Precise contact-free temperature measurement is the formula for reliable laser driven manufacturing processes

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- Invited Paper -

Abstract

Laser beam heat treatment has been established during the last years as a complementary technology for local hardening treatment tasks at tool manufacturing, automotive industry and many others. Recently developed new high power diode lasers and a lot of process supporting systems lead to an increase of industrial laser hardening applications. The presentation starts with information about the basics of laser heat treatment. After that a review about suitable lasers and recommended systems for reliable and well adapted laser heat treatment processes is given. Examples of last ten years transfer of laser beam hardening into industry are presented and discussed.

Keywords: Laser; Heat Treatment; Measuring and Control Systems

1. Introduction

Heat treatment for getting better wear resistance or higher strength is a standard procedure for machine parts or automotive components made of steel or grey cast iron. Conventional heat treatment or hardening processes are done in furnaces, vacuum chambers, or plasma systems. Other conventional technologies are used for partial heat treatment like laser heat treatment does. Laser processes have the reputation of being very precise but less efficient. And only a mass production will motivate high investment and operating costs. This opinion has been set at times when CO_2- and lamp pumped Nd:YAG-lasers have been the only high power sources commercially available for industrial applications. Laser cutting and welding have such tremendous advantages over their competitive technologies because of the usage of a very well focusable beam. At those applications customers decided for laser technologies very soon. Heat treatment with lasers uses larger laser spots and the difference to conventional local heat treatment technologies is less immense. Most industrial applications of laser heat treatment are done because other technologies came to their limits. More frequently the ideas of integration in production lines and demands of one-piece-flow concepts have pushed the laser application of heat treatment in the last years as explained in Bonss (2006). Monitoring and controlling of production processes is required for achieving high quality products constantly. Fast laser heat treatment processes need fast noncontact temperature acquisition. Usually pyrometers or fast infrared cameras are applied for such measurement. Since interaction times at fast laser processes are rather short very fast controllers are necessary that are adapted to the specifics of lasers. The lack of such controllers on one hand and the tendency of pyrometer manufacturers developing digital systems for a more convenient use on the other hand have driven Fraunhofer IWS into the development of a fast analogous infrared pyrometer and a suitable controller for laser applications. Drawback of infrared pyrometers is the single spot measurement. The information is integrated over a given spot size and the position of the spot is fixed. For some 3D-applications, multi-spot laser heat treatments, and wide scanned laser spot sizes a single measuring spot and averaged signal over the spot dimension doesn't fit to the needs. A lateral resolved

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measurement is necessary to acquire temperatures on a large field of interest. One possibility has been introduced at LIM 2001 by Bonss (2001): Mechanical scanning of the pyrometer spot. This method is rather slow with standard pyrometers and needs to know roughly where the irradiated area is. Fast scanned measuring spots need very fast pyrometers to get a lateral resolution of the thermal spreading [4]. Infrared sensitive camera systems, so called thermographic cameras, overcome these problems with their large field of view and with fast collecting thermographic images of heated surfaces. But commercial available systems are either suitable for very high speed observation or rather low temperatures for instance for architecture applications. In both cases the price is unacceptably high for heat treatment applications of steel. If laser heat treatment is an alternative to conventional flame or inductive hardening at well selected applications the laser source itself is a very expensive tool in comparison. For a successful market penetration of laser heat treatment it is essential to keep the costs for equipment as low as possible. Driven by those aspects a thermal imaging system has been developed for temperatures above 700 °C which bases on a comparatively cheap CCD camera. The optimum laser spot length and width is necessary to get optimum results. In most cases standard optics coming with the laser from the manufacturers are applied. These can be designed for a certain application and they deliver a fixed laser spot geometry. A slight variation can be done by working out of focus, but homogeneity gets poor in those positions. It is known since Seifert (2004), that the laser beam scanning technology can be used for high power diode lasers in the multi-Kilowatt range as well as for CO_2-lasers. The scanning is sufficiently fast and continuous and wide heat fields are generated, like done with a fixed-lens optic. Hardening track widths of 60 mm and more become possible.

