even though the reflectivity of the steel doesn't change significantly with the inclination angle (until 50 °) the hardened layer is located only at the radius. That means with one step the side of the part cannot be directly hardened. The hardened layer goes without from the starting of the radius until the other end regardless to the material composition (see figure 3.25 for example). This effect shows us the heat conduction and the absorbed light is the limitation for the perfect hardening of these radii. By this means the radius has to be hardened from 3 sides to achieve a longer tool lifetime (see 3.32). It's an interesting fact that the thermal conductivity of the material didn't have a strong influence on the layer thickness even though they are quite different (1.2379 → 21 W/mK; 1.2312 → 35 W/mK; 1.1730 → 50 W/mK; on room temp. Source: Meusburger material data sheet 6). Therefore the thickness of the layer must be also dependent from other factors such as the change of thermal conductivity on elevated temperatures, but this theory needs a longer investigation and this thesis won't discuss it. These experiences can be applied to every radii if the central angle of the radius stays $\geq$ 90°. By much higher angles the inclination angle is much better along the path so a lot wider layer can be achieved (see figure 3.28).

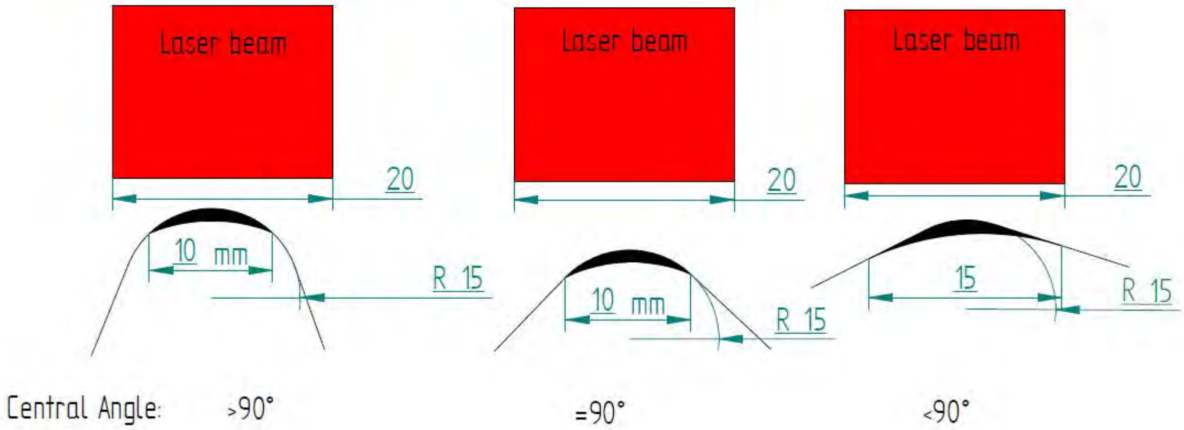
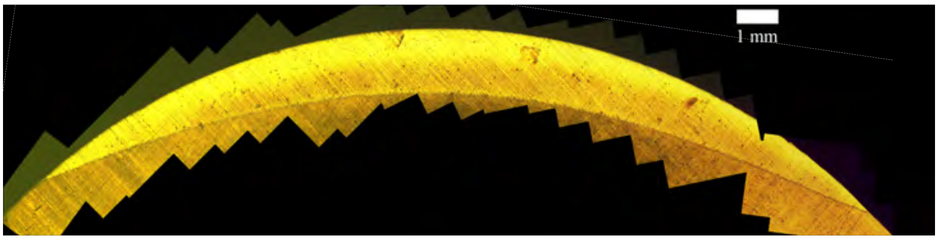
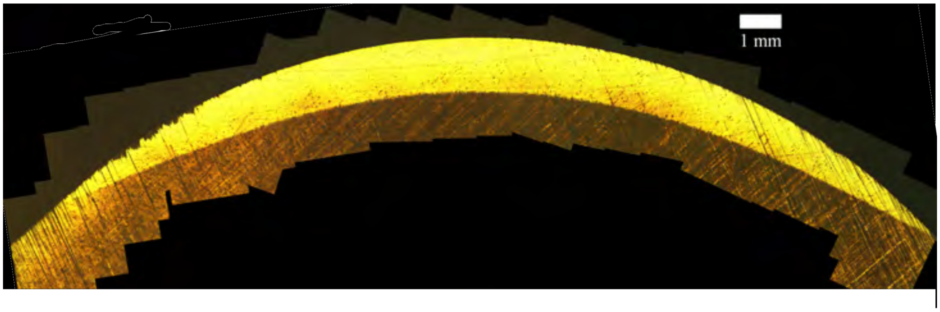


Figure 3.28: Difference of central angle to the width of the hardened track. Source [5]

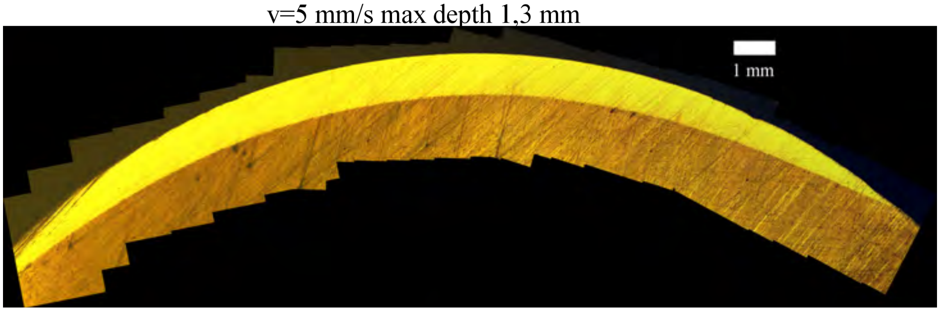
In the followings the same investigation was performed except the radius changed from 5 mm to 15 mm and the spot size was increased from 15 mm to 25 mm to cover the whole radius.



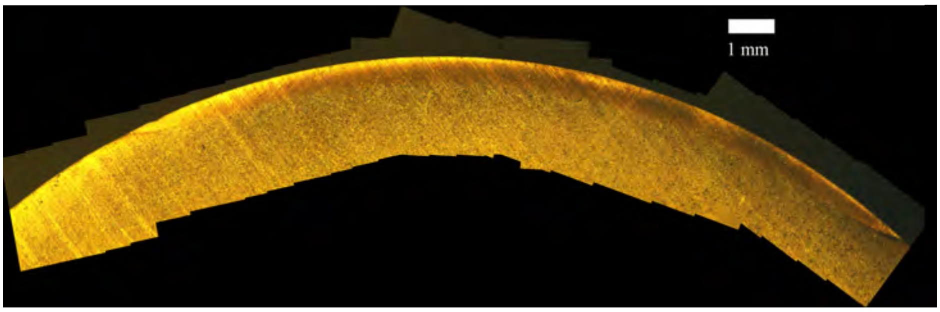
v=3mm/s max depth 1,6 mm



v=5 mm/s max depth 1,3 mm

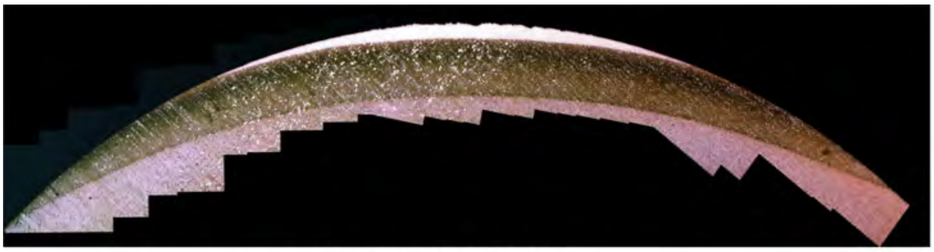


v=10 mm/s max depth 0,95 mm

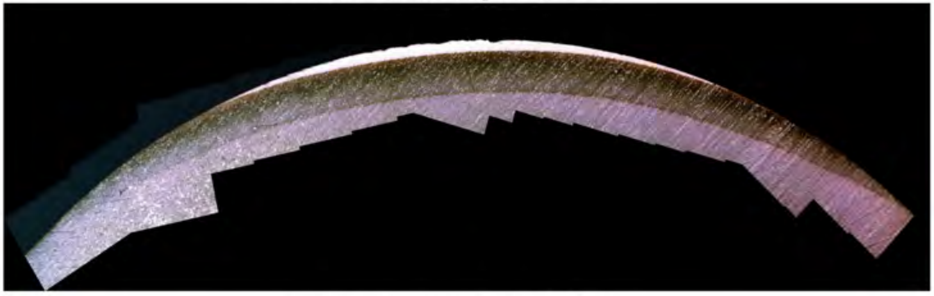


v=20 mm/s max depth 0,58 mm

Figure 3.29: Specimen made from 1.2312, tracking velocity varies from 3 to 20 mm/s, R15 mm radius etched with Nital 2%. Source [5]

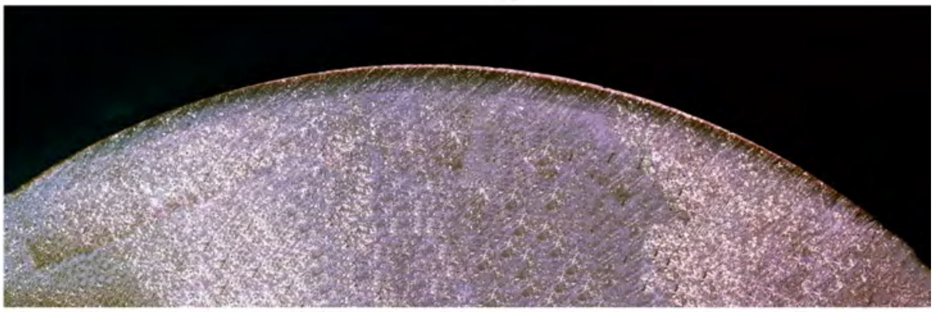


v=3 mm/s max depth 1,5 mm



v=5 mm/s, max. depth 1,15 mm

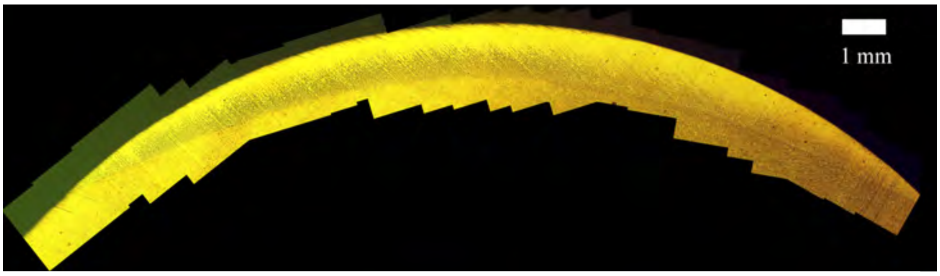
v= 10 mm/s, max. depth 0,8 mm



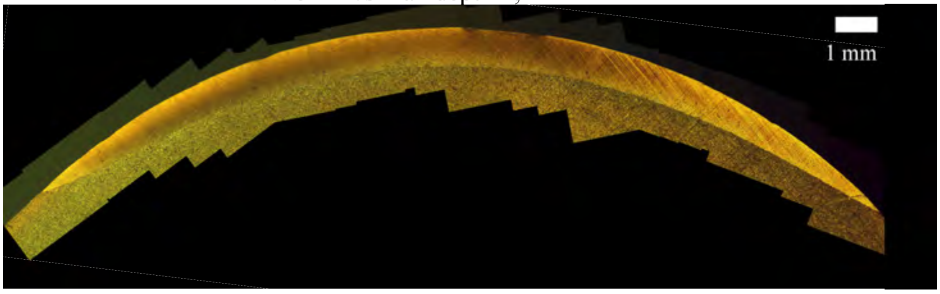
v=20 mm/s, max. depth 0,5 mm

Figure 3.30: Specimen made from 1.2379, tracking velocity varies from 3 to 20 mm/s, etched with Nital 2%. Source: [5]

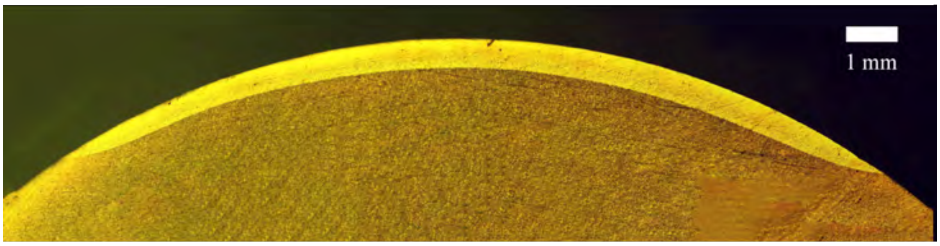
v=3mm/s max depth 1,3 mm



v=5 mm/s max depth 1,2 mm



v=10 mm/s max depth 0,9 mm



v=20 mm/s max depth 0,6 mm

Figure 3.31: Specimen made from 1.1730, tracking velocity varies from 3 to 20 mm/s, R15 mm radius etched with Nital 2%. Source: [5]

As seen in the photos it's impossible to make a constant layer thickness over the radius, because the thickness decreases until the end of the radius, then simply disappears. Therefore in case of steel bending/deep drawing a better method is needed to cover the whole radius including the side of the tools and to prevent the wear.