2. Laser Heat Treatment

Laser surface hardening is a heat treatment process for steel and grey cast iron. The surface temperatures are above austenitization temperature, but closer to the melting point than at classical furnace hardening, because of the comparably short interaction time. Fast quenching is done by self quenching. That is caused by the heat flow into the remaining cold material. Hardness penetration is typically in the range of 0.1 to 1.5 mm. For high alloyed steels, which do not need a very fast quenching to form martensite, the penetration can be up to several millimeters. To be hardenable with laser, unalloyed steel grades need to have a carbon content of at least 0.3% or more. For laser heat treatment a several square millimeters large spot moves relatively to the parts surface. Finally hardened tracks or spots are typical results. An all side hardening is not possible. Overlapping tracks causes annealing zones at previously hardened ones. Typical necessary laser power is the range of 500 W up to 6 kW. Therefore just high power lasers are suitable heat sources, which usually work in infrared range of light. The heat input is effected by absorption of laser power at the surface and subsequent heat conduction. Nd:YAG, Yb:YAG or GaAs-based high power diode laser deliver suitable radiation. All those systems have a proper beam quality for laser heat treatment processes and can use a flexible fiber for beam delivery. High power diode lasers can be used directly without fiber as well. Regarding the investment and running costs high power diode lasers are the best choice of lasers at present. Since their appearance on the market as kilowatt laser systems in 1997 several installations at heat treatment shops verify those lasers as ready for industrial application.

3. Temperature measurement in laser heat treatment

The temperature measurement device can be used lateral or co-axial with the laser optics. In case the pyrometer is mounted lateral at the laser optics measuring is done non-perpendicular to the laser interaction surface. The measuring spot of the pyrometer has to be adjusted to the position where maximum temperature appears to get information about maximum temperature. The measuring signal can get lost, if edges and contours shadow the pyrometer measuring view, i.e. at heat treating the ground of grooves or bore holes. Even though this variant is used for industrial mass production, the efforts to ensure a reliable quality are high. Main advantage of the direct measurement is the fact that the measurement is not influenced by the laser optics an its specific signal damping and the calibration values of the manufacturer can be used. Nevertheless contamination of the pyrometer optics can cause significant measuring errors (compare tab. 1) and re-calibration and adjustment is needed regularly. Because of the known problems with lateral pyrometer measurement a co-axial measurement through the laser optics is the better choice. For this task special optical components are used, what let the laser radiation pass and reflect the NIR measuring wavelength towards the pyrometer. If this outcoupling plate is at the position of the collimated laser beam, the pyrometer is focused by the lenses of the laser optics, shape and size of the measuring spot are changed. Using a pyrometer co-axial at the laser optics requires a correction of the characteristics of the pyrometer or a calibration in as-mounted state. An example of co-axial temperature measurement in industrial mass production is shown in figure 5. The investigation of typical measurement setups for laser heat treatment has shown that the best wavelength range for temperature measurement between 1000 and 1500 °C is 650 nm to 2100…2500 nm. The wavelengths of the laser heat sources (800 – 1070 nm) are not available for a temperature measurement, because the reflected laser radiation is much more intense than the NIR temperature radiation of the hot and glowing object. To avoid measuring errors special blocking filters with a high optical density at the discrete laser wavelength or wavelength band have to be used. Towards longer wavelengths the working wavelength of the pyrometer is limited by the optical properties of glass lenses, additional beam shaping optics, shielding glasses and outcoupling optics typically made of fused silica and optimized with special coatings. A short response time of the measuring sensor is required because the interaction time of laser and matter during a heat treatment process is within the range of milliseconds to seconds. If all the preconditions for temperature measurement in laser heat treatment are taken into consideration, thermal radiation detectors based on the widely-used silicon or InGaAs photo diodes are suited for laser heat treatment.

3.1. Requirements for accuracy of the temperature measurement

The requirements for the accuracy of the measurement devices are given by the dependency of the heat treatment result on the temperature. As result of a typical industrial process the hardness distribution across the hardening zone is measured and surface hardness and hardening are depth detected.