3.4.2 3 times hardening

This method is used by heavily worn tools usually working with steel sheet. The main customer here is the automotive industry where several mm-s of steel needs to be drawn in one step. These tools are usually made of cast iron and cannot be hardened with conventional methods or in some cases from special tool steels. By this mean these tools have to hardened not only on the radii but also afterwards where the steel sheet is spilling on the surface. A three times hardening is advised (especially by 90° central angle) in this case, this means the bending radius will be hardened from the side and the top and at least from 45° (see figure 3.24). This creates a super hard layer on the radius and (depending on the geometry of course) a 10-20 mm long hardened track on the side and the top (figure 3.32. In the following the result of the 3 track hardening will be shown with the same materials and same radii as in the former section (figures 3.33, 3.34 and 3.35.

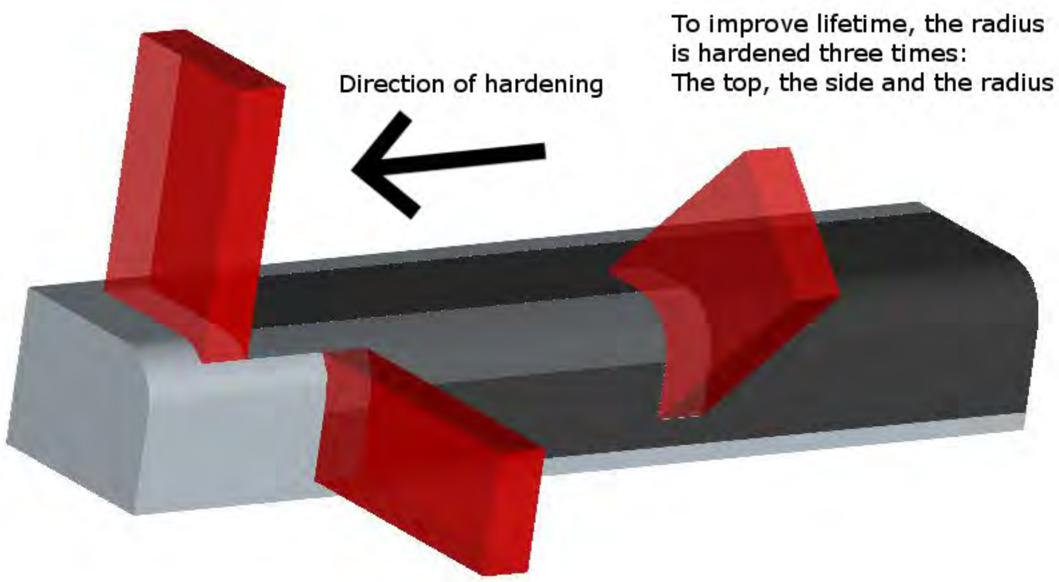


Figure 3.32: The “three time hardening” on a schematic picture. The gray zone is already hardened and covered by oxide layer. The red spot is the laser beam. Source [5]

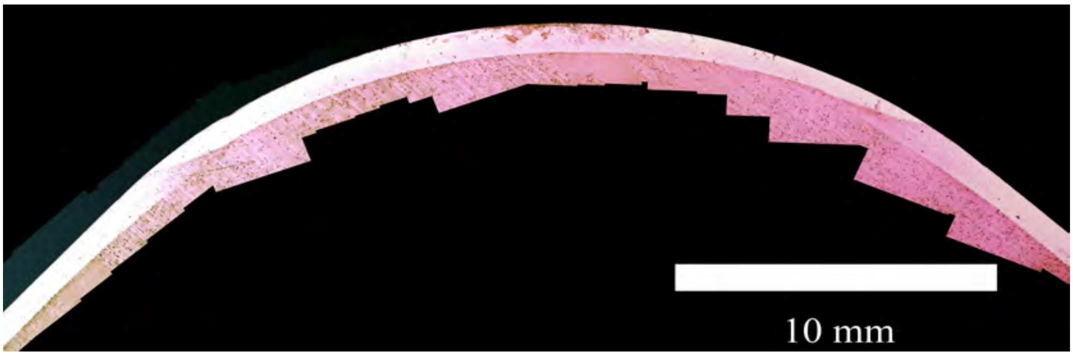


Figure 3.33: Specimen made from 1.2312, v=10 mm/s R15 mm radius etched with Nital 2%. Source [5]

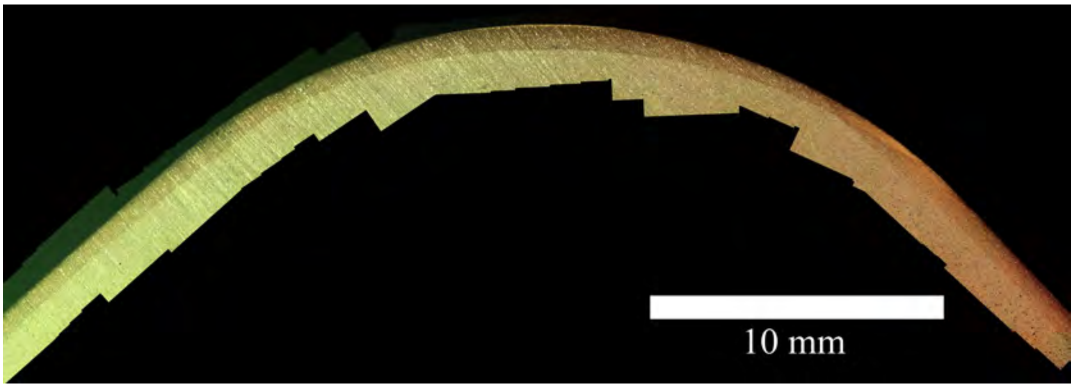


Figure 3.34: Specimen made from 1.2379, v=10 mm/s R15 mm radius etched with Nital 2%. Source [5]

Figure 3.35: Specimen made from 1.1730, v=10 mm/s R15 mm radius etched with Nital 2%. Source [5]

As a result a longer lifetime can be ensured and the adhesion and scratching of the surface can be significantly reduced. The overlapping zones are also visible if one takes a closer look, the tempered zone is very small. The heat affected zone of the nearby tracks unfortunately reduce the hardness of the firstly created layer by back tempering. Reducing the number of overlaps can reduce the number of backtempered zones and the lower hardness areas on the surface. Therefore a higher number of nearby tracks during laser hardening of the radii is not advised.

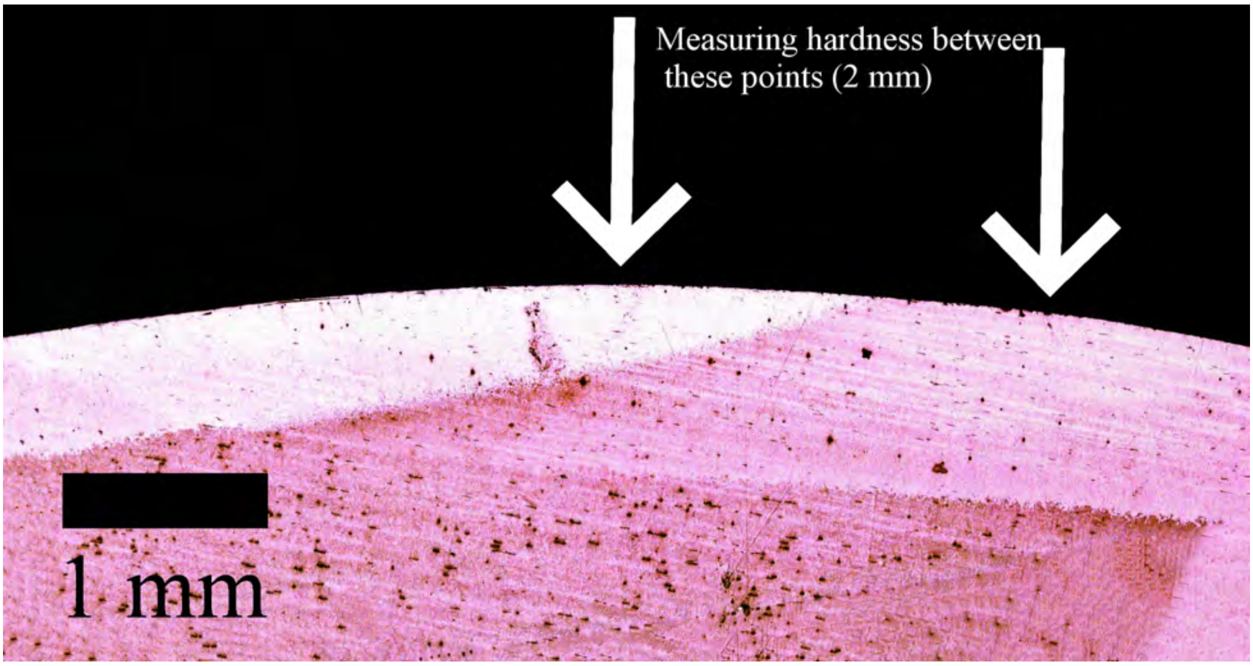


Figure 3.36: Overlapping zone of the 1.2312 specimen. Source [5]

After measuring the overlapping zone the hardness values drop only 5-10 HRC. In the following figure 3.37 we can see the hardness values along the radius measured every 0.1 mm with UCI measuring device. Before the test to reduce failures the oxide layer was completely removed by p1500 sandpaper and the surface was cleaned with acetone to remove oils. The hardness measurement was taken from the side (parallel with the page) so it's not visible on the micrograph (see figure 3.36). Other studies experienced a very similar result (figure 3.38).