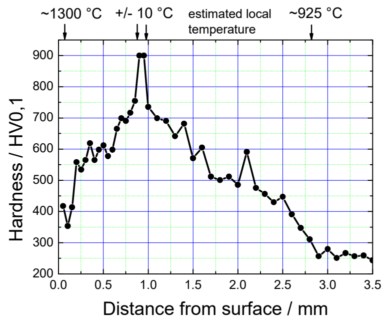

Fig. 1. Hardness over penetration at a laser heat treated surface, pre-heated part made of X155CrVMo12.1, temperature gradient estimated from experimental data of heat treated samples.

Fig. 1 shows an example with a strong dependency of local hardness on the maximum local temperature during the hardening process. The hardness-to-temperature-curve shows a maximum at temperatures around 1200 °C. The decrease of the hardness towards higher temperatures is caused by stabilization of retained austenite that is not transformed to martensite after quenching. The real surface temperature has to be within a band of several 10 K for generating a hardness level >700 HV at that steel.

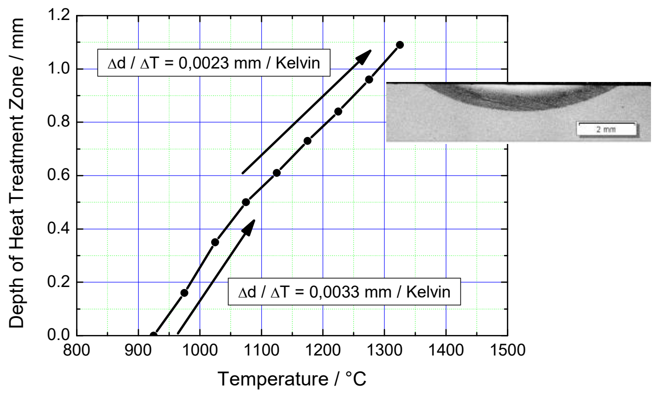

Fig. 2. Depth of the hardening zone (d) in dependence of the surface temperature (T), flat samples made of tool steel X155CrMoV12.1, depth was measured in the etched cross section (example at top of diagram).

The dependency of the process temperature on the hardening result was analyzed for samples of carbon steel and tool steel and was investigated for selected industrial applications. Fig. 2 shows one example. The hardening process starts when the surface temperature exceeds the material specific austenite start temperature (~ 900 °C in fig. 2) and a hardened volume is generated after quenching. At surface temperatures above this threshold the hardening depth shows a strong dependency on the maximum surface temperature. For typical laser heat treatment processes with process feed rates of 100 – 500 mm/min the hardening depth is growing by several 0.001 mm/K. Not only the generation of a reproducible hardening result but also good process stability is an important criterion for a reliable industrial production.

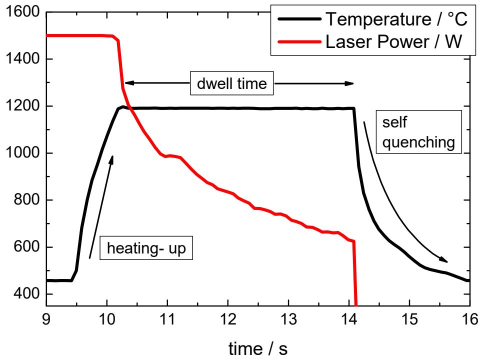

Fig. 3. Process data of a temperature controlled laser heat treatment process of the end face of a screw, temperature measured with pyrometer MAURER KTR 1075.

To ensure the optimum surface temperature during the process precise temperature controllers are used. In dependency on material, geometry and surface quality of the parts temperature fluctuations of ± 1 to ± 10 K are typical for industrial processes today (Fig. 3). In particular cases a temperature deviation of +5 to +10 K can cause instable laser processes with oscillating temperatures because of forming oxide layers, delamination of those, and local overheating of oxide layers in combination with overreaction of the process control. In conclusion temperature measurement needs to be accurate and reproducible during laser heat treatment. Precision of ±5 K of the measurement and a calibration method with a suitable higher accuracy are required.