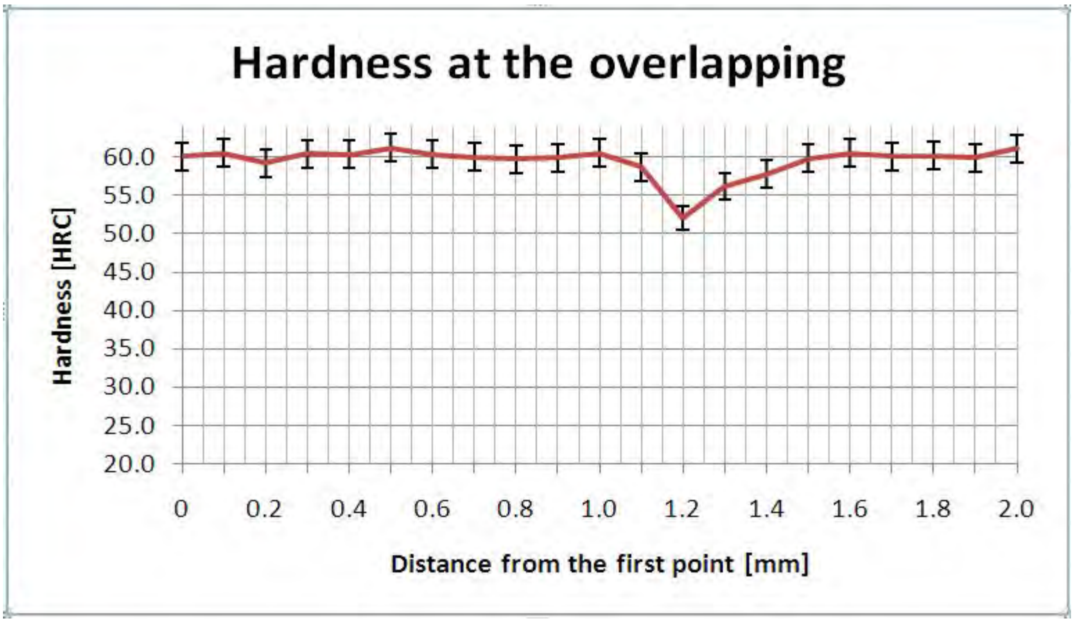


Figure 3.37: Hardness measured on the surface in HRC between the two points. Source: [5]

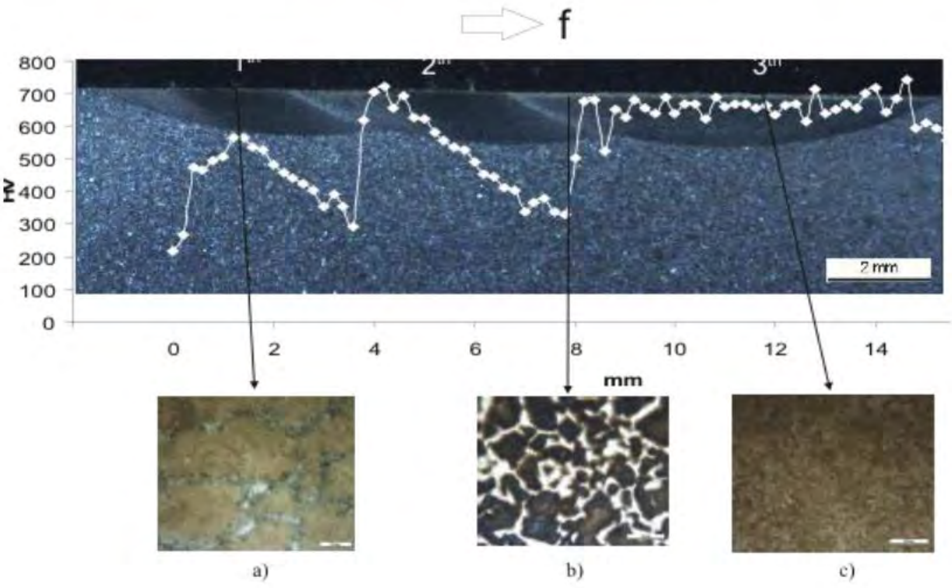


Figure 3.38: Hardness measured on the surface in HRC between the overlapping tracks. Source: [15]

3.4.3 Layer thickness - micrographs

The layer thickness is varying from 0,3 mm to 1,5 mm depending on the process parameters (see figure 3.39), but in this case the thicker is the better, because the part won't become brittle.

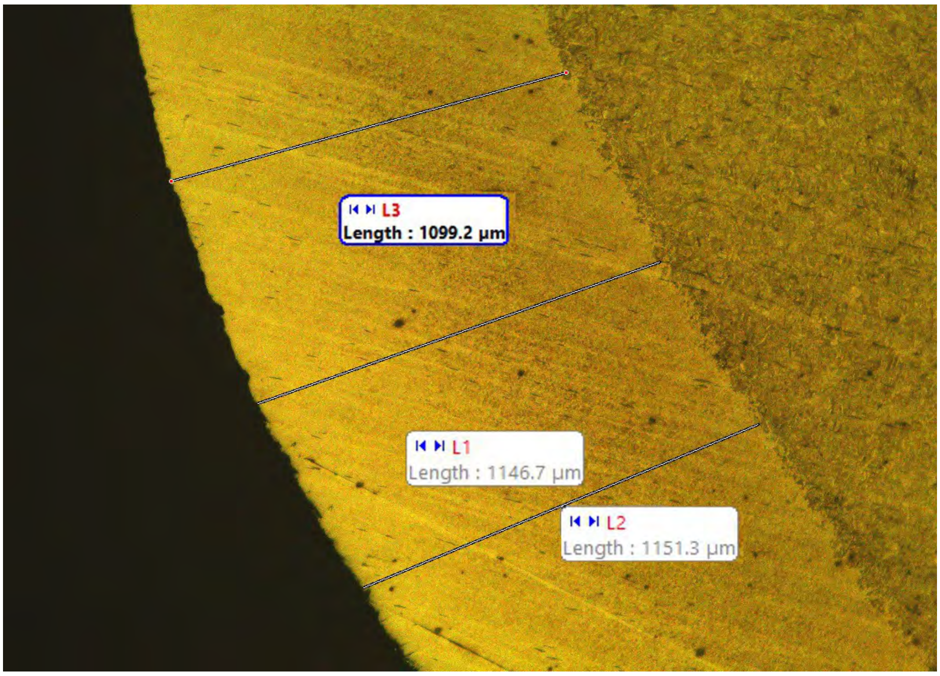


Figure 3.39: Specimen made from 1.2312, v=5 mm/s R5 mm radius etched with Nital 2%. Source: [5]

In this picture we can see the border of a fine grained hardened layer and the bulk material. This picture can also show us the increased chemical resistance of the martensitic structure. The Nital used for etching leaves the outer layer unharmed but the inner areas getting darker with the time.

3.4.4 Examples for hardening of radiuses: Bending and deep drawing tools

In this part some real life examples will be shown where the lifetime of the tools have been improved by several times of the original (unprocessed part). The first figure 3.40 shows a bending tool for the automotive industry. The gray lines in the middle are slightly elevated geometries with an approximately 5 mm bending radius. The sides of the tool were hardened with the "3 times hardening" method, to ensure wear resistance where the blank scratches the surface. The part was from annealed cold working tool steel. The reached hardness values are written on the surface after testing in HRC. If we would harden the tool in furnace the cost would be more than 500 EUR not to mention the price of afterwork of the hardened material. With laser hardening it costs appr. 400 EUR and the part can be used immediately.

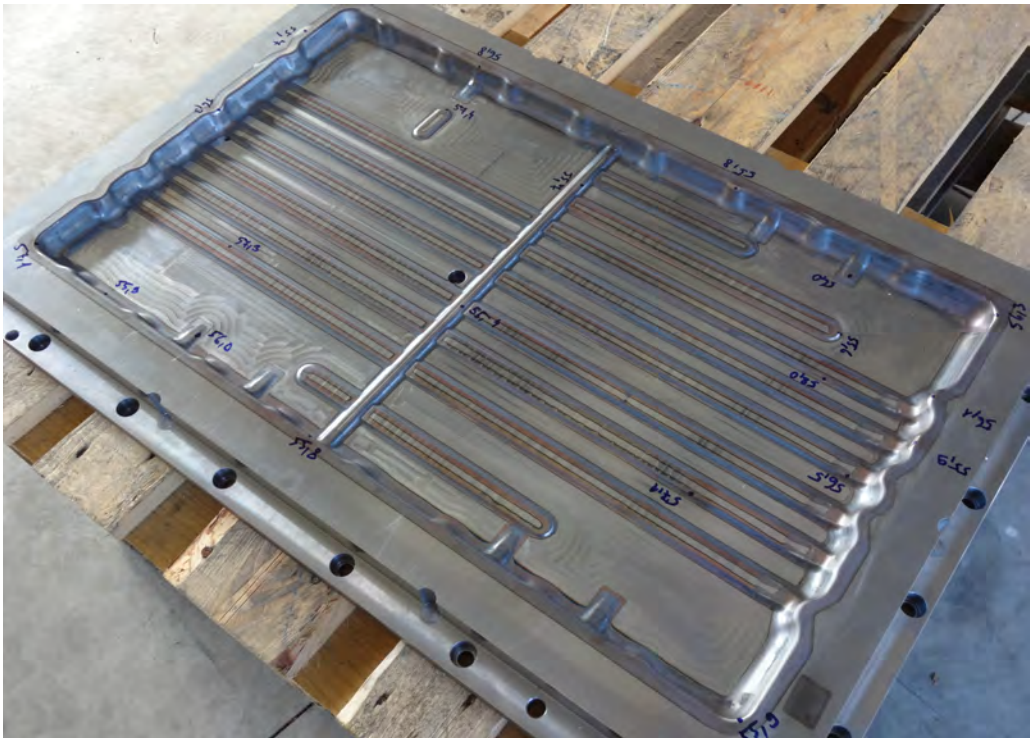


Figure 3.40: Deep drawing tool, automotive industry. Source: [5]

The following picture shows a smaller part. Due to it's complexity the same problems occur if one tries to harden it in an oven. The heat treatment allowance needs to be even 1 mm to correct the deformations. In this case the geometry was measured before and after laser treatment with 3D laser scanner and the part stayed in the tolerance. The hardness of the tracks (gray lines) is written on the surface after measuring on figure 3.41. The tool is hardened first on the top, then on the side and at least on the bending radius with a quite small (6,5 mm long) spot. The machining after hardening of the tool is spared (appr. 200 EUR) and this hardness could not be reached by conventional heat treatment due to the risk of embrittlement. The cost of laser harden was appr. 150 EUR.

Figure 3.41: Deep drawing tool, automotive industry. Source: [5]

3.5 Cutting and punching tools

By the creation of punches, toolmakers are continuously balancing between the lifetime, the brittleness and the cost of the tool. Increasing the hardness ensures a longer lifetime because the abrasive wear is lower, but the high hardness can also improve the probability of chipping and the manufacturing costs are increasing too. According to the studies of Södeberg and Hogmark [30] the lifetime of the tools can be easily improved by switching to HSS tools, but in case of a huge cutting tool the material change could make the cost of tool even an order of magnitude higher, which is impossible to sell. But if one sticks to the conventional tool steels the wear mechanisms can be avoided by a good chemical composition and hardness combination. Especially by lower cutting speed (or even intermittent cutting) the lower hardness of the bulk material is very important to prevent the chipping. By combining the soft bulk material with a fine grained cutting edge, the productivity can be increased easily increased without risking the cutting edge.

3.5.1 Angle of the cutting edge

The smaller angle of the cutting edge decreases the heat conductivity of the material, so the operator needs to be more careful not to burn the edges of the tool.

In some cases it's advised to lower the hardening temperature with 50 or even 100 °C to reach the efficient cooling rate. For this cause the these geometries are having often thinner layer compared to radiuses. For the best result there's a possibility to use special designed laser heads which are capable to harden more sides of the standardized bending tools respectively to it's function. Unfortunately there's no such head at the BuBenLaser company, so the simplest geometry (edge-angle 90°) will be investigated and evaluated.

3.5.2 90°edge

This is the simplest geometry, which is good example to examine the results of laser hardening (see figure 3.42). In this section the influence of the process parameters will be demonstrated on the layer thickness and what is the optimal for cutting tools. During the cutting of sheet metal the edge experiences high stress. If one cuts structural elements the abrasive wear is even higher, so the cutting edge turns quite fast into a radius. Unfortunately by simply using a harder material won't help because it will tend to chipping of the cutting edge. After cutting the tool also experiences a split in it's back. This means it will get worn also during the exiting through the die and the punch. So the "ideal" hardening method is combine the bulk material's hardness with an optimal surface hardness.

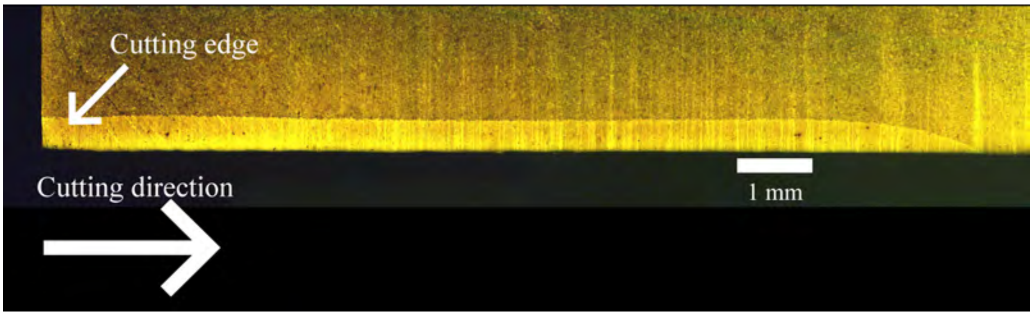


Figure 3.42: Cutting edge with the hardened layer. Source: [5]

As seen in the picture during the cutting process the sheet metal meets always with hardened material and in case of wear the tool can be several times sharpened before it needs to be hardened again. This gives the customer a reliable and cheap solution where the cutting tool lifetime can go up to 5 times of the original (or unprocessed part). This experience was made at the company by customer feedback.

3.5.3 Heat treatment from one side

There are several ways to harden the cutting edge, in this section three ways or angles will be described from which almost every other possibilities can be extrapolated. Respect to the cutting direction three different irradiation angles will be investigated: 90°, 70°and 45° (see figure 3.43). To see how the cutting edges influenced by the tracking speed, sections were created from different materials hardened by two different tracking velocities. After etching with 2% Nital the hardened layer is clearly observable on the following figures 3.44, 3.45 and 3.46.

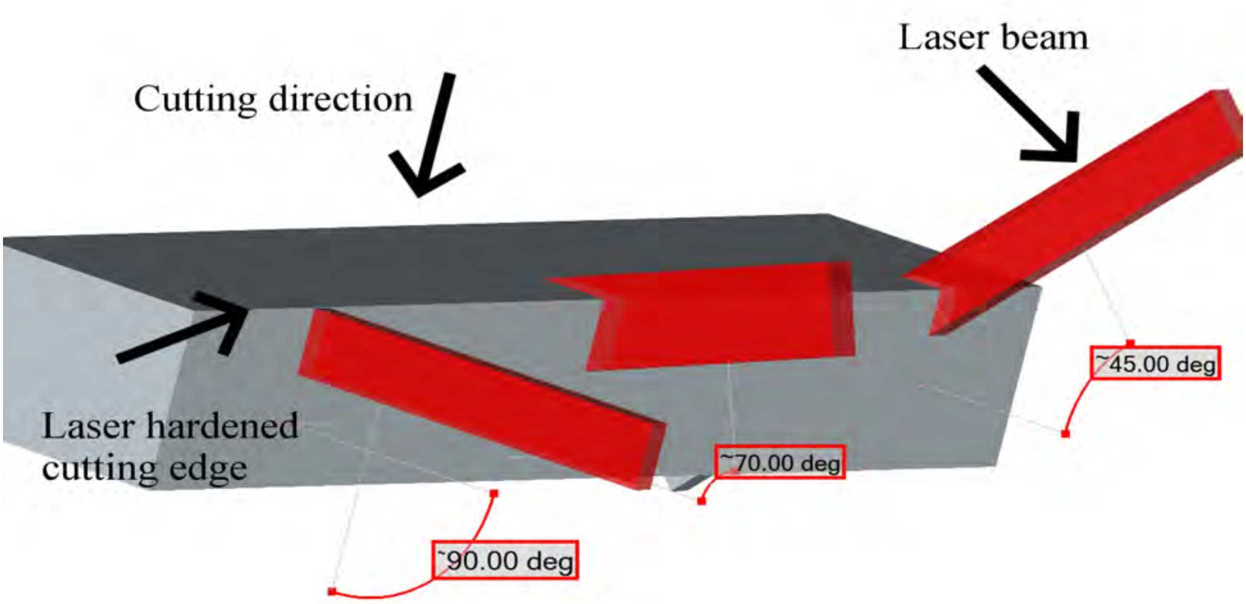
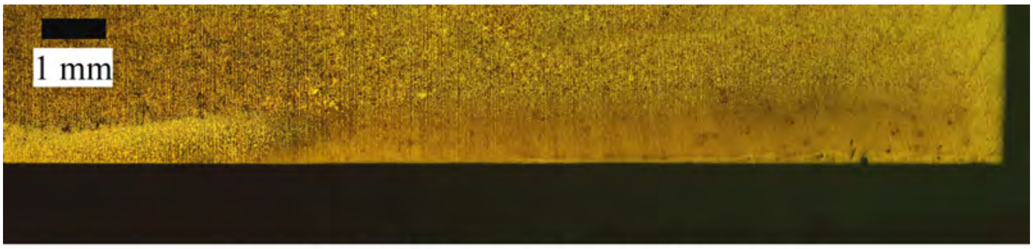
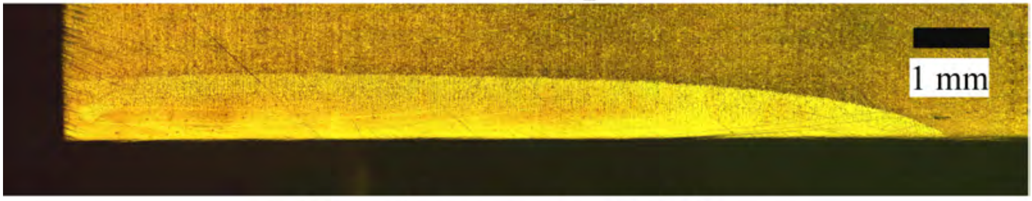


Figure 3.43: The sketch of the laser hardening of cutting edges with different irradiation angles respect to the cutting direction. Source: [5]

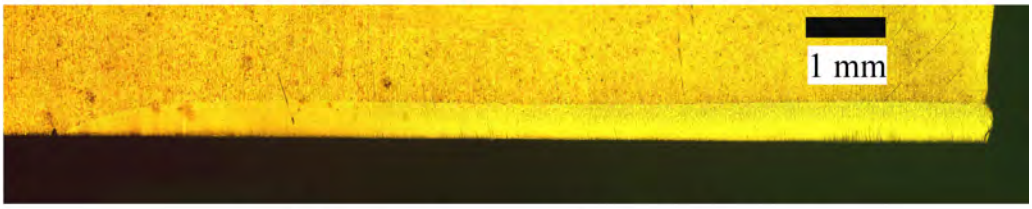


v=3mm/s max depth 1,1 mm



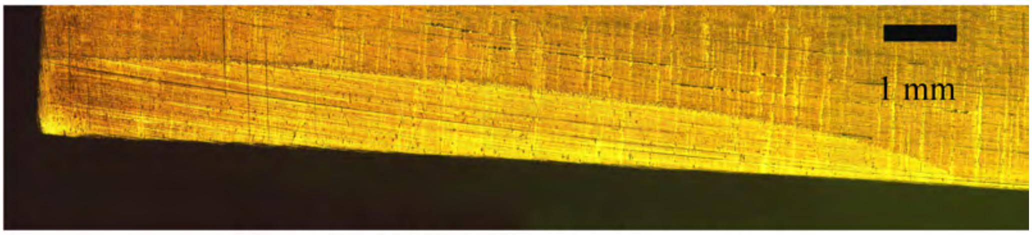
v=5mm/s max depth 0,8 mm

v=10 mm/s max depth 0,6 mm

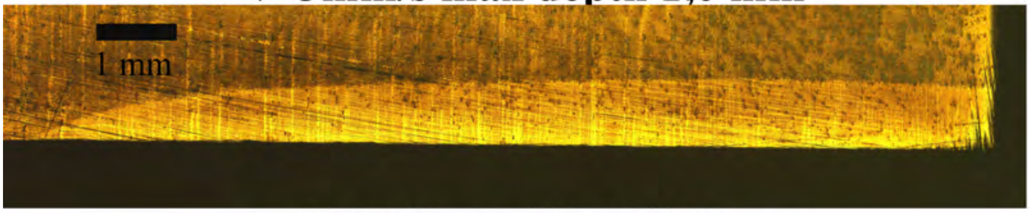


v=20 mm/s max depth 0,45 mm

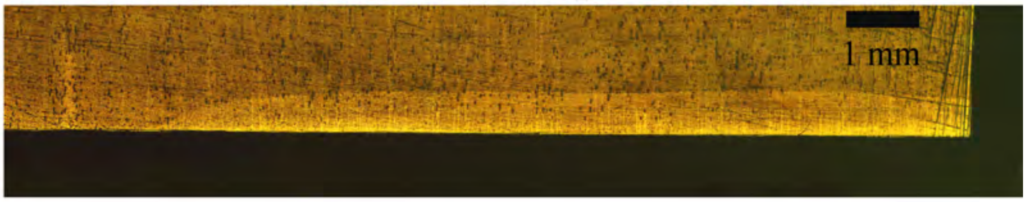
Figure 3.44: Laser hardening of cutting edges made of 1.1730. Angle of incident 90°. Source: [5]



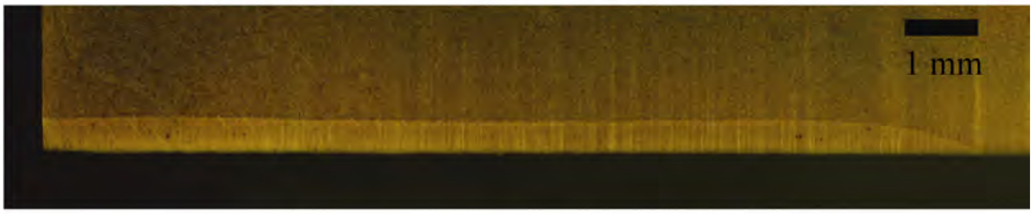
v=3mm/s max depth 1,0 mm



v=5mm/s max depth 0,8 mm

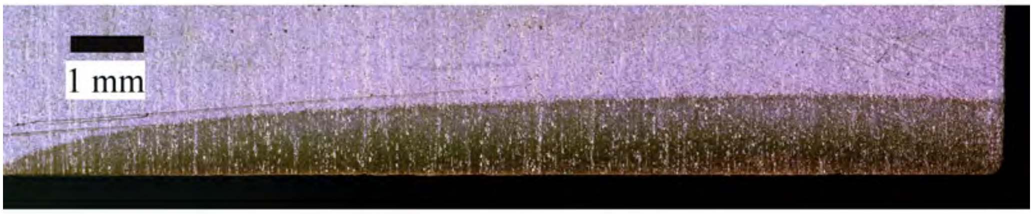


v=10 mm/s max depth 0,6 mm



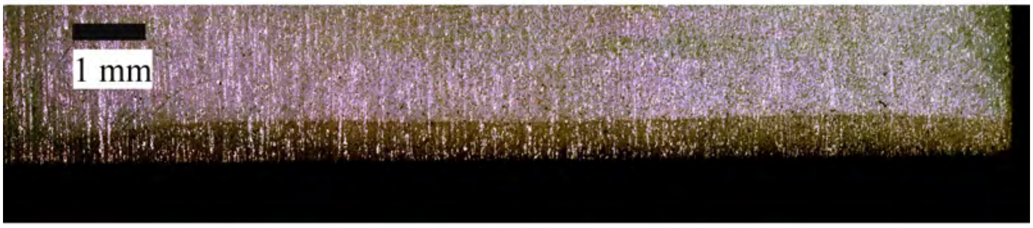
v=20 mm/s max depth 0,45 mm

Figure 3.45: Laser hardened cutting edges made of 1.2312. Angle of incident 90°. Source: [5]