3.2. Calibration and inspection of temperature measurement devices

The calibration of radiation thermometers with blackbody or fixed-point radiators is established at national metrology institutes as Hollandt (2003/2007) explains. Selected temperature measurement devices, typically used in laser heat treatment, were tested and analyzed at PTB in Berlin using the variable temperature blackbody HTBB3200pg. Different influencing factors on the indicated temperature value have been investigated, e.g. contamination of the optical components, a varying working distance, defocusing of the optics, and varying the aperture size of the blackbody emitter. It could be varified, as one result, that optical temperature measuring devices, typically used in laser heat treatment, have the potential to measure temperatures with accuracy of a few K. But a variety of influencing factors can cause total measuring errors in a dimension of several 10 K. Tab. 1 illustrates the effect of contaminated pyrometer optics and Fig. 4 depicts the effect of varying the furnace aperture between 6 mm and 30 mm, the so called size-of-source-effect.

Table 1. Influence of contamination of pyrometer optics for temperature measurement with pyrometer MAURER KTR 1075 (manufacturer calibration) at PTB Berlin. The contaminated front lens has been used for several years for laser processing in a laterally assembled pyrometer viewing unprotected at the laser/metal interaction zone.

TBlackbody / °C	TClean - TContaminated / K
1004	18
1113	18
1222	19
1300	26
1409	32

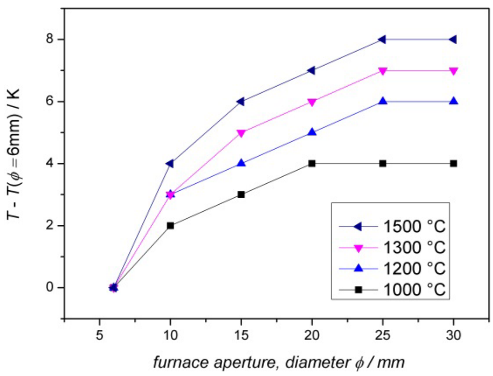

Fig. 4. Influence of the size-of-source effect (SSE) on the temperature characteristics of a thermal imaging system based on a CCD camera.

To achieve the aimed accuracy with temperature measurement devices that are electrically, optically and mechanically fully integrated into complex machines at industrial sites, the on-site calibration and inspection with mobile devices is needed. Only the in situ calibration in the final machine set-up guarantees a high precision of the temperature measurement.

4. Systems development

4.1. E-MAqS

The camera based sensor system got the name »E-MAqS«, which is an acronym for *E*mission *M*atrix *A*c*q*uiring *S*ystem. An industrial grey scale CCD camera is used with sufficient sensitivity in the near infrared. Hardening is done at surface temperatures above 700°C, therefor the signal is high enough to get thermal images with adequate accuracy. The visible light and the laser light are cut off from the incoming radiation with special filters. The camera generates an image at a single wavelength of 740 nm. All grey scale values can be assigned to local temperatures at a laser irradiated surface therefore. Calibration has been done with a standard black body radiator. The nonlinear correlation between temperature and grey scale value is taken into account by the software of »E-MAqS«. The temperature range can be adjusted by changing parameters like exposure, attenuation and aperture. Applying »E-MAqS« as a coaxial adapted system, the specific attenuation of the laser optics must be taken into account. The thermal image is analyzed by the software. A lot of different features and algorithms are able to deliver more or less localized information on the heat treatment process. Having a lateral resolution of about 656 x 495 pixel even very small hot spots can be measured if necessary. In contrary to such very sensitive measurement a more averaged measurement is possible by integration over a certain amount of pixels. A rectangular window can be chosen within the field of view. Disturbing noise and process artifacts outside of this window