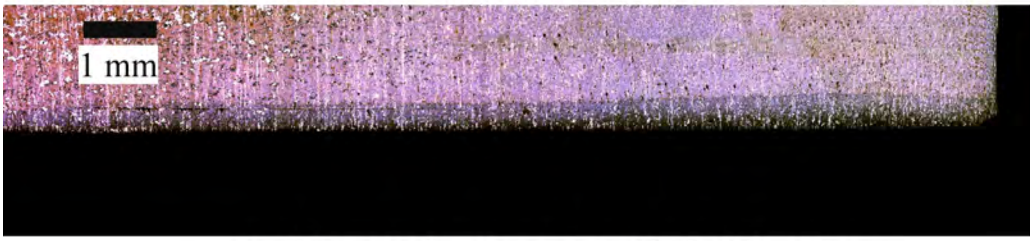


v=3mm/s max depth 0,9 mm

v=5mm/s max depth 0,7 mm



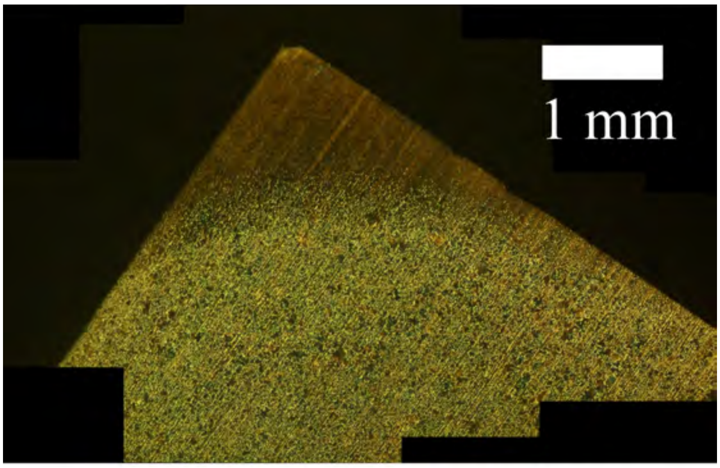
v=10 mm/s max depth 0,5 mm



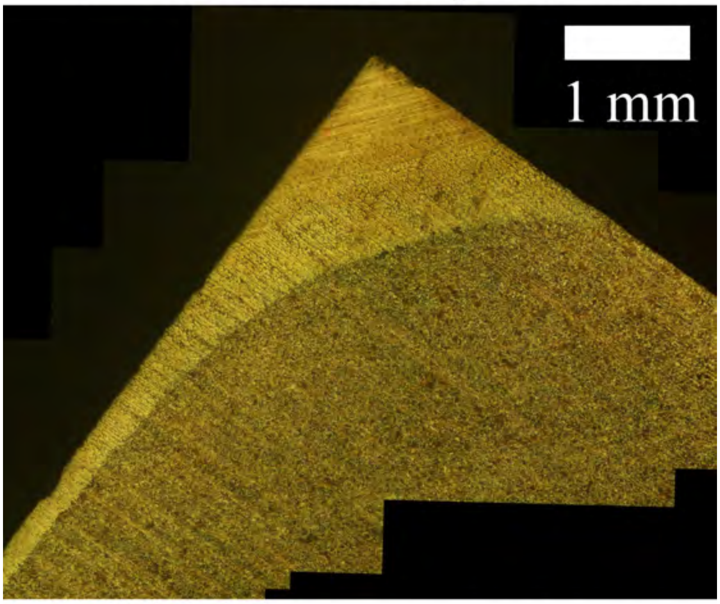
v=20 mm/s max depth 0,35 mm

Figure 3.46: Laser hardened cutting edges made of 1.2379. Angle of incident 90°. Source: [5]

In the following figures (see figures 3.47, 3.48 and 3.49) the cutting edges can be observed where the 45° inclination angle was used. The tip is always slightly molten (on 1050 °C temperature) (see 3.50), therefore the operating temperature needs to be lowered (under 1000 °C). This results a way thinner layer (the maximum thickness from the tip is less than 1 mm) and a lower hardness (under 60 HRC). Not to mention these edges can not be resharpened, since the hardened layer is located directly at the tip. Without the hardened steel on the side the blank can scratch the surface of the tool and soon the products going to have a burr. This collides with the goal to reach the possible highest hardness and quality, so this method is neglected.

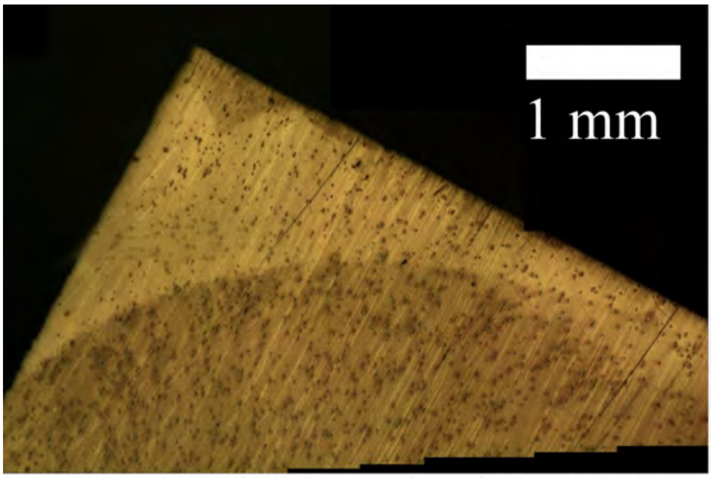


v= 3 mm/s, max. depth 1,5 mm

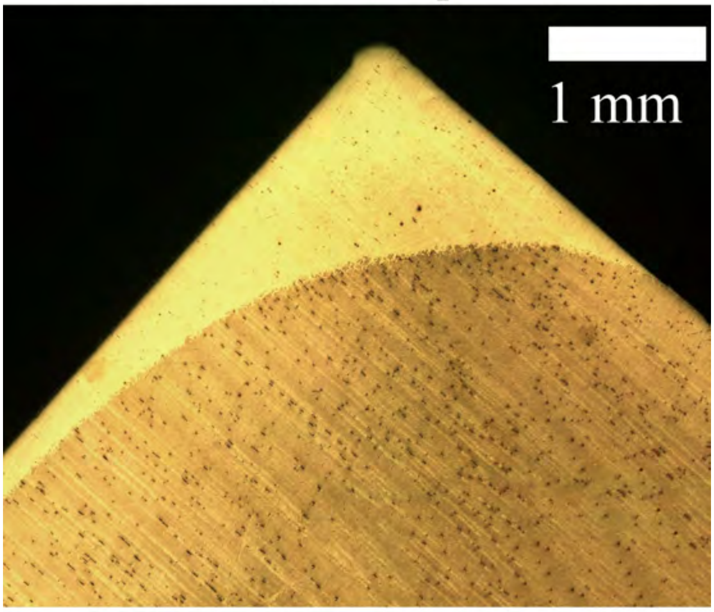


v= 10 mm/s, max. depth 1,4 mm

Figure 3.47: Laser hardened cutting edges made of 1.1730 irradiated with 45° inclination angle Source: [5]

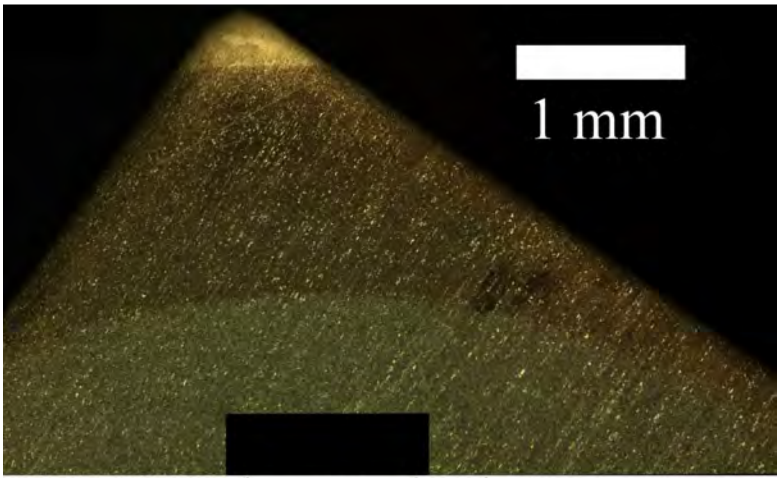


v= 3 mm/s, max. depth 1,5 mm



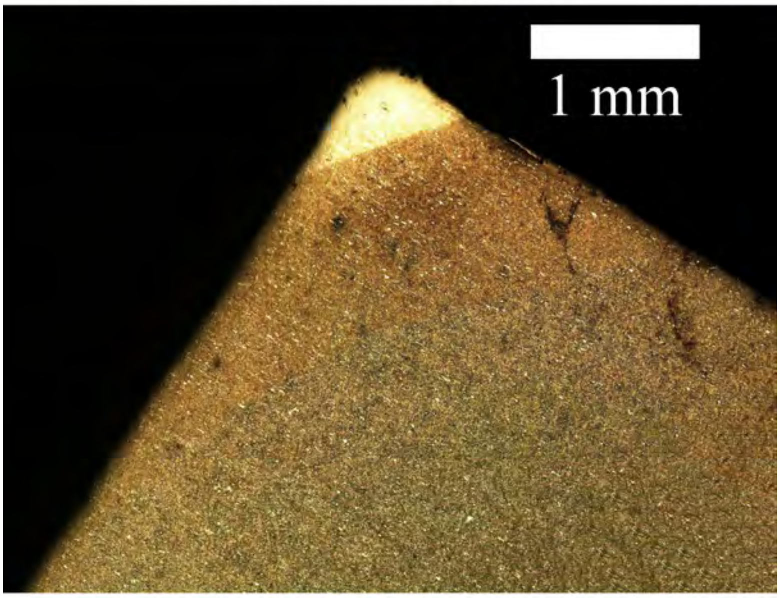
v= 10 mm/s, max. depth 1,4 mm

Figure 3.48: Laser hardened cutting edges made of 1.2312 irradiated with 45° inclination angle Source: [5]



[redacted]

v= 3 mm/s, max. depth 1,7 mm



v= 10 mm/s, max. depth 1,4 mm

Figure 3.49: Laser hardened cutting edges made of 1.2379 irradiated with 45° inclination angle Source: [5]

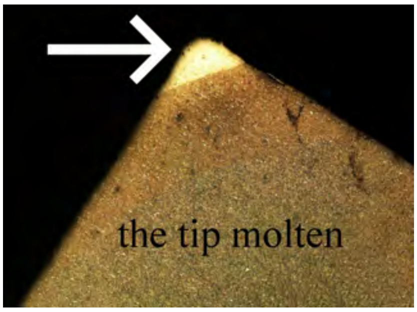


Figure 3.50: Molten edge, the molten material is white, the edge becomes a radius. Source: [5]

The following figures (figures 3.51, 3.52 and 3.53)show the test results of the hardening with 70° inclination angle. On the figures a beneficial hardness layer can be observed, the layer is thick at the tip (hard against punching forces -but the risk of embrittlement rises) and still there's a layer on the side. The problem is the same with the 45° inclination angle, that the tip of the cutting edge is slightly burned (on 1050 °C), therefore the cutting edge is destroyed. If the controlling temperature is lowered under 1000 °C the edge stay intact, but the layer thickness is way smaller (under 1 mm) and the hardness decreases (under 60 HRC).

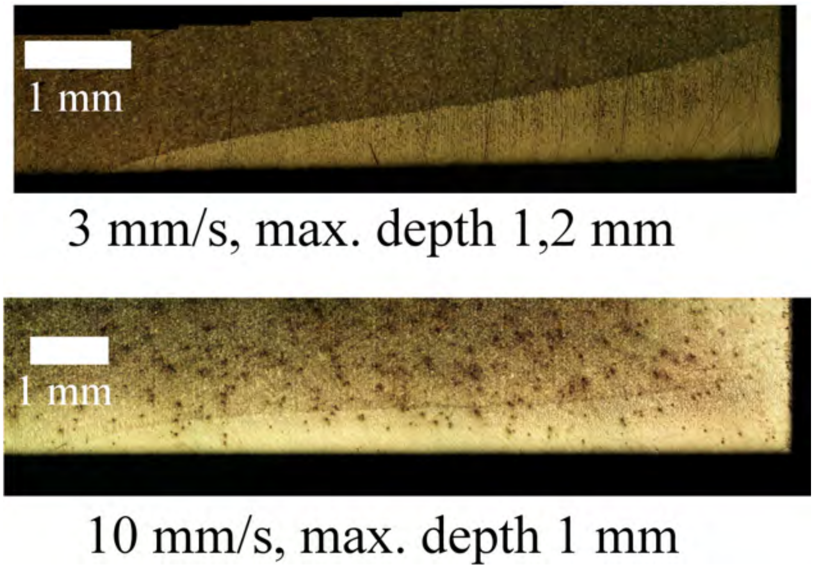
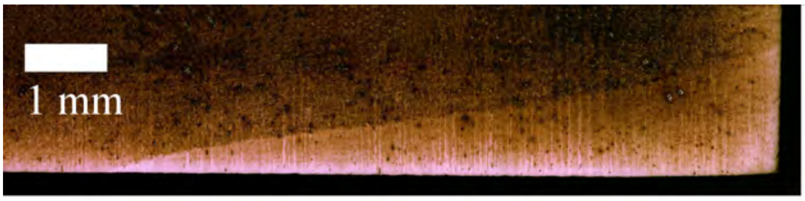


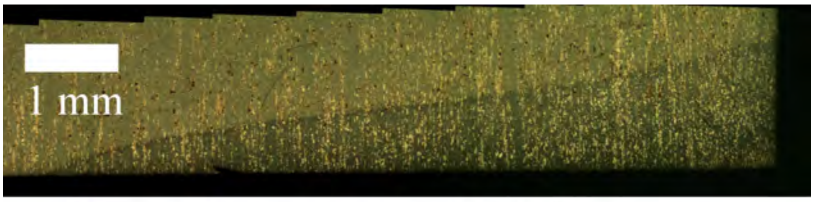
Figure 3.51: Laser hardened cutting edges made of 1.1730 irradiated with 70° inclination angle Source: [5]



3 mm/s, max. depth 1,3 mm

10 mm/s, max. depth 1 mm

Figure 3.52: Laser hardened cutting edges made of 1.2312 irradiated with 70° inclination angle Source: [5]



3 mm/s, max. depth 1,3 mm

10 mm/s, max. depth 1 mm

Figure 3.53: Laser hardened cutting edges made of 1.2379 irradiated with 70° inclination angle Source: [5]

The effect of heat accumulation can be experienced by lower tracking speeds. This means the hardened layer continuously gets bigger as we approach the tip. By other inclination angles than 90° the melting of the tip can be observed. Even though the overall power during the process didn't change these samples would be destroyed from the aspect of the customer. The risk of burning was unpredictable because the pyrometer sometimes lowered the power with 5-10 %, which was enough to leave the edge intact. So these edges had to be hardened with significantly lower temperature to avoid the damages, which made the layer thinner and the hardness a few HRC smaller. To avoid this, it's possible to use a manual power control, but than every cutting tool has to be programmed individually which makes the industrial usage impossible. The hardness of the samples were also measured approximately 1 mm from the cutting edge with an UCI measuring device as seen in table 3.4.

Material	v=3 mm/s	v=5mm/s	v=10 mm/s	v=20 mm/s
1.2379 (K110)	60,1	60,4	59,5	59,7
1.1730 (C45)	58,9	61,3	61,6	61,5
1.2312 (M200)	62,1	61,7	62,9	62,6

Table 3.4: Hardness measurements of cutting edges, scanning speed varies between 3-20 mm/s, in HRC, deviancy is less than 3 %. Source: [5]

Since the hardness of the 1.1730 steel slightly decreases with lower speeds (appr. 1 HRC) if the tool is not in the risk of breaking it is advised to use lower speeds to grant a thicker martensitic layer. The best results showed the hardening with 90°irradiation angle, since the cutting edges stay intact every time and they can be resharpened several times (depending on the amount of wear).

3.5.4 Microscopic structure

The microscopic structure shows the best representation of hardened cutting edges. Near the tip there's a 1,0-1,5 mm hardened layer which contributes to the lifetime extension very well. The back side of the tool is also hardened to avoid the scratches after cutting several hundred times. If one thinks about refurbishing of the tool, it's possible almost until the whole hardened layer disappears (with thinner layer the lifetime is shorter accordingly). If the bulk is still usable after several re-grinding, it's possible to re-harden the surface so the customer can use it again without consequences (figure 3.54) .

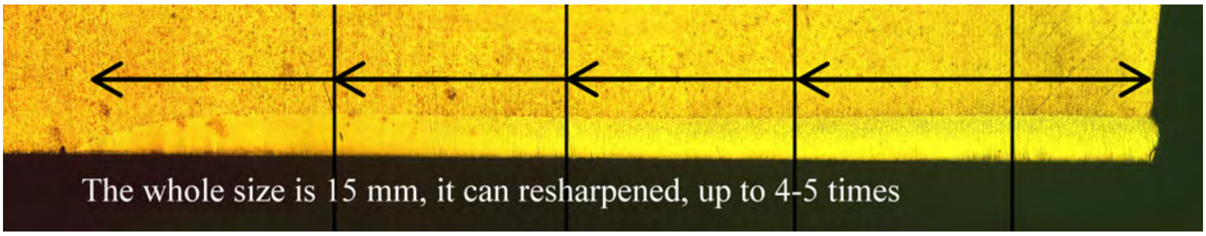


Figure 3.54: The cutting edge can be several times reused. Source: [5]

Compared this to the laser hardened edges with other inclination angles, it's clear that the customer gets a constant layer thickness so they can calculate with constant lifetime after every resharpening. As the layer is also somewhat thinner the risk of embrittlement is also smaller. The inclination angle can be varied from 45° to 0° but if the power control doesn't follow the shape of the hardened surface (e.g. on line power control by scanner head) it's not advised to use bigger inclination angle than 10°. This can cause severe burn of the edge by heating up only the tip and the sides of the edge won't get enough power to reach even 1000°C. In this case you will get a quite small and thin hardened layer with the possibility of destroying the working edge.

3.5.5 Example for cutting edges

The cutting tool on figure 3.55 was made by a big hungarian toolmaker company for the automotive industry. The complexity of the finished tool makes the hardening with induction or oven heat treatment without allowance impossible (it would cause huge deformations). The laser hardened tool can be used right after the treatment, only some polishing needed. The gray track around the cutting edge is the hardened layer covered with an oxide scale. The geometry was programmed manually and the hardness is measured after laser heat treatment near the edges. The material is cast steel (1.2333) and it's in an annealed state (nominal hardness appr. 30-35 HRC). The laser hardening costs about 150 EUR. Unfortunately the lifetime increase is not open for public, it's an internal data of the company.

Figure 3.55: Laser hardened cutting tool from the automotive, the irradiation angle is 90°. Source: [5]

The following tool on figure 3.56 is used only for cutting of plastic and it had been hardened with 90° inclination angle. The engineers of the company said the tools work 5 times more than the original version. The finished part can be observed on the figure 3.56. With regrinding the tools the overall lifetime could be extended by 300 %. This increase was reached with 1.2379 tool steel and after the process the cutting edges were 60-62 HRC hard 3.57. By this mean the customer saved the price of 2 new tools.

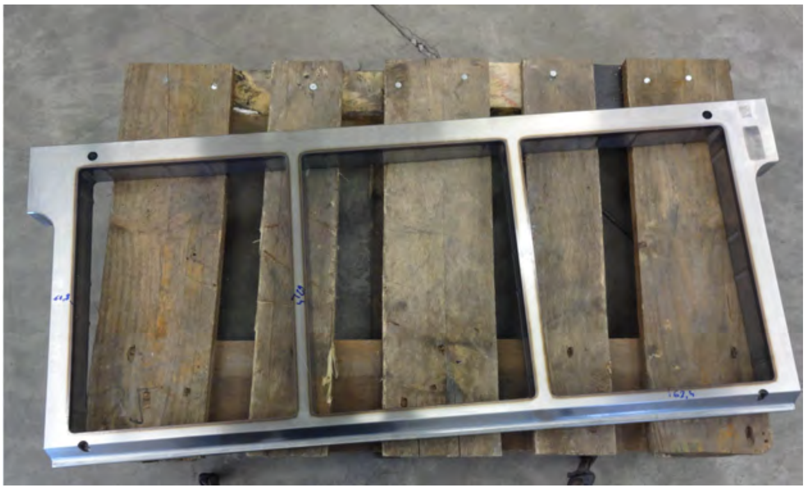


Figure 3.56: Cutting tool from the top. Source: [5]

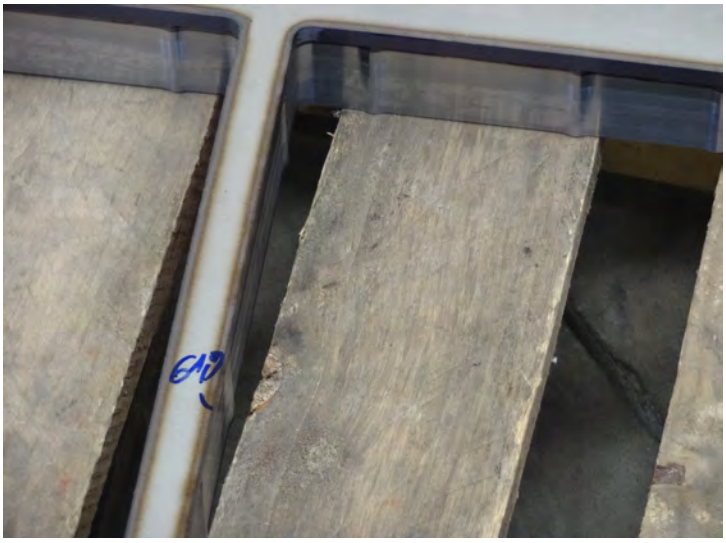


Figure 3.57: The cutting edges directly after hardening. Source: [5]

This small cutting insert on figure 3.58 was made for the automotive industry. The material is a tool steel in hardened and annealed state (35-40 HRC). The hole is too small to harden from the side (which is desirable) so it had to be harden from the top. It would be better to harden from the inside, but there's no laser head on the market for such small diameters (⌀10 mm and 8 mm). Since the part is quite small (and therefore cheap) the hardening costs had to be kept low. The hardening costs about 20 EUR. The edge is hardened appr. 1 mm deep in the cutting direction. The lifetime of the tool is almost the same of the oven hardened type so the machining costs were radically decreased (appr. -50 %).