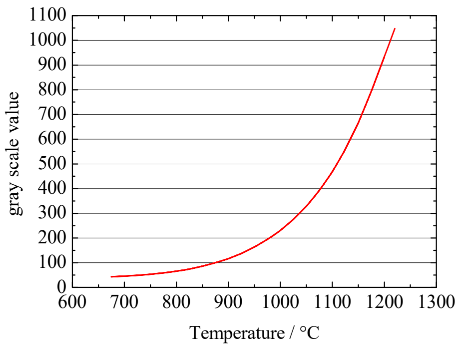

Fig. 5. Typical dependency of grey scale values on the surface temperature at given attenuation, filter set and shutter adjustment.

are not taken into account generating temperature values. Applying this window and integration over the whole window make »E-MAqS« work like a pyrometer with an rectangular measuring field. The frequency of »E-MAqS« is about 220 Hz. »E-MAqS« comes with a Windows®-based PC. The software acquires the image stream information and makes all necessary transformations to give that information as an analogue voltage via D/A-converter to a closed loop control. Or it is given as a digital value via internal memory to a control software. This closed loop control gives a sufficient setpoint information to the heat source preferably via analogue voltage. A miscolored and size-reduced image is shown during the process at the user interface on the screen. These images can be stored for quality documentation issues. A robust aluminum housing covers the sensing head of the system at industrial applications in harsh environments. A permanent flow of pressurized air or nitrogen into the housing avoids internal pollution. The filter set can be moved aside by a pneumatic linear stage to get a clear visible image for adjusting or test operation. An aperture of about 30 mm is the interface to the process. This can be covered by a shielding glass or connected to laser optics for coaxial measurement.

For fast calibration a LED-based device has been developed. The LED-device is a tiny handheld box that acts as a calibrated emitter which matches to »E-MAqS«. A fast recalibration of the system is possible after change of laser optics or other signal affecting components.

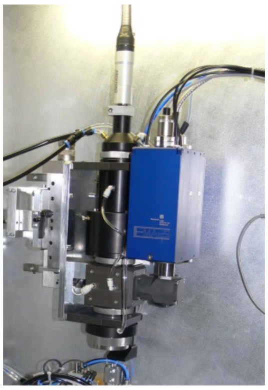

Fig. 6. »E-MAqS« with aluminum housing mounted to an optics of a high power diode laser for coaxial measurement.

Fig. 7. »LEDS« LED-based calibration system for camera based temperature measuring device.

4.2. LompocPro

»LompocPro« is the base component of measuring and control systems developed by Fraunhofer IWS. During its more than ten year period of development and application it has been perfectly adapted to customer's needs., Different temperature measuring equipment can be connected, depending on the application. Laser power, beeing the controlled value, is regulated following a suitable set value. This set value can be surface temperature for solid state processes, and, preferably, melt pool size for liquid phase processes like cladding, brazing or remelting. The control can be connected to the fast pyrometer »E-FAqS« as well as to the camera based system »E-MAqS« or to any other standard pyrometer. LompocPro is a control for various laser technologies, such as hardening, brazing, heat treatment, heat conduction welding and cladding. It is especially suited for the control of fast processes by applying a specific control algorithm. A lot of control parameters give a high flexibility due to individual adjustment of control behaviour. Specifically at laser processes the difference of necessary control behavior of a process start and a running process might be dramatically large. Taking this into consideration, some specific parameters are available. A graphic display shows all relevant process data during the process to the operator giving a fast overview. All settings and process data including the temperature images are stored in customized folders. Any available bus system is a standard interface to machines and devices. Wiring of digital I/O's is possible as well.

4.3. LASSY

The scanning optics »LASSY« (Fig. 8) has been developed for industrial use. Compact size and low weight make »LASSY« a component to all kind of laser treatment machines. The scanning optics are suited for lasers in the wavelength range from 808 to 1070 nm (diode, Nd:YAG; Yb:YAG) and has no focusing component. A laser optics with a rectangular or round focal spot with minimum focal length of 300 mm minimum is necessary in front of the input of the scanner optics. The spot size of that optics depends on the required hardening depth. Typical suitable spot lengths are in the range of 4 to 16 mm. All sensitive components of the scanning head are cooled with water or compressed air to prevent heating-up, caused by absorbed laser power or back reflected laser or heat radiation.

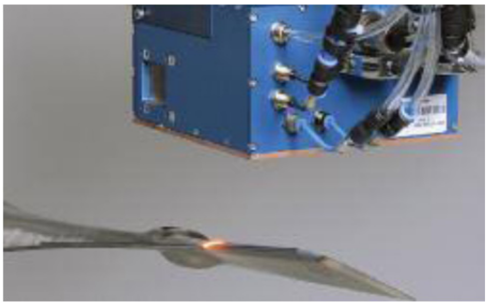

Fig. 8. »LASSY« at turbine blade hardening.

The optics have been designed and testes for laser powers up to 10 kW. All mechanical components are made of Aluminum and are water cooled to resist scattered laser light. The size of the scanning head is about 190 mm x 195 mm x 120 mm. The power supply has its own PLC. That monitors several temperatures at sensitive positions and at the mirrors as well as the behaviour of the scanner motor. Advantage of such scanner system is the high flexibility in contrary to optics with a fixed rectangular spot or zoom optics. Change of scanning width and scanning function can be done during a running process. Adaption to local different hardening track size and especially to local different heat flow conditions is possible. Via an integrated scanning function generator the operator is able to adjust the intensity profile of the laser spot (Fig. 9). This is an outstanding feature for optimum laser heat treatment.

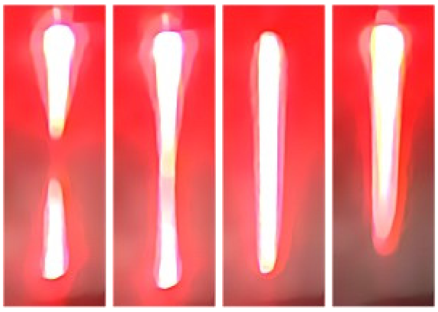

Fig. 9. Laser power density distribution, detected with special infrared camera (spot size: about 6 x 80 mm^2), optimization via scanning function.

5. Examples

5.1. Example 1: Inner valve Seat

An inner valve seat at the ground of a bore hole needs to be hardened. Material is a hardenable free machining steel ETG 88 (AISI 1144) with about 0.45% Carbon. Having the hardening as the last step in process chain and preventing oxidation therefore, the laser process is done in pure Nitrogen atmosphere. Figure 11 shows the cross section that was to be targeted. The temperature dispersion is given at Fig. 10. For that application a ring shaped laser spot has been applied.

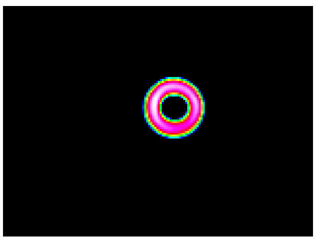

Fig. 10. Temperature dispersion during a typical laser hardening process of a valve seat like Figure 11, measured with »E-MAqS« camera system coaxial thru the laser optics with ring shaped laser spot.

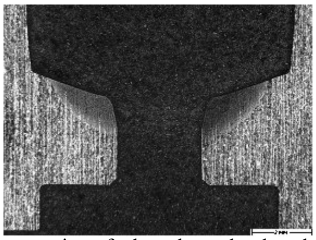

Fig. 11. Cross section of a laser beam hardened valve seat.

At an efficiency of about 40% for fiber coupled high power diode lasers 15 kJ of electrical energy is used from the wall plug. In that case even the reduced efficiency of the laser process because of the shielding gas atmosphere with 40% laser absorption needs much less electrical power than comparable induction processes. The applied 0.0042 kWh per part is only a tenth of the electrical energy of an optimized induction process. In case of accepting oxidized surfaces the absorption increases to about 80% and the necessary electrical energy for laser beam hardening of the same part would be only 5% of the comparable induction process.

5.2. Example 2: Turbine blade hardening

An Example at what the control »LompocPro« is applied as well as the camera based temperature measuring system »E-MAqS« and the dynamic beam shaping system »LASSY« is turbine blade hardening. Turbine blades of last stages of steam turbines get worn by water droplet erosion. A local increase of hardness can increase the life time of such blades considerably. On the other hand operation conditions can be driven into the extreme to get maximum efficiency of turbines, specifically for base-load power stations. Materials are mostly martensitic hardenable Chromium steels like X20Cr13, X12CrNiMo12-2-2, X10CrNiMoV or comparable. Advantage of other technologies like flame hardening or induction hardening is the very short dwell at very high temperature that prevents grain coarsening at maximum dissolution of carbides. Higher hardness and better wear resistance is the result of it.

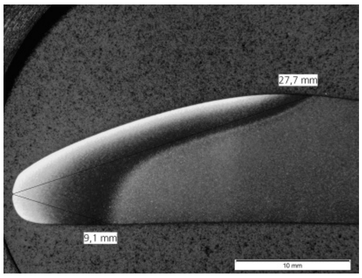

Fig. 12. Typical cross section of a laser hardened turbine blade.

During the process all data like surface temperature, laser power, thermal images and inside machine view videos are stored for re-traceability. By applying a controlled laser hardening process a very constant quality of heat treated turbine blades is achieved. Adaption to complicated geometries and heat flow conditions is possible with the dynamic beam shaping system. A scanner system is much cheaper than a collection of a lot of different optics, if high flexibility of spot geometry is necessary. And scanner is the only option if changes of spot geometry and intensity profile are necessary during processes.

5.3. Example 3: Hardening of brake levers

Another application that is almost impossible to laser harden reliably without a camera based temperature measuring system is an inner calotte of a brake lever made of 42CrMo4 steel for truck trailer disc brakes. Task is to apply a hardening zone that covers just the inner of a ball shaped calotte without propagating into the lever arm. Customer wants to avoid the risks caused by a structural kerf at a high bending loaded lever area. On the other hand an as-forged part shall be hardened before any machining processes can produce any reference surfaces.

Fig. 13. Brake lever, laser beam hardened in as-forged state.

The defined clamping therefore is difficult. The advantage of the laser process applying no forces to the part that is treated can be used successfully. A rotating laser beam is applied to heat the calotte inside. Therefore a specific device with rotating mirrors was developed. It is noise damped and equipped with an air flow and suction system to support the self-quenching and removes

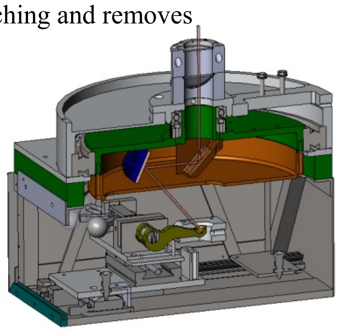

Fig. 14. Rotating mirror device for laser hardening of brake levers.

dust and remains of burning corrosion inhibitors. Lifetime of the rotating air cooled mirrors is about 60.000 parts in real three shift production. The process control »LompocPro« enables reliable processes and with a specific adapted watchdog process quality is checked and process failures are detected. Since as-forged parts can vary in surface quality and carbon content in near surface regions a very non-sensitive process is necessary as well as an optimized process evaluation routine. Important for such processing is a reliable camera based temperature measuring system.

6. Summary and Conclusions

Laser heat treatment is today supported by well-equipped systems. A temperature guided laser power control in combination with camera based or high speed temperature measurement enable highly reliable processes. Operators are supported and the barrier of application of laser heat treatment is reduced. For companies who need to heat treat a large variety of parts with very different demands concerning the heat treated area a dynamic beam shaping system is advantageous. All presented systems are proven in numerous industrial applications. Situation for industrial application of laser heat treatment is better than ever since laser sources come down in price annually, multiple optics configurations are available and a lot of equipment is developed for running reliable processes without being a laser specialist. The key to successful application of that technology now is the know-how of the process developers combined with the courage of production engineers for applying new technologies.

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