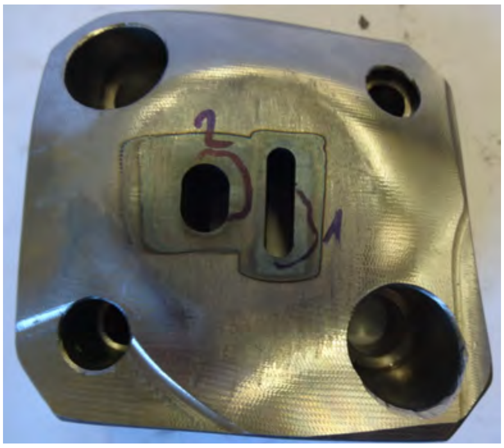


Figure 3.58: Laser hardened cutting insert from the automotive. Irradiation angle -90° respect to the cutting direction. Source: [5]

3.6 Other examples from the industry

3.6.1 Piston for hydraulic press

This piston is used in a huge pressing machine. The outer cylinder had to be hardened (gray lines on figure 3.59), because it may get scratches with the time. To avoid this it was hardened up to 56-60 HRC so the maintenance and downtime costs can be reduced dramatically. The change of such element is about 1 shift (8 hours) and in normal case it has to be maintained (welded and lathed) every 5 years. According to former estimations the company can spare about 16 hours of downtime for the price of 5 hours downtime.

Figure 3.59: Huge piston for hydraulic pressing machine. Source: [5]

3.6.2 Injection moulding tools

The last figure 3.60 shows a plastic injection mold was made for the automotive industry. It was used for creating fiber reinforced plastic parts of cars. For this reason it was advised to harden the area where the molten plastic mixed with the fibers first enter the mold. Typical problem that the surface of the mold changes by the time as the plastic slowly erodes the steel. In this case the hardening of each tool costs about 200 EUR, which is appr. 5-10% of the new tool's price. The formerly estimated lifetime of the tools already exceeded more than 10%, but the company still waits for more results.

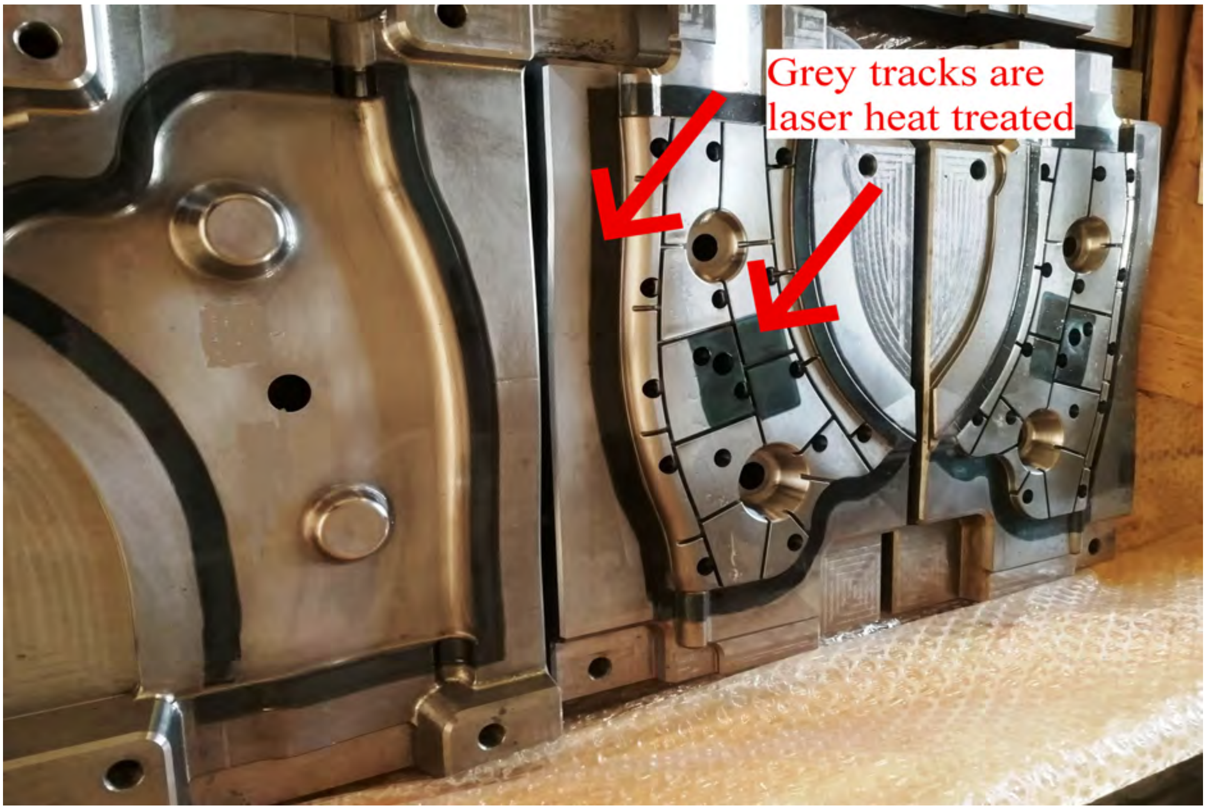


Figure 3.60: Injection moulding tools, used for fiber reinforced plastics. Source: [5]

3.6.3 Robotic grippers

These parts on the figure 3.61 were made from 1.1730 (c45) intentionally to be sent to laser harden right after machining. This is due to the possibility of hardening to higher values (58-60 HRC) after finishing the parts (practically there's no deformation). The only afterwork was to clean the parts from the oxide layer then they were ready to be shipped. The gray tracks show the hardened functional surface. The costs of laser hardening were appr. 10 EUR each compared to volume hardening which would be appr. 4-5 EUR each without after heat treatment machining. Fortunately the customer needed the part as soon as possible and without afterwork, so they could ship the part 3-4 days earlier. As a benefit the customer can ship the parts in time (for almost the same price), they don't need to pay penalty and they don't loose trust of their customer.

Figure 3.61: The grippers were made to pick up shaft-like parts from a palette. Source: [5]

3.7 Conclusions

After these experiments these methods were tested on real parts (as seen in the examples) and the customers feedback were the same. They experienced 100-500 % more tool life compared to the estimated for the same or lower costs. The average cost of the laser hardening of deep drawing and cutting tools in the automotive was about 3-10 % of the price of new tool, which is compared to an average lifetime improvement of 10-30 % is a good result. It was also very beneficial, that the lead time of hardening was always under 3 working days and this proves the reliability and velocity of the hardening process. The "3 times hardening" seems very effective against abrasive wear of deep drawing tools and bending tools. The experiments showed that the overlapping zones have a very small affection to the overall hardness of the bending radius. After laser hardening of cutting tools used for steel blanks, the same lifetime could be achieved as with volume hardening. The best irradiation angle of cutting tools was found, which is appr.

90° perpendicular to the cutting direction. This should be used to reach a constant layer thickness along the edges and to eliminate the risk of burned edges. The metallographic pictures showed that the functionality of the tools is also has to taken into account, so they can be resharpened several times. Therefore a further lifetime improvement of the cutting tools was reached. This also proved that for lower costs the same lifetime can be reached without the risk of pitting. For the companies in the automotive industry this technology is a unique and effective way to lower maintenance and tooling costs. To further improve this technology a CAM program should be developed which can identify the problematic features on 3D models and after selecting the surfaces which need to be hardened the program is generated automatically with the best possible parameters. Another important part is the acceptance. To make this technology overall in the industry accepted a standardized heat treatment methodology should be developed. This means the quality control of laser heat treated parts needs to be standardized and a step-by-step description needed, how to harden different kind of steel tools.

Chapter 4

Introduction to the Company Budai Benefit Ltd. and the BuBenLaser Laser technology workshop

4.1 History

The Budai Benefit Ltd. was founded in 2002 by the two owners Tamás Káldy and László Draskóczi. The company's main purpose was the managing of different industrial projects and engineering consultancy. One of the first bigger projects was in Tatabánya in aluminium pipe extrusion company. Some of the extrusion lines had to be partly disassembled and then continuously maintained. After a few years the several technical and efficiency problems induced a development in the spare parts, because the downtime costs in such lines during changing the extrusion wheels and inserts are too big. Hence, the Budai Benefit Ltd. design and manufactured a lot of extrusion parts and now the company representatives are constantly selling these spare parts to international companies from Netherlands, Italy, Poland, Czech Republic and Russia. The main benefit of these special parts is huge increase of life expectancy which could go up to 3-4 times the original. This company finished the production of pipes in 2008 and the lines were moved to Kalisz, Poland. The maintenance was still made by Budai Benefit but the long traveling routes to Poland required the company the train the company employees of the producer. Later after 2006 the company started to work on specific technical solutions and got involved not only in the development and design but also in the production. As the production grew the company was a major supplier of tools of different big OEM-s in the car manufacturing and in the tea industry. The first idea of laser machining burst out in 2012 in Germany on a exhibition. The owners saw some examples of laser systems and the endless applications of the technology. After consulting the Fraunhofer Institute in Dresden the owners decided to contact an industrial partner of IWS (Institut für Werkstoff und Strahltechnik) to see the financial site of these machines. The company ALOtec was very helpful and after a longer discussion the owners participated on a training which included the basics of robot programming on Reis robots, laser hardening principles and guidelines for hardening of different materials. The first impressions led to an agreement to buy the first laser system. The biggest concern was to find an optimal place for such "job-shop" where the demands of smaller and bigger customer can equally satisfied all over Hungary.

Figure 4.1: The presentation room of BuBenLaser. Source: [5]

Figure 4.2: The workshop from the outside. Source: [5]

After creating the circumstances for the work (pressurized air, cooling systems, stronger concrete, laser resistant walls etc.) and the preparation finished the laser system arrived at the end of 2014 (see figure 4.2 and 4.1). This was the born of BuBenLaser which is partly a compound word from the company's name Budai Benefit. The 3 kW Laserline diode laser mounted on a SRV40 type REIS robot with different optics was brand new technology in Hungary and was totally unfamiliar to the Hungarian industry except a few big car manufacturers. The machine's biggest benefit was a heat camera to ensure a continuous temperature control during the hardening and welding processes to avoid the unnecessary melting and damaging the parts surfaces. Unfortunately the change of the different optics was quite slow, so the machine was mainly used for experimental purposes. The first industrial application was still made by this machine and made for the Hungarian Suzuki. The laser hardening of longer guiding pins was a huge success, so the increasing demand for laser hardening resulted in 2015 in a second and a third machine. The second one was a 4 kW Laserline diode laser mounted on a Fanuc robot (type: M710iC 20L). The optical system allowed an adjustable spot size between 6,5 and 72 mm so the track width can be changed during the hardening process. This ensures a higher flexibility and a higher working rate because there are several examples where the change of spot size is inevitable. The optical system is a Laserline Zoom Homogenisator, which means the intensity of the laser power vertical to the beam track is almost constant (a top hat distribution). Unfortunately this attribute is only at bigger spot size achievable, so at smallest spot the distribution is rather Gaussian. The other machine was a 500 W Alphalaser for manual laser welding and cladding with or without wire. This machine is capable to weld different materials from normal carbon steels to HSS with wire sizes from 0,1mm to 1,2 mm in diameter. After the customers recognized the high quality work of our employees the welding jobs started to flow and now this division is in craving after new colleagues. In 2016 the owner found another promising technology, the manual carbide coating with electrodes. This small and handy system can coat tools made of steel with a hard metal layer in the thickness between 40 to 100 microns. There are three commonly used materials in this application: tungsten-carbide, titanium-carbide and Stellite. All of them achieve a hardness up to 70 HRC and are very heat resistant. Due to the moderate surface roughness of this layer (appr. 11 Ra) this is usually applied in the industrial forging tools, where the surface quality of the finished part is still quite low. At the beginning of 2016 the company had to realize the fact that the laser hardening and cladding technology got a so big clientage that the investment in a new hardening and welding machine became necessary. The (currently) last machine arrived in 2016 and had almost the same preferences as the second robot. The machine had a 5 kW Laserline Diode laser applied on a Fanuc robot (M20iA-10L). The zoom homogenisation is almost the same except, the beam width (parallel to tracks) compared to the second one is not 5 mm but 6 mm. This resulted an almost same maximal intensity per square mm at the same spot size. Even though the machine is mainly used now for laser hardening, it's also used for laser cladding. Thanks to the speed couplings the change of the laser head from hardening to welding takes only 10 minutes. At this point I need to mention that this machine is not only capable of wire cladding but also possible to repair big surfaces with laser cladding with powder. Powder cladding means the welding material (which is usually rather a wire) is produced in a powder form and is continuously melted into the surface. The powder form allows to use a variety of materials which aren't producible in wire form, such as hard metals. This is also brand new technology in Hungary but the technical details for the different materials (to avoid porosity, pitting, cracks etc.) is still under development. As the big car manufacturers in Hungary started to send bigger amount of bending and pressing tools for laser hardening, the directorate realized the workshop is too small to handle such amount of steel and cast iron. There was a hard decision to make: the workshop have to be enlarged. This means the construction works start this year and three new chambers will be built with a bigger office for the management of the work flow. The first machine into the chamber will arrive around February of 2018 which shows that the company's growth is quite rapid compared to any other companies. I did not mention several other thing which also been bought to ensure the high quality of our work such as a variety of hardness testers (e.g.: ultrasound tester, Leeb tester and hardness testing files), but these papers aren't for describing these issues. Anyway I hope this growth and the unbroken interest of the market let the company to be major supplier of the manufacturers not only in the car industry but also in other segments. I think with a good marketing strategy the company is capable to compete with west European firms not only in prices but in quality as well.

4.2 The workshop and the machines

The first robot was bought in 2014 after the collaboration with the Fraunhofer Institute. The machine has a 3 kW Laserline diode laser with different changeable optics mounted on a Reis robot (see figure 4.3). The laser itself is located on the arm, an therefore the collimation lenses are directly focusing the beam on the surface. The focused spot size for laser hardening can vary between 5 mm and 22 mm and the welding spot size is 3 mm x 1,5 mm spot.

Figure 4.3: The Reis robot with the 3 kW diode laser mounted on the EOA. Source: [5]

The second robot (see 4.4)was bought from a different company and it has therefore a different control system. It has 3 m wide working area and a 4 kW diode laser. The laser light itself is produced in an external source and then it's transferred to the head through a glass fiber. With this machine we were able to harden shafts up to 5 m-s and pressing tools up to 10 tons. On the right there is the control system of the laser with laser diode bars directly under the monitor. On the left there's a peripheral rotating actuator for the hardening of shafts and concentric parts.

Figure 4.4: The Fanuc robot with zoom optics on the end of the arm. In the black conduit contains the pressed air for the crossjet, the cooling water for the head and the glass fiber. Source: [5]

The next machine is the manual, Nd:YAG laser welding machine for repairing of smaller failures (see figure 4.5). This is one of the highest power manual laser welding machines in Hungary. With 500 W we are able to weld 1 mm thick wires made of HSS and other materials. The huge benefit of this machine is the high reliability and the mobility. The excitation is achieved by flash lamps in the water cooled laser cavity.

Figure 4.5: The 500 W Nd:YAG laser welding machine with adjustable head and other equipment. Source: [5]

The last system (currently) is a smaller Fanuc robot with a 5 kW diode laser source (see 4.6). This machine is designed to have different heads, so the operator can harden and weld with wire or powder on the same system. It's also installed on a mobile metal palette, so it can temporarily moved to other places in the workshop or even to the customer. The powder welding system can also weld such materials which are very hard to be produced in wire form: Stellite, ceramics etc.

Figure 4.6: This machine is located in a smaller chamber, so it's used mainly for the hardening of smaller parts. The wire feeder is mounted on the right side of the robot (red box). Source: [5]

Chapter 5

Epilogue

The aim of this thesis was to give a short introduction to the basics of laser technology, especially the laser hardening, and to give detailed information about the benefits of using laser hardening on pressing/punching tools in the automotive industry. This work also gives details about the different effects during and after the laser hardening process including the build of oxide layers, the deformations and other not very obvious side effect. Some of the main preconditions of laser hardening are also mentioned and of course the obligatory safety systems which need to be always very well adjusted to avoid serious injuries. After discussing the circumstances the thesis describes the typical geometries which occur on pressing tools and cutting tools. The primal issues are also discussed including the overlapping of laser tracks, the hardening of bending radii and cutting edges. The conclusions and the experience show a very similar outcome: The laser hardening will be very beneficial for high value and high precision tools. This also applies when one thinks about sustainability and profit. If the company is able spare money by not buying new tools for the same car model, than the nature can be also better conserved.

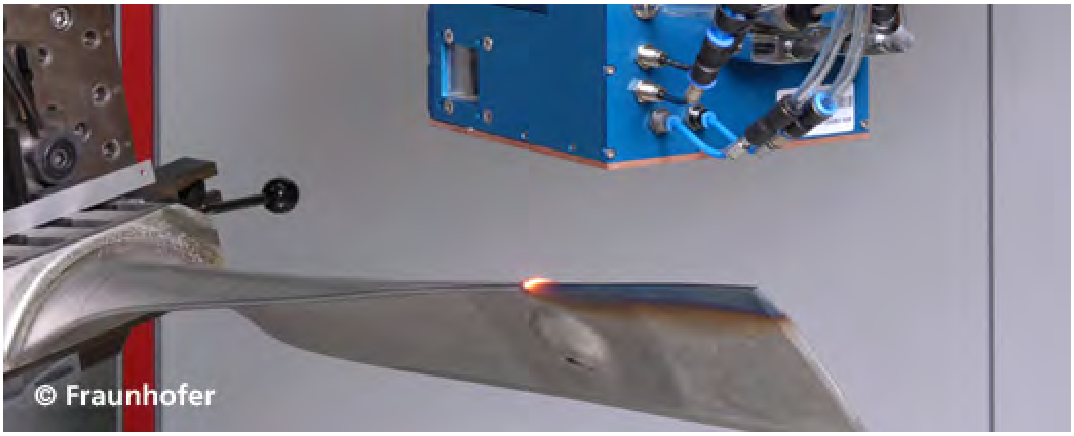


Figure 5.1: Laser hardening of a turbine blade by the Fraunhofer Institute, Dresden. Source [33]

This process is not widely known, the main phenomena are still not fully understood, but the industry is ready to adapt it. It is also a job for this thesis to make the process understandable and easily recognizable. It's clear there are a lot of areas where the conventional hardening and coating methods can't give a satisfying answer.These solutions are still in search by agile engineers and company workers, so hopefully the laser hardening will be also part of the conventional methods and it will be accepted everywhere as an alternative to other hardening processes.

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Chapter 6

Appendix

Wolfurt, 23. 11. 2017

Material No.: 1.2379

Designation
DIN: X 155 CrVMo 121
AFNOR: Z 160 CDV 12
UNI: X 155 CrVMo 12 1 KU
AISI: ≈ D2

Indicatory analysis:

C	1.53
Si	0.30
Mn	0.35
Cr	12.00
Mo	0.80
V	0.80

Strength: ≈ 850 N/mm^2

Thermal conductivity at 100 °C: $21 \frac{W}{m\,K}$

TechnicalTip

- secondary hardening, very good base material for nitriding or coating

Character: high-alloy **steel for through-hardening** with moderate machinability; extremely wear resistant and low warpage, good dimensional stability, toughness and through hardenability

Application: mould plates and inserts as well as wear plates and cutting dies with increased wear resistance

Treatment by

Polishing:	possible when hardened
Nitriding:	very well suited, due to the fact that the hardness of the base material will not fall below 60 HRC
EDM:	possible, Structure eroding not possible
Hard chroming:	possible
Etching:	not possible, coarse carbides are washed out

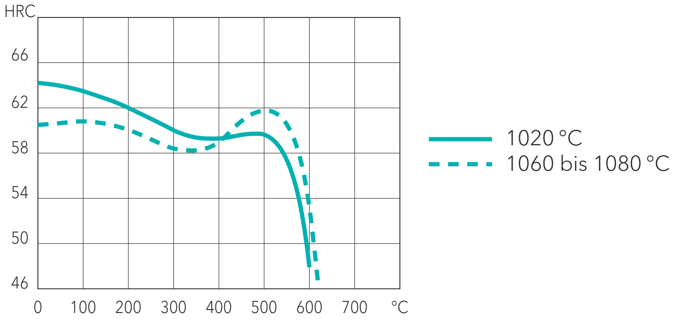
Heat treatment:

Soft annealing:
800 to 850 °C for about 2 to 5 hours
slow controlled cooling of 10 to 20 °C per hour to about 600 °C
further cooling in air, **max. 235 HB**

Hardening:
curing temperature: see **tempering chart**
quenching in oil/air/hot bath
obtainable hardness: 63–65 HRC

Tempering:
slow heating to tempering temperature (to avoid forming of cracks) immediately after hardening;
triple tempering at max. secondary hardening temperature is recommended;
rapid cooling following the tempering improves the dimensional stability;
maximum hardness achievable after tempering: **60–62 HRC**

Tempering chart:



Material No.: **1.2312**

Designation
DIN: 40 CrMnMoS 86
AFNOR: 40 CMD 8.S
UNI: -
AISI: P20 + S

TechnicalTip

- for increased surface quality requirements use material grade 1.2311.

Indicatory analysis:

C	0.40
Si	0.40
Mn	1.50
Cr	1.90
Mo	0.20
S	0.06

Strength: ≈ 1080 N/mm²

Thermal conductivity at 100 °C: $35 \frac{W}{m\,K}$

Character: alloyed and pre-toughened **tool steel**, with excellent machinability in the hardened condition because of the Sulphur additive; high dimensional stability

Application: plates for mould tools and dies with increased requirements on strength; high-tensile machine parts

Treatment by

Polishing:
technical polishing possible; for higher surface requirements we recommend 1.2311 or 1.2738

$\left.\begin{array}{l}\text{Etching:}\\ \text{EDM:}\end{array}\right\}$ not recommended

Nitriding:
increases the steel's wear resistance

Heat treatment:

already pre-toughened, usually no heat treatment required

Nitriding:
before nitriding, stress-relief annealing at 580 °C (Meusburger standard) is recommended

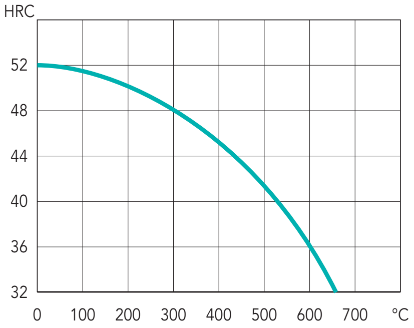
Hardening:
840 to 860 °C

Cooling:
to 180 °C/220 °C in oil/hot bath

obtainable hardness: **52 HRC**

Tempering:
slow heating to tempering temperature immediately after hardening; minimum time in furnace: 1 hour per 25 mm part thickness.

Tempering chart:



Wolfurt, 23. 11. 2017

Material No.: **1.1730**

Designation

DIN: C 45 U
AFNOR: XC 48
UNI: -
AISI: 1045

Indicatory analysis:

C	0.45
Si	0.30
Mn	0.70

Strength: ≈ 640 N/mm²

Thermal conductivity at 20 °C: $50 \frac{W}{m\,K}$

Character: unalloyed **tool steel** with excellent machinability; chilled cast steel, suitable for flame and inductive hardening

Application: unhardenend parts for mould and jig construction or plates and frames for tools and dies

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Treatment by

Polishing:
Etching:
EDM:
Nitriding:
Hard chroming:
} not usual

Heat treatment:

Soft annealing:
680 to 710 °C for about 2 to 5 hours
slow controlled cooling of 10 to 20 °C per hour to about 600 °C;
further cooling in air, **max. 190 HB**

Hardening:
800 to 830 °C
quenching in water
obtainable hardness: **58 HRC**
hardening depth: 3–5 mm
max. 15 mm through hardening thickness

Tempering:
slow heating to tempering temperature immediately after hardening, to
180 to 300 °C depending on desired hardness
1 hour per 20 mm: min. 2 hours

Tempering chart: