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# State of the art of Laser Hardening and Cladding

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## Abstract

In this paper an overview is given about laser surface modification processes, which are developed especially with the aim of hardness improvement for an enhanced fatigue and wear behaviour. The processes can be divided into such with and without filler material and in solid-state and melting processes. Actual work on shock hardening, transformation hardening, remelting, alloying and cladding is reviewed, where the main focus was on scientific work from the 21st century.

**Keywords:** laser shock hardening, laser transformation hardening, laser remelting, laser alloying, laser cladding

## 1 Introduction

2005, being the Einstein year, has a special importance for laser technology.

In fact, lasers – because of their wide applications – are still a story of success within materials processing and manufacturing. The market is still growing, while not only enhanced laser beam sources of well known types like $CO_2$-, Nd:YAG- and diode laser systems are offered, but also new principles like the disk and fibre laser [Gru2003] and even femto second laser [Mei2003] are coming up for materials processing. These developments show that there is still a huge potential for new beam sources, which of course set the demand for additional system technology developments.

The feasible applications and recent developments cover all groups of manufacturing processes. Work on forming [Vol1994, Vol1995a, Vol1995b, Vol1995c, Vol2005, Li1998], drilling, cutting and ablation [Sch1997, Mei2004, Sco2003], joining [Vol2003, Vol2004, Pos2002, Lan2003] and changing material properties [Hab2003, Par2003, Gei2003] is currently done at the authors institutes.

This review paper is focused on the surface properties of materials and its changes by laser treatment, i.e. hardening and cladding, both for production and repair of structural parts. The state of the art is given with respect to the process principles and development, the use of modeling, the achievable properties and sample applications. It covers processes which change the properties of the original material (shock hardening, transformation hardening, remelting) but also processes which apply additional materials (alloying, disperging, cladding).

## 2 Laser shock processing

### 2.1 Process Principle

Laser shock processing (LSP) is also known as laser shock peening, lasershot$^{SM}$ peening or laser peening.

It represents a further development of classical material adaptation methods by introducing residual stresses by hydrodynamic expansion of heated plasma. The shock wave is a result of ablation of material layers via intensive absorption of laser radiation ($I > 1$ GW/cm²). The material surface originates a phase transformation from solid to material vapour. The plasma is developed in the gas phase which absorbs the energy directly from the laser radiation and from the reflection on the material surface. The expanding plasma causes a shock wave into the atmosphere and into the material.

The generation of shock waves can be realized by two different methods: Direct and confined ablation, **Fig. 1**. During direct ablation the plasma expands directly into the surrounding atmosphere. The process of confined ablation includes a water, glass or quartz overlay (transparent for the laser light) on the top of the surface which prevents the expansion in the atmosphere and causes an about ten times higher pressure on the material surface. Melting and material removal are reduced as well [Eis1998, Scm2002, Mon2002].

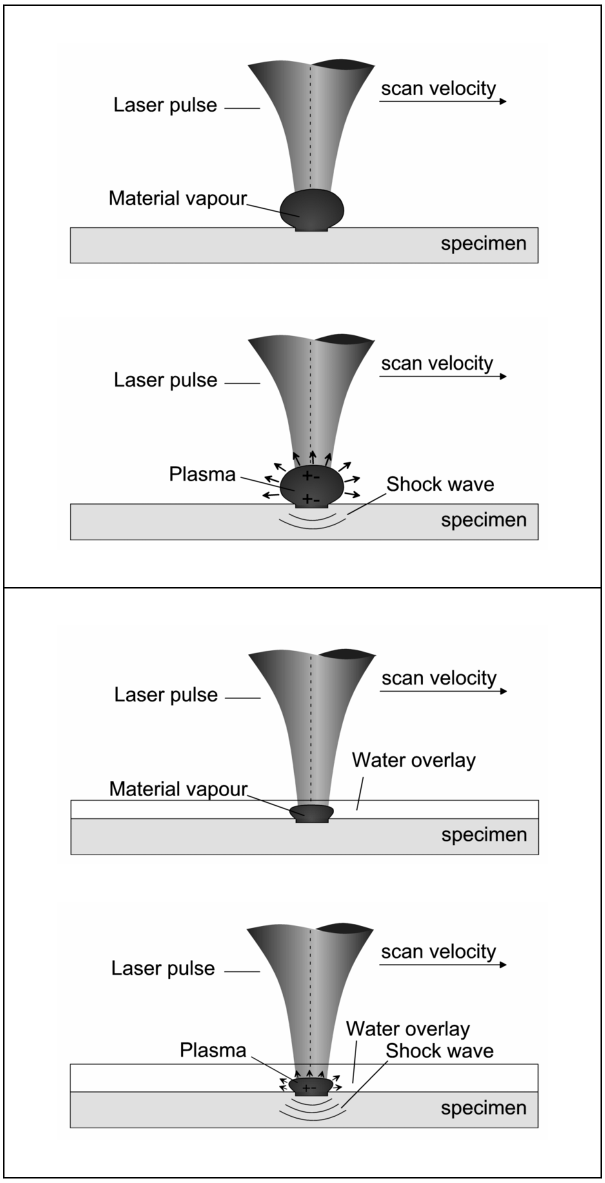

***Fig. 1:*** *Principle of laser shock hardening. Top: direct ablation, bottom: confined ablation. (BIAS)*

Laser absorbing coatings (e.g. black paint) can be used as a sacrificial layer to increase the pressure and to protect the material from damage caused by ablation and melting [Alt2004]. The pressure of the shockwave causes residual stresses in a depth of several millimetres, since local plastic forming causes stretching of a small area, which stands under pressure by the surrounding elastically formed material after release of the pressure, **Fig. 2**.

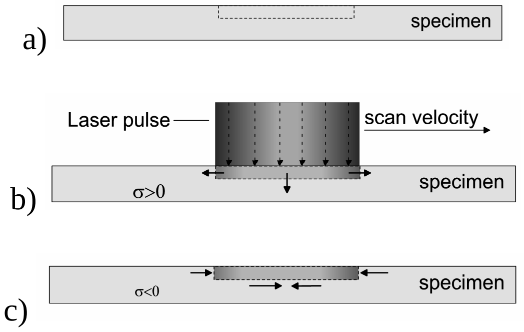

***Fig. 2:*** *Principle hardening by induced pressure. (BIAS)*

## 2.2 Process development

The possibility to generate shock waves by laser pulses was discovered in the early 60s by Askar [Ask1963] and White [Whi1963].

Further investigations resulted in laser induced shock waves with increased impact, which were able to cause compressive stresses higher than the yield strength of metals [Gre1966, Ske1968]. Laboratories in the USA and France started at that time with feasibility studies to apply LSP for modification of material properties as an alternative to shot peening and deep rolling [Mon2002]. Most investigations are done with pulsed Nd:YAG or Nd:glass-lasers, as they provide the highest energy density. Eisner [Eis1998] showed that excimer lasers can also be used. Pulsed $CO_2$ - lasers are theoretically also suitable for LSP. More recent experimental studies showed that laser induced shock waves can also be used for laser stretch-forming of small aluminum parts of 50 µm in thickness and 1-12 mm in diameter to form a spherical cup [Scu2004, Scu2005].

It was discovered that compressive residual stresses of 70-80 % of the yield strength could be generated into steel and aluminium alloys for 1-2 mm in depth by LSP [Eis1998]. Hence fatigued life and strength could be increased to a level above the one of shot peening or deep rolling. It was generally found out that LSP has no disadvantages compared to conventional processes in terms of mechanical properties: The roughness for LSP is significantly lower than for shot peening. Additionally there are no geometrical limits for areas to be treated by LSP as long as the area can be seen [Alt2004, Mon2002]. The fretting fatigue around fastener holes could be doubled through LSP in 7075-T6 aluminium alloy as Montross [Mon2002] reports. Also stress corrosion cracking for stainless steel can be enhanced by LSP, whereby austenitic steels seem to be more suitable than martensitic steels [Sce1997]. Residual stresses produced by LSP, hardens the surface of metal specimens. The shock hardening effect decreases with rising distance from the surface [Mon2002].

### 2.3 Modeling

The modeling work of LSP consists mainly of the modeling of shock pressure, the modeling of the residual stresses and the modeling of stress/strain evolution.

For the analysis of the shock pressure are there some models, in which it was assumed that the laser irradiation is uniform and therefore shock propagation in the confining medium and the target is one-dimensional [Cla1981, Fab1990]. In Morales's calculation system SHOCKLAS a one-dimensional model was used for the estimation of the pressure wave applied to the target material in LSP process [Mor2004]. In order to increase the model accuracy in micro-scale LSP, an improved modeling method for the analysis of shock pressure was developed, in which the fraction of plasma internal energy used to increase the pressure of plasma and the radial expansion of plasma was taken into account [Zha2004].

The FEM method was firstly used by Braisted [Bra1999] to calculate the residual stresses in LSP [Mon2002]. Later Peyre [Pey2003] developed an axis symmetric FEM model for calculation of the residual stresses induced by laser peening. In his model, with considering the hydrodynamic attenuation of shock waves and the elastic-plastic behaviour of the material, some parameters were taken into account such as: the shock yield strength of the metal Hugoniot Elastic Limit (HEL) and the Hugoniot curves. In comparison with the experimental results on a 12Cr steel and a 7075—T7351 aluminium alloy, his work showed a good agreement with the experiments [Pey2003].

Shock wave propagation generated by a fast impact of amplitude p in a duration of t in the work piece is a basic phenomenon in LSP. With regarding to the high strain-rate, which can exceed 106s 1 within the target material, generated in LSP, some assumptions are applied in [Bra1999] for the modeling such as: materials can be modelled as elastic-perfectly plastic, all the plastic deformation occurs at roughly the same high strain-rate, and a linear equation of state is valid.

It is known, that the temperature fields are needed to calculate the stresses in LSP and the surface absorptivity is affected by the surface temperature. Thorslund [Tho2003] developed a mathematical model to study the effect of laser irradiance and its time modulation on the temperature distributions in the work piece and plasma plume. It is shown that the irradiance rate has more effect on the material temperature than the actual irradiance I(r, t) [Tho2003].

### 2.4 Materials properties

Laser shock processing has mainly been done on aluminium alloys, but also titanium alloys, steel and copper have been successfully treated with LSP.

Extensive investigations were done in fatigue life enhancement on 6061-T6 and 2024-T3 aluminium [Rub2004, Oca2004, Yan2001] alloys as well as on Ti-6Al-4V [Nal2003]. The improvement of fatigue strength for welded joints of 18 Ni marging steel by 17 % [Ban1990] and for welded joints of 5456 aluminium [Cla1981] is reported.

The hardening by LSP has been done on aluminium alloys with significant improvement of non heat-treatable 5086-H32 and overaged 2024-T3 and 7075-T73. The hardness of weld zones of 5086-H32 aluminium could be increased to the level of the parent material [Mon2002]. Yilbas [Yil2003] investigated hardening of mild and stainless steel. The hardness could be increased 1.7 times compared to the base alloy hardness, whereby the increase of hardness is due to dislocations generated in the shock affected region. Eisner [Eis1998] increased the hardness of titanium from 130 to 190 HV 0.025 at the surface with a common excimer laser. Pitting corrosion behaviour of stainless steel has been improved through LSP by Peyre [Pey2000]. It is assumed that residual stresses and work hardening are the reasons for corrosion improvement, mainly by interface-like effects around the inclusions.

### 2.5 Applications

Since fatigue life and fatigue strength can significantly be increased through LSP, a high interest on applications for heavy loaded parts can be reported.

General Electrics received more than 20 Patents on LSP. High cost, low volume parts such as compressor blades, turbine fan blades, rotor components, discs, gear shafts and bearing components are well known applications for LSP [Alt2004, Mon2002, Zhu2003]. Turbine fan blades were laser peened in order to increase the durability and resistance to foreign object damage. Fastener holes in aircraft skins can be treated by LSP to repair micro cracks [Mon2002]. Future applications for LSP are shown in micro electromechanical systems (MEMS) such as micro engines and micro-switches made out of copper and aluminium in order to increase fatigue life and wear resistance [Zha2002].

## 3 Laser transformation hardening

### 3.1 Process principle

Laser transformation hardening is a technique to obtain hard and wear resistant surface layers with a typical thickness of 0.5 to 1.5 mm.

The process principle including laser beam and shielding gas is given in **Fig. 3**.

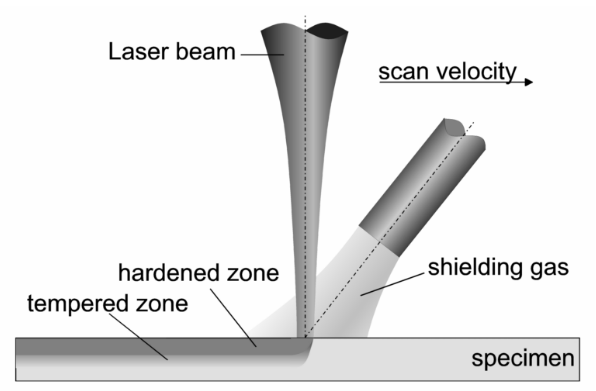

***Fig. 3:** Process principle Laser transformation hardening. (BIAS)*

It is applied on carbon steels with 0.4 to 1.5 %C. The technique of laser transformation hardening can be seen as the opposite of conventional transformation hardening. In conventional hardening the product is heated by flame or in a furnace to a temperature above the Ac temperature where the structure is transformed from the initial ferritic/pearlitic structure (a + $Fe_3C$) to an austenitic γ phase where the carbon is dissolved in the steel, **Fig. 4**. This process is a reversible equilibrium transformation which requires, dependent on the temperature and the composition some time, typical a few minutes. Hardening takes place when the material is subsequently cooled down at a so high cooling rate that there is not enough time available for the reverse transformation and the secretion of carbon. Instead of the ferritic a structure the very hard martensite is formed. Below the Ms temperature of about 250°C the austenite transforms almost instantaneously to martensite. The carbon is not excreted now but remains in the crystal structure. Together with this transformation a volume expansion occurs, which introduces advantageous residual stresses into the surface improving the mechanical properties like wear- and fatigue resistance.

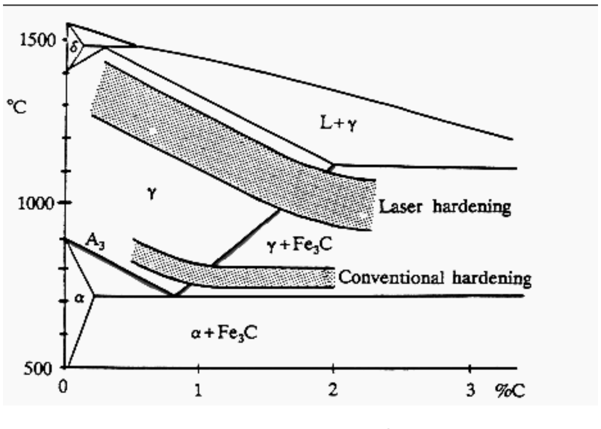

***Fig. 4:** Fe-C phase diagram (a: ferrite, g: austenite, Fe3C: cementite, L: liquid) (Univ. Twente)*

Normal hardening takes place when the heated product is cooled down suddenly by water or oil. The outer layer cools first and fastest where at deeper layers the cooling rate is lower allowing a reverse transformation to the original structure. The end result depends strongly on the cooling rate and the geometry of the product.

In case of laser hardening the bulk of the product keeps cool. Only a surface layer is heated by the laser. Cooling takes place by quenching the base material (self quenching). Because heat transfer takes place by conduction within the steel this cooling rate is much higher than in water where vapour production restricts the cooling rate. As a result:

- The surface temperature for conventional hardening is low to reduce the distortion and to restrict the heat content in the bulk.
- For laser hardening on the other hand, the surface temperature should be as high as possible because a) this shortens the time to complete the transformation to austenite while b) a high temperature gradient is required to heat a sufficient thick surface layer in a short time. A short time and high temperature gradients are also required to prevent heating of the bulk material.
- The Ac3 line ranges from 723 to 910 °C at 0 %C for equilibrium conditions. However, at heating rates over 1000 °C/s the α to γ transformation temperature increases above 900 °C for carbon steel. It should be kept in mind that the transformation temperatures are affected by the microstructure as well as by the presence and the distribution of alloying elements.

Transformation hardening is applied on hypo eutectic steels (0.4 - 0.8 %C) as well on hyper-eutectic steel (> 0.8 % C) and cast iron. Two examples are given in **Fig. 5**.

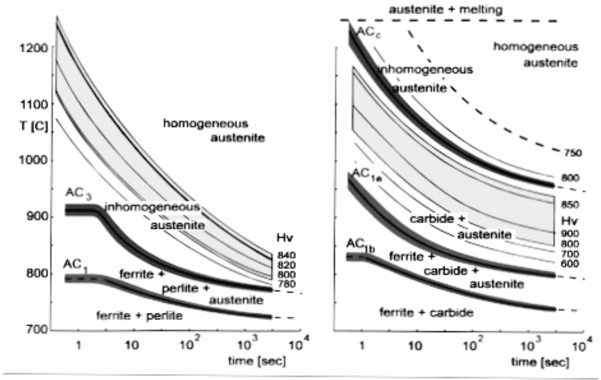

***Fig. 5:** Time-Temperature-Austenite (TTA) diagram with lines of resulting hardness. Left C45, right 10Cr6. [Orl1973]*

In case of the hypo-eutectic C45 steel there is above the Ac3 line still inhomogeneous austenite. It requires time and/or a higher temperature to get it homogenized which for this material results in the maximum hardness. With a processing time of typical one second an optimal surface temperature above 1200 °C is found. Thereby it should be considered that the temperature below the surface is always lower.

Hence for maximum hardness and hardening depth the surface temperature should be as high as possible (for this material). The upper limit is given here by the requirement that surface melting has to be avoided.

The picture for the hyper-eutectic 100Cr6 steel, **Fig. 5** right, is quite different. First difference is that homogeneous austenite cannot be obtained during the short processing time. But it also shows that homogeneous austenite is not necessary for maximum hardness now. Instead the maximum hardness of HV 900 occurs at lower temperatures in the area of austenite + carbides.

### 3.2 Process development

When developing a process one should fulfil some requirements determining most process variables.

First the hardening depth will be prescribed, e.g. 1 mm. Then, based on the material and the required hardness, the desired surface temperature is found by data as given in **Fig. 5**, e.g. a surface temperature of 1200 °C. From the materials data the transformation temperature is given, e.g. TAc3 = 900 °C. For this example one could consider the heat flow into the material as one dimensional. Then the temperature on a depth z follows by:

$$T_{z,t} = \frac{AI}{l}\sqrt{4at}\,ierfc\sqrt{\frac{z^2}{4at}} \qquad \textbf{\textit{Eq.1}}$$

At the surface where z=0 this reduces to

$$T_s = \frac{AI}{l}\sqrt{\frac{4at}{p}} \qquad \textbf{\textit{Eq.2}}$$

Considering now that at the hardenings depth zh the temperature is just TAc3 one obtains

$$\frac{T_{Ac3}}{T_s} = \sqrt{p}\ \ ierfc\sqrt{\frac{z_h^2}{4at}} \qquad \textbf{\textit{Eq.3}}$$

The only unknown quantity in this **Eq. 3** is the laser interaction time t, for the given example it is t = 1 s. With t and **Eq. 2** an absorbed power density of 1180 W/cm² is necessary. The real laser power depends on the absorptivity which has to be measured experimentally. In general metal surfaces reflect most of the laser radiation. The absorptivity ranges from less than 10 % for $CO_2$ - lasers to 40 % for Nd:YAG lasers. In both cases a (graphite) coating is applied to enhance the absorptivity to above 80 % improving the process efficiency considerably.

Next item to be discussed is the spotsize and the scanning speed. The one dimensional treatment is only valid when the penetration depth of the heat is small compared to the spotsize, which in general will be the case. Then the interaction time easily follows from the spotsize and the scanning speed. In **Fig. 6** a hardening diagram is shown for a laser spot 7 mm in diameter on die steel as an example. Instead of the equations given above here the more complex equations for a circular spot with a top-hat power distribution were applied [Spr1992]. The top line shows the melting temperature as the upper limit. Further 3 lines of constant hardening depth (0.1, 0.5 and 1.0 mm) are shown.

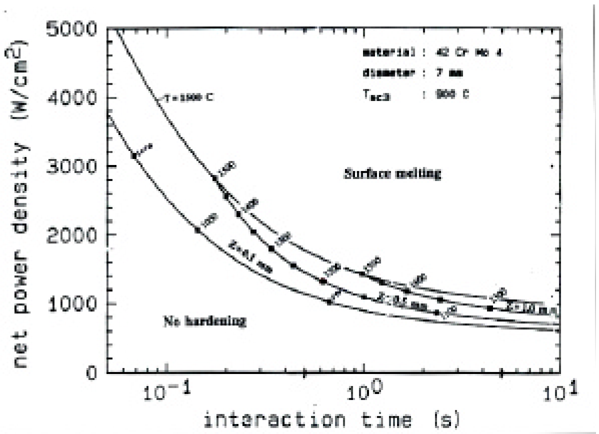

***Fig. 6:*** *Hardenings diagram for 42CrMo4 steel (Univ. Twente)*

The most serious problem is that the (vertical) range in power density is small. Moreover, because the net power density is the most uncertain parameter by reason of variations in spotsize and absorptivity. The calculated surface temperature is given along the lines. By measuring the actual surface temperature the laser power can be controlled in such a way that the surface temperature and the corresponding hardening depth are maintained on the required level.

The procedure is first to select the required hardening depth, then select the best surface temperature. Next the diagram in figure 6 will show the corresponding interaction time.

These insights in the process have lead to the development of temperature control systems to obtain the right hardening and to prevent for surface melting. This is industrial applied now by scanning optics for laser hardening. An example of the schematics is shown in **Fig. 7**. Here the set-up is moved by a robot or other manipulator over the surface while on the mean time a scanning mirror moves the spot with high speed perpendicular over the track. The temperature at the spot is measured simultaneously by a pyrometer along the same optical path and used as sensor signal for real time temperature control during the scanning. The width of the scanned zone can be varied by the CNC control. Since the scanning is fast compared to the heat transfer the heat source can be considered as a rectangular source moving across the surface. In this way wider tracks are obtained compared to hardening with a single spot.

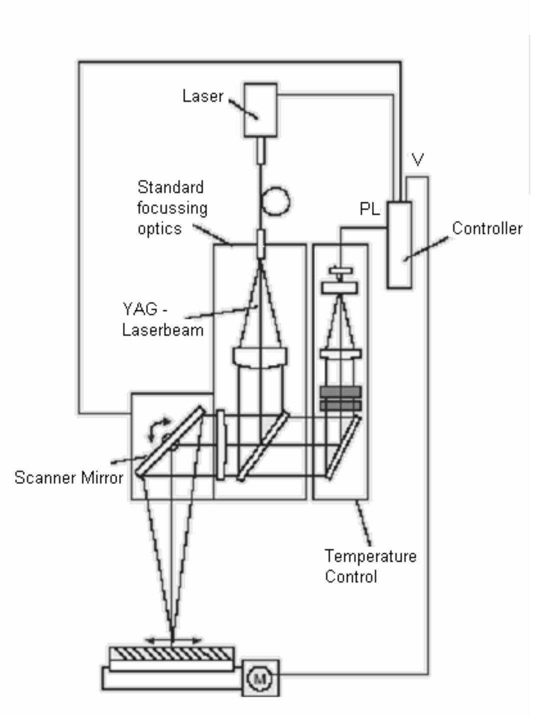

***Fig. 7:*** *Example of a scanning hardening system [Pho2005]*

In this example a Nd:YAG laser with an optical fiber was used, offering flexible freedom of motion. Similar developments are described by Hannweber [Han2004] and Seifert [Sei2004] who apply a high power diode laser which is mounted directly on the robot.

The transformation to martensite and bainite can be monitored real time by measuring the acoustic emission [Boh2004] which is generated by the rapid release of strain energy inside the material. This technique is capable to investigate the displaced character of the phase transformation but is not used in industry. Because the acoustic signal is related to the cooling phase, there is no possibility to apply this technique in process control.

### 3.3 Modeling

Modeling is done to study the influence of the process parameters on the thermal cycle and thus the hardening result and at the other hand the effect on the residual stresses.

The classical line is to calculate the heat distribution as result of a steady heat source. **Eq. 1** is an example for the well known one dimensional heat conduction in a half infinite solid. Such formulas are also available for a circular spot with a top hat or a Gauss distribution. For a first approximation however the one dimensional approach satisfies.

Next the movement of the laser beam over the material is taken into account. This results in an extra (convective) term in the heat conduction equation. [Rom1999] has shown that the dynamic transfer function $H_s = T_{x,y,z,s}/P_{l,s}$ induced by a point source leads to easy expressions in the frequency domain. The results show that up to a bandwidth of 100 Hz the measured temperature can follow variations in the laser power but at higher frequencies the gain becomes too low while the phase shift becomes unacceptable. The phase shift increases at an ever increasing rate with increasing frequency which can be attributed to the infinite process order. The phase shift becomes larger for higher beam velocities.

Most modeling work was done at simple flat geometries. For complex shapes, however, they cannot be applied. For such products Finite Element Methods (FEM) are applied more and more. Most commercial FEM packages are prepared already for steady of moving heat sources and they become faster and get easier user interfaces. They result usually in temperature distributions and the temperature-time history on certain depths below the surface. The user should interpret the results by knowledge from TTA and TTT diagrams. They are, however, less appropriate for the high heating and cooling rates of 1000 to 10 000 K/s. Already in the eighties the effect of phase transformations and the influence of stress on the phase kinetics were studied, resulting in realistic phase distribution in the work piece [Ron2000, LinL2001]. Geijselaars [Gei2003] applied this for laser hardening adapting the model of phase transformation kinetics to specific phenomena connected to rapid thermal cycles such as incomplete austenization and grain grow at high temperatures including phase evolution laws and transformation induced plasticity. His emphasis is on the description of macroscopic phenomena, rather than on what happens exactly inside the crystals. The fraction of each phase present is treated as a state variable. The variation of this phase fraction is subject to kinetic equations, so that different thermal histories will result in different phase fraction distributions. On this base the eventual phase distribution and hardness, the residual stresses and distortions are calculated. These methods are not mature for industrial applications yet. The main challenge is to capture the behaviour of the different materials in just a few state variables as required for this method. This will require still extensive future work.

The prediction of fatigue behaviour of laser hardened specimens by FEM is a further new development that was done in the last 5 years. Hosenfeldt [Hos2001] described this for flat specimens with one or two hardening tracks with different overlapping. The computation of the place of crack formation and the fatigue strength of specimens similar to components were developed by Baierl [Bai2002] and Schnack [SchS2003]. The continued studies of this work are described in the paper about the fatigue limit of pulsed laser hardened steel contained in the presented proceedings.

### 3.4 Materials properties

A wide range of ferrous materials can be laser transformation hardened.

In principle all steels which are applied for conventional hardening are suitable for laser hardening. Actually the application area is even wider because in case of laser hardening even with low carbon content starting from 0.35 %C hardening will occur. Applications are found in plain carbon steels e.g. C45 but more in steels for dies like 42CrMo4 or X40Cr13, heavy duty and ball bearing steels like 100Cr6, tool steels like X210CrW12. Above 0.8 %C the carbon is present as hard $Fe_3C$ phase. Laser transformation hardening is in principle also applied on cast iron. In that case the cast structure is not the best for laser hardening. In such cases the top layer is remelted by the laser and hardened on one and the same process cycle (see chapter 4).

### 3.5 Applications

Despite the superior properties obtained by laser hardening, there are two principal restrictions of the process limiting the applications.

First the process requires the laser beam moving over the processed surface so the hardening is by its nature sequentional. Although the process itself is fast, it is hard to compete with batch wise processes where series of products are hardened simultaneously in a furnace. The other restriction is that the width of a hardened track is limited to the width of the laser spot moving over the surface. By hardening a wider surface by overlapping tracks it should be taken into account that the heat of the last track will anneal a small zone of the already hardened track.

Within these two boundary conditions there are numerous applications just taking advantage of these characteristics. Almost all applications utilise one single track for localized hardening on high loaded surfaces, mostly edges or seal rims on the product. An example is given in **Fig. 8**. The main benefits here are that the hardening is just there where wear takes place and that the hardening is a final operation without thermal distortion of the product.

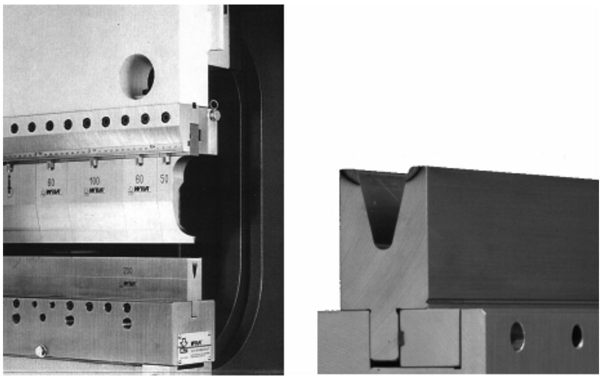

***Fig. 8:*** *Laser hardened tools (left: courtesy Demar Laser, right). [Pho2005]*

Other examples are the hardening of the edges of dies for sheet metal forming in the automotive industry [Clu2004] and plastic injection moulds at high loaded places on the surface.

The second limitation, restricting overlapping areas can be overcome by hardening just single tracks. This is done for cylinder liners in diesel engines. The density of the (slanted) tracks corresponds with the wear load along the liner. Sometimes it was proved to be advantageous to have softer regions along the hardened tracks. From wear experiments it was found that hard abrasive particles have been caught and imbedded in the shoulders of the hard tracks. Because the volume expansion the hardened zone will rise a few µm above the original surface and creates an improved geometry for carrying the load and lubrication.

Last application to be mentioned is laser surface hardening to improve the fatigue strength by generating compressive stresses in the hardened zone. This is generally the result of volume expansion by the martensite formation.

## 4 Laser Remelting

The remelting with laser beams has been studied in many research centres since approximately 20 years.

The process and variants of it were developed and applied in many fields. This paper deals with laser melting of metallic materials as a process for macro materials processing. The processes of selective laser melting, rapid prototyping or direct laser sintering are not included. Also the processes of structuring surfaces and polishing where the ablation is the main process are not implied. These restrictions were necessary due to the main focus of the paper on methods for hardness improvement.

### 4.1 Process principle

The process principle is visible at **Fig. 9**.

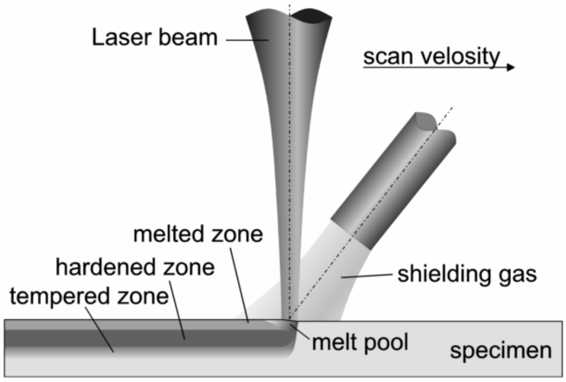

***Fig. 9:*** *Principle of the process (BIAS)*

The laser beam heats the base material up to the melting point and above but not up to the evaporation. Because of a relative movement of the laser beam and the base material a track is generated that consists of the remelted zone and the heat affected zone (HAZ). The geometry of the remelted zone and the HAZ depends on the laser power and the geometry of the focal point on the surface of the work piece (beam intensity), the scanning speed and the absorption of the laser beam at the surface. To avoid oxidation during the process a shielding gas is used in most cases which can be applied coaxial or in off-axis direction.

## 4.2 Process development

A well known variant of the laser remelting process is the remelting of grey cast iron.

The laser remelting has advantages to TIG welding because of a better contour accuracy and therefore less machining afterwards. To avoid crack formation after the remelting and to reach a better behaviour of work pieces at cyclic loading a combined process of inductive preheating and remelting of cast iron was developed by Wetzig [Wet1998].

A process for smoothing surfaces after Electro Discharge Machining (EDM) or milled surfaces was developed by Willenborg et al. [Wil2003]. It is a combined process of remelting in the first step and evaporating + remelting in the second step. The smoothing in the first step occurs because of the tendency of the melt pool to take up minimal surface energy. The depth of the melted zone is between 10 and 100 µm. For the process Nd:YAG lasers and Nd:$YVO_4$ slab lasers were used with a scan head with a scanning speed up to 5 m/s. Applications for this smoothing process are forging dies and medical implants for example. A smoothing process of tabs of magnetic recording head gimbal assemblies was described by Singh et al. [Sin2002]. A q-switched frequency doubled YLF laser, operating with around 100 Hz was used for this purpose. The melting zone has a comparably low thickness of 3 µm. The smoothing effect works like described above and causes better wear behaviour of the tabs. Because of this 5 to 10 times more load/unload cycles of the recording head are possible.

To create wavelike frozen structures on aluminium surfaces a process was developed by Mosaner et al. [Mos2003]. With a KrF excimer laser the surface is heated by laser pulses above melting temperature. Because of liquid wave motion the structures can be created.

## 4.3 Modeling

The laser remelting process was modeled with different methods to achieve different aims.

A 2D-model to simulate the grain structure formation during solidification, e.g. for casting processes or laser remelting processes, was already described by Rappaz et al. [Rap1996]. Analytical models to predict the microstructure of Al-Fe alloys have been developed by Gilgien et al. [Gil1995].

The diffusion controlled processes during the laser remelting of nodular cast iron were modelized by different scientists. Lepski [Lep1997] modelled the dissolution kinetics of spherical graphite particles subjected to diffusion and convection. Grum et al. [Grm2002] estimated the size of the shells of martensitic or ledeburitic microstructure around the graphite nodules in the HAZ of remelted nodular iron. Lima [Lia2000] modelled the morphologies of austenite and the primary dendrite spacing influenced by different scanning velocities in a cast iron.

Kasula et al. [Kas2003] calculated the resulting temperature, the stress distribution, the width and depth of the melt pool with a 3D enthalpy-based finite element model. The model based on a three-dimensional transient heat equation taking into consideration the power intensity of the Gaussian laser beam and the phase diagram of the material.

For the laser remelting of a structural steel Haranzhevskiy et al. [Har2004] modelled the formation of crystal patterns and verified the model experimentally. The result was a microstructure selection map for predicting mechanical properties in the remelted zone as a function of the energy parameters.

Liu et al. [LiuW2004] developed a model to estimate the 3D melt-pool geometry and the single crystalline melt pool solidification for single-crystal nickel-base superalloys. He found out that the geometrical parameters of the melt-pool have profound influences on the dendrite growth velocity and the growth pattern.

The delimitation of the remelted and the heat affected zones on a steel (AIR 1045) was estimated by Cheung et al. [Che2005]. This model based on the finite difference method and has been compared with another numerical method from the literature and has been verified experimentally.

## 4.4 Materials properties

The remelting of cast iron is probably one of the first applications of the laser remelting process.

Therefore the influences of process parameters like scanning rate, laser power and geometry of the specimens on the microstructure, hardness, phases and residual stresses of the treated rim zones of the cast iron were studied by various scientists, e.g. by Domes et al. [Dom1994] and Grum et al. [Grm2001]. With remelting process it is possible to get a ledeburitic layer with good wear resistance and high hardness. The choice of the right process parameters and if necessary the heat treatment can avoid crack formation.

Besides the cast iron the microstructure and therefore the mechanical properties of steels can be influenced by laser remelting. A high alloyed steel was laser remelted by Wu [WuR2000]. After the treatment a layer of austenite and ledeburite was observed with a strong tempering stability up to 500 °C.

Further studies were executed [Lim2001] and [Kum2001] on materials that were sensitised to intergranular corrosion (alloy 600 and austenitic steel). It was detected that the laser remelting causes a lower degree of sensitisation to intergranular corrosion comparable to the not laser treated specimen. Further in the case of cold worked austenitic steel (5 to 25 % forming level) a trend was observed that an increase of the forming level decreases the degree of desensitisation by laser surface melting [Kum2001].

In the case of pitting corrosion of stainless steels studies with the laser remelting process were also carried out [Kwo2003], [Car2002]. An enhanced corrosion resistance were observed attributed to the dissolution or refinement of carbide particles or inclusions and in the case of a martensitic stainless steel the presence of retained austenite [Kwo2003].

Beside the iron based alloys other metals were also laser remelted using Nd:YAG lasers and CO2 lasers. Different kinds of bronze were laser remelted to improve the hardness and therefore the wear resistance and the (cavitation) corrosion resistance successfully [Tik2000], [Tan2004]. Because of the highly refined and homogenized microstructure [Ben2001] the cavitation erosion resistance was improved up to 5.8 times compared with as-received bronce [Tan2004]. Furthermore copper cast alloys, laser remelted, show an increase of the hardness of 60 % up to 100 % and an improvement of the wear behaviour due to sliding action [Win2001].

The growth of the dendritic structure of laser remelted Cu-Mn alloys and DD2 single crystal (Ni-alloy) was studied by Yang et al. [Yag2004], [Yag2002]. He observed that there is an influence of the amount of copper in Cu-Mn alloys on the dendritic growth. Alloys with 27.3 wt.% and 31.4 wt.% copper show no dendritic growth but cellular structure [Yan2004]. In the case of the DD2 single crystal the microstructure of the molten pool is strongly affected by the orientation of the base metal and the scanning direction [Yag2002].

Another laser remelted material was TiAlCrNb where cooling rates of 105 to 107 K/s occured. The result was a lamellar structure and an increase of the hardness from 315 to 568 HV [LiuY2000].

A variant of the remelting of an aluminium alloy (2014-T6) for pitting corrosion protection is described by Chong et al. [Cho2003]. He used a 3 kW Nd:YAG laser with a line beam profile produced by a parabolic line segmented optic. The pitting corrosion resistance was increased by the laser remelting process but in comparison with the remelting with $CO_2$ - laser (Gaussian beam) a coarser microstructure was obtained what is a drawback for the pitting corrosion resistance.

## 4.5 Applications

The laser remelting process is used in many fields e.g. for crack repair, for smoothing of surfaces [Sin2002], [Wil2003] and to improve mechanical behaviour of the treated rim zones.

Sun et al. [Sun2001] described the crack repair of a hot work tool steel. The decrease of impact toughness by the high hardness of the HAZ was corrected by a heat treatment.

Soft soldering joints can be remelted to get an improvement of hardness and strength properties of the joints [Her2002]. The pull-off strength increases 10 to 40 % and the fatigue strength also increases. Similar to that the dynamic fatigue and the corrosion resistance of welded seams of aluminium alloys can be enhanced by laser remelting [Vol2005]. This enhancement is based on the reduction of geometrical grooves and the evenly distributed alloying additions.

A special surface structure of AlSi-based cast alloys can be achieved by laser remelting [Nay2004]. The remelting causes a fine cellular structure were the intercellular regions consists of silicon and CuAl. Because of the differential wear of the soft aluminum phase and the hard silicon or CuAl phase microfluidic channels and pits for oil retention were produced. This topography is suitable for engine applications.

A further wide application of the remelting process is the remelting of special rim zones e.g. coatings generated by plasma spraying. Detailed studies in this field have been already done e.g. by Gasser [Gas1991]. He remelted plasma sprayed and flame sprayed layers of different materials on structural steel and alloyed steel with a $CO_2$ - laser. The result was – thats one can say in general - an increase of the density of the remelted layer (lower porosity) that causes better wear behaviour, higher bond strength and better corrosion resistance. These effects were also observed at $CO_2$ - laser remelted plasma sprayed coatings of NiCrAlY and NiCrAlY - $Al_2O_3$ [WuY2001] and $Cr_3C_2$ / NiAl and $W_2C$ - WC/Co [Iwa2002].

Tuominen [Tuo2000] studied oxy-fuel sprayed Inconel 625 on steel Fe 37 remelted with Nd:YAG-laser. He detected that the heat input per unit length influence the corrosion behaviour. Only the remelted layers generated with low heat input per unit length have passive corrosion behaviour.

Kulka [Kul2003] remelted borided 41Cr4 steel. The remelted zone has lower microhardness than only borided layer and a reduced hardness gradient to the base material. The wear resistance is improved in comparison with rim zones after conventional treatment (e.g. hardening or toughening).

Further studies were done in the field of laser remelting of Electro Discharge Machined (EDM) rim zones of a heat treatable steel [Hab2005]. Different from [Sin2002] and [Wil2003] where very thin layers were melted with special scanner optics or lasers these studies were carried out with a conventional pulsed fibre coupled Nd:YAG laser. The thickness of the melted zones ranges between 80 and 320 µm. One main point of these studies is the fatigue strength of the specimens that remarkably decreases by EDM treatment, **Fig. 10**. The laser remelting causes fatigue strength a little above the value of the untreated specimen. High amounts of retained austenite (up to 60 %) were observed in the melting zones that cause a slowly growth of the crack during dynamic loading compared with untreated or EDM treated specimens.

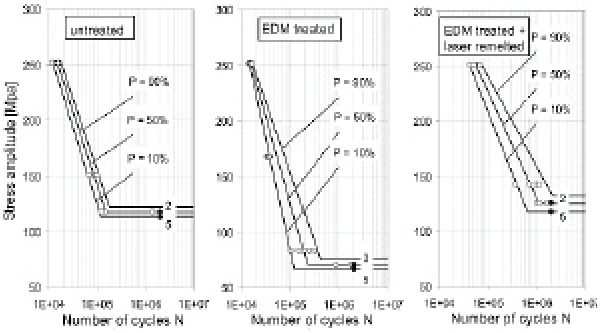

*__Fig. 10:__ Wöhler lines of notched specimens (radius of the notch 5 mm), loaded by cyclic three point bending load, with different treatment of the notch. (P= fracture probability, black points= not fractured specimens with declaration of their quantity) [Hab2005]*

## 5 Laser alloying and dispersing

### 5.1 Process principle

A laser surface remelting process that involves the addition of filler material with the principal aim of altering the chemical composition of the remelted metal is generally known as laser alloying.

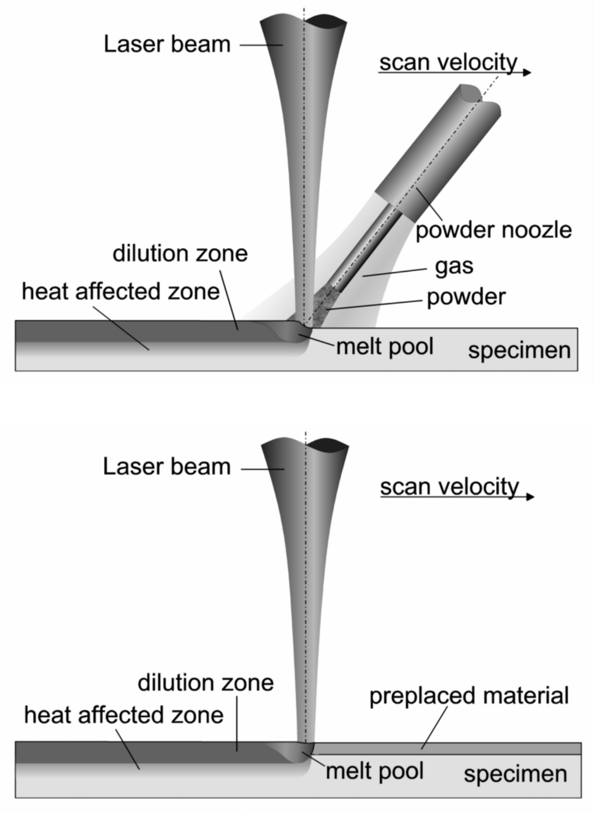

*__Fig. 11:__ Principle of laser alloying and dispersing. top) single step process, bottom) two step process (BIAS)*

As illustrated in **Fig. 11**, a laser beam is scanned across the surface of a work piece in order to melt a layer of material in a heat conduction mode. In the molten state, the metal is enriched with alloying elements which may be introduced from either gaseous or solid consumables using a variety of delivery techniques. In a single step process, gas, powder or wire feedstock is delivered continuously into the melt pool through a nozzle mounted at the laser device, **Fig. 11top**. In a two step process, in contrast, a layer of filler material is pre-deposited onto the surface of the workpiece by e.g. thermal spray, printing or other methods, and a subsequent laser remelting step is applied to fuse and mix both base and filler material, **Fig. 11bottom**.

As the width of the treated surface layer that can be achieved by a single pass of the laser beam is limited, larger surface areas require multiple adjacent passes of the laser process applied in a side-by-side manner.

In laser alloying, a full dissolution of the solid constituents of the filler material and a homogeneous distribution of the alloying elements in the melt is generally desired. In contrast to this, laser dispersing applies the same process principle to introduce disperse solid particles into the melt pool that will not fully dissolve during processing and thus form a metal matrix composite material rather than an alloy. In all cases, the in-situ alloying process is followed immediately by rapid cooling and solidification, as the laser beam is scanned across the surface. Cooling rates in the range of $10^3$ - 106 K/s [Pir1995] and solidification velocities are generally comparable to a laser remelting process, since laser parameters and travel speed will typically be in the same range, which may produce fine microstructures under non-equilibrium conditions [Hor1992].

### 5.2 Process development

Mainly high power $CO_2$, Nd:YAG, and diode lasers have been used for the purpose of laser alloying and dispersing.

Due to the clear advantages of their shorter wavelengths and due to their higher efficiency, the latter systems have been preferred in some recent investigations. However, few works have addressed the effect of the shorter wavelength on the process behavior in more detail. Guyenot, for example, reports the benefits of using diode lasers for alloying of aluminum with preplaced silicon powder that has a comparatively high transmissivity at this wavelength, which results in a favorable coupling of energy into the process under the given boundary conditions [Guy2004].

In the field of process development, recent investigations concentrate on solutions for the filler material delivery, as well as the appropriate choice of laser parameters for a given material combination and set-up, and the on-line process monitoring and control.

Gas alloying for example, which has preferably been used to form nitrogen-rich layers on titanium alloys, is generally performed in an ambient atmosphere environment with only local gas supply from a process gas nozzle directed at the melt pool [Wei1995]. A better command of the process, however, is gained when using a controlled atmosphere in a closed process chamber or shield gas bell, which allows for adjustment of a desired nitrogen partial pressure by mixing with argon [Bre1997]. Moreover, a closed-loop temperature control of the melt pool may be applied in order to establish a well-defined alloying process [LinK2004]. In short-pulse laser nitriding of aluminum and steel, it is understood that the alloying process involves the formation of highly reactive plasma, and depends strongly on the composition and pressure of the backing gas [Scha2002]. In this case elevated nitrogen pressures can be used to enhance the nitriding effect.

For alloying using powder feedstock, various nozzle designs and arrangements were investigated in an effort to minimize entrapment of oxygen from the ambient atmosphere. It was found that the overall effect was comparatively small, and that for example using a shield gas shroud had a minimal effect. There was, however, some influence if both laser and gas nozzle were arranged with an oblique angle of 15° towards the work piece [Tra2002].

Of course, laser parameters have an impact on process behaviour and the resulting melt pool geometry. It was found that the molten layer becomes unstable at critical depths and alters its shape in response to convective flow patterns [McC2002]. The Marangoni number provides an understanding of the influence of the material properties on convection and subsequently the melt shape, being inversely proportional to depth squared, viscosity, and thermal diffusivity, and directly proportional to the surface tension gradient, and thus it is possible to influence the Marangoni flow and control the shape of the melt pool using e.g. an appropriate beam profile.

A significant problem is the high sensitivity of laser alloying to process disturbances and to small changes in processing parameters. For example, a change of only 10 % in absorbed laser power can cause a change of up to 50 % in case depth [Rom1998]. Therefore a variety of sensors have been developed for process monitoring. For example, the mass flow of the consumable powder was monitored via detection of the emitted thermal radiation [Bac1998]. Moreover, real time process control can help to increase the stability, reproducibility, efficiency and productivity. A feedback control system using melt pool surface area as a quality parameter and employing a digital thermographic camera or a monochromatic pyrometer have been used to ensure constant processing quality during laser alloying of Ti with nitrogen [Röm1998]. In a comparable approach, a pyrometer is successfully used in combination with a laser reflection probe during alloying of steel with WC / Co and dispersing with TiC [Klo1997].

A dual-frequency electromagnetic sensor has been developed for non-contact, non-destructive monitoring and control the level of dilution in laser alloying processes [Li1996]. However, the method has limitations e.g. with respect to the material combinations.

In a more recent work, the laser surface alloying process was considered to have multi-input and multi-output non linear coupling and time varying behaviour for which it is difficult to design a model-based controller [Sie2001]. Instead, a model-free self organizing fuzzy control method with on-line learning abilities was employed to laser power and traverse velocity simultaneously in a closed loop controlled laser alloying process. The performance was reported better than that of a traditional PID controller and traditional fuzzy controller [Chn2004].

## 5.3 Modeling

Three aspects of laser beam alloying have mainly been addressed by process modeling: temperature field and melt pool geometry, transport and distribution of the alloying elements in the melt pool and the subsequent solidification behaviour of the in-situ alloyed material.

Thus efforts have been made to model these phenomena in some detail.

For example, a quasi-stationary analytical process model showed a linear dependence of the melt pool depth on laser power and an inverse dependence on the square root of the relative beam velocity [Bor1997]. The model accounted for the latent heat of fusion and the energy balance of reactions within the melt pool. It was validated by experiments on Ti6Al4V alloyed with nitrogen, and experiments on AISI304 alloyed with pre-placed chromium.

Powder heating during travelling through the laser beam and in the melt pool has been investigated in detail. Particles can be heated to very high temperatures in the laser beam depending mainly on the particle size, beam intensity and interaction time [Kap1997]. When entering the melt pool, the powder achieves thermal equilibrium with the pool within microseconds. Factors influencing the distribution in the melt pool by the marangoni effect are the injection momentum of the powder into the pool, the melt pool geometry, and the laser beam parameters [Kap1998].

Heat, momentum and solute transport in laser alloying of aluminium in a single step process using continuously fed powder have been modelled using a quasistatic two-dimensional model [Pir1995]. The process induced typical temperature gradients in the order of 106 K/m are the driving force for Marangoni convection which is decisive for mass transport and the resulting concentration field. In particular, it was found that convective mass transport led to a concentration maximum in a certain depth beneath the surface, which was supported by experimental investigations. Furthermore, an increased concentration can be observed near the surface, which goes back to unmelted powder particles gathering at the very surface at the end of the melt pool, thus preventing an efficient Marangoni convection in this area.

Modeling of two step alloying of a Ni layer predeposited on an Al-bronce substrate using a modified one-dimensional approach predicted the convection behaviour with respect to the effects of travel velocity and the size of the laser beam spot (and thus laser energy density) [Liu1997]. As confirmed experimentally, lower laser energy, larger melt pool dimensions and shorter interaction time result in insufficient convection and incomplete alloying.

The development of a laser molten Al pool alloyed with Ni under the influence of static magnetic fields with different strengths was simulated numerically [Vel2001]. Whilst due to a complex system of vortices an alloyed layer with an extension of about half the maximum pool depth was achieved when no field was applied, the presence of a static magnetic field suppressed the system of vortices, and the flow situation was damped resulting in a shallower alloyed layer.

A number of investigations have been made into solidification of in-situ alloyed layers [Guo1998, Dut2002a, Cha2002]. These emphasize for example the role of undercooling and the instability of the solid-liquid interface during solidification under non-equilibrium conditions. It was pointed out, however, that the role of diffusion (compared to convection) has often been underestimated in modeling of mass transport [Cha2001]. Three-dimensional equations of mass, momentum, and energy conservation have been simultaneously solved numerically using a pressure-based semi-implicit finite volume technique. It was found that the accuracy of the numerical solution of species concentration distribution in laser surface alloying depends on a constitutional supercooling criterion which in turn depends on appropriate values of diffusion coefficients in order to satisfy conditions of propagation of a stable planar solidification front.

The calculation of the latent heat effect during in-situ alloying of intermetallic compounds revealed a significant influence on the solidification process and the microstructure at short interaction times where e.g. the dendrite arm spacing becomes independent of travel speed [Wid2002].

## 5.4 Materials properties

The aim of laser alloying or dispersing is always the improvement of certain properties in the surface layer of a material.

It has been applied to a variety of base metals using a large number of different alloying elements and disperse particles, respectively. The vast majority of investigations, however, involves either the light alloys (titanium, aluminum and magnesium) or steel, and the primarily addressed functional properties are wear and corrosion resistance.

For enhancing the corrosion resistance of a commercial magnesium alloy, laser alloying with mixtures of Al and Mn was suggested [Dut2002b]. It was shown that the hardness was increased by a factor of 7-10, while the corrosion rate in NaCl solution decreased to a sixth of the previous value which was attributed to the formation of oxides on the surface. The formation of various point defects in this alloy system due to the rapid quenching associated with laser surface engineering suspected to cause a deterioration of physical and electrochemical properties of the laser treated components was studied in detail by positron annihilation lifetime spectroscopy [Dut2004a]. The defect characteristics of the alloyed zone have been correlated with the microstructure, phases and microhardness of the surface modified layer. In order to improve the wear resistance of a commercial magnesium alloy, simultaneous dispersion of Al2O3 particles and alloying with Al was carried out by feeding a mixture of the powders. Microstructure, phase analysis, microhardness and wear resistance of the surface layer was evaluated as a function of laser parameters, and a significant improvement of properties was reported [Dut2004b].

Laser gas alloying of titanium with nitrogen produces extremely wear resistant layers. For laser nitriding under controlled atmosphere, microstructural features like dendrite spacing and properties like microhardness, Young’s modulus and electrical conductivity were investigated as a function of nitrogen content [Bon2000]. Particular attention was given to wear and dynamic strength. It was concluded that such layers are well suited wherever high sliding wear resistance is required in combination with high specific strength or bio-compatibility.

For laser dispersing of titanium, several methods of delivery and predeposition of $TiB_2$ powder including thermal spray and paste printing were evaluated. Powder particle size, powder mass flow rate or layer thickness, respectively, laser parameters were decisive for the process behavior. It was found that compact, large scale borides of 45 - 125 µm were more suitable for sliding wear in dry contact [Kol2004]. In contrast to that, a fine scaled boride structure with particle size of 5 – 63 µm was recommended for best cavitation resistance [Mat2004].

Aluminum alloys with enhanced surface hardness and wear resistance were produced by laser surface alloying of continuously fed Cr, Mo, and Nb powders [Alm2002]. The microstructure of Al-Cr and Al-Mo alloys consisted of particles of intermetallic compounds dispersed in an Al matrix. The hardness of the surface layers varied in the ranges 130 – 260 HV and 95 – 180 HV, respectively. The wear resistance of Al-Cr alloys was higher than that of Al-Mo alloys. The wear mechanism in these alloys was predominantly adhesion, material transfer, and delamination, with a minor contribution of abrasion by microcutting and microploughing. The Al-Nb alloys, in contrast, consisted of primary Al3Nb dendrites and a small volume fraction of interdendritic alpha Al. Despite the high hardness of 500 – 650 HV, the Al-Nb alloys had no tendency to crack, which was attributed to the interdendritic film of alpha-Al. These alloys presented very high wear resistance due to the high volume fraction of hard $Al_3Nb$. The wear mechanism was purely abrasive, by microcutting and microploughing.

The crevice corrosion resistance of Al alloy AA7175-T351 was improved by laser alloying with Chromium. Immersion tests and free potential measurements in NaCl solution indicated a corrosion resistance comparable to plated material [Fer1996]. It was concluded that local treatment of areas susceptible to crevice corrosion was feasible to prevent corrosion.

Overlapping of individual alloying tracks is required for treating large areas. For multi-pass alloying of AA2014 Al alloy with Cr, W, Zr-Ni or Ti-Ni, microsegregation within the planar front zone of laser melted samples and microstructural coarsening in the reheated zones at the laser track overlaps was found. During electrochemical testing microsegregation within the overlapped areas lead to initiation of pitting corrosion in most of these cases, indicating the detrimental effects of overlapped processing on the corrosion performance [Wat1998].

The addition of Cr and Ni and carbides (SiC and WC) during laser surface alloying produced surfaces with both enhanced hardness, wear resistance and corrosion properties compared to the base AlSI 4340 steel material [McC1999]. These effects were due to the evolution of unique microstructures, where chromium and nickel reduced the formation of martensite that is useful to increase hardness and prevent cracking. A substantial dissociation of the carbides into elemental silicon and tungsten was also observed. Undissociated carbides and some martensite formation provided substantial increases in the microhardness. However, the improvement of both the mechanical properties and corrosion resistance was found to be self-exclusive due to the reduction of the carbides and the subsequent inability of the matrix to prevent cracking.

An iron based metal matrix composite materials for abrasive wear resistance was obtained by alloying an iron based material with a $Cr_3C_2$ powder which dissolved to form the matrix of the composite with 15 %Cr and 0.3 %C. Additional NbC powder was dispersed in the matrix, which provides high hardness and limited solubility in molten iron [Col2001]. The optimal proportion of reinforcement for dry sliding and three-body abrasion was 20 wt.% NbC and 10 wt.% NbC, respectivelly. It was concluded that this type of material might be useful to replace more expensive hardfacing alloys like stellites.

## 5.5 Applications

It has been shown many times that laser alloying and laser dispersing are capable of producing layers with outstanding properties that meet the demand of many applications.

A number of recent investigations has deepened the understanding of the process behaviour as a prerequisite for developments like process control which are enabling the technology for industrial application.

Prospective applications lie in the field of tooling, where for example laser dispersing of zirconia in tool steel and cast iron has been used to improve the wear resistance of metal forming tools [Haf2002]. A temperature controlled process was used for this application, where the lifetime of the tools was multiplied and the friction between tool and sheet reduced.

Titanium has applications in the field of medical technology, where an increased wear resistance is desired in combination with high corrosion resistance. For instance, controlled atmosphere gas alloying offers a potential in abrasive and sliding wear applications [Bon2001]. Dispersing of titanium with borides ($TiB_2$, $ZrB_2$, $CrB_2$) was found to be particularly suitable for sonotrodes where caviatation resistance is the main requirement. A reduction of wear by 70 % was reported [Mat2004].

The current trend of using iron cylinder sleeves or liners in aluminum automotive engine blocks creates a costly manufacturing step that also negatively impacts engine performance, weight, and packaging. The potential to provide a cost-effective wear resistant surface on aluminum engine blocks via laser surface alloying has been demonstrated in a number of recent works.

A sophisticated system technology with rotating optics and continuous powder delivery was developed that specializes in processing of surfaces of cylinders in crank cases using Nd:YAG lasers of up to 4 kW. Compared to earlier investigations, the laser power was scaled up in order to achieve industrially relevant processing times. The shape and the diameter of the focus can be flexibly adapted to the requirements of the process [Len2001]. Furthermore, a specific honing process was established to achieve the required surface topography on laser alloyed hyper eutectic Al-Si material with small silicon crystals serving as the load bearing constituent [Fis2001]. The tribological behavior of laser alloyed cylinders was tested in various engine test runs. Both wear and oil consumption was considered very promising. As an alternative to Nd:YAG lasers, diode lasers were intended to offer a higher process efficiency and thus lower cost.

Both the performance and manufacturing issues related to this critical automotive application, have been studied in detail [Hop2000], and it was established that as-processed dimensions and roughness were adequate for honing and operation, and as-honed dimensions were within to specifications and adequate for operation. Compatibility with current piston/ring set appeared satisfactory. Even in a worst-case scenario, savings of 3 US$/bore compared to iron liners were estimated. In this work it was also concluded that diode laser systems might provide even more significant savings and be easier to implement on manufacturing floor.

Recently, diode lasers of up to 6 kW have been used for alloying of Al cylinder liners with Si powder, enabling for a reduction of processing time by 40 % compared to the 4 kW Nd:YAG laser. The homogeneously alloyed layers contained primary silicon precipitates to a depth of up to 1 mm, with a silicon content of around 35 vol.-% in the layer, **Fig. 12**. It was stated that the process could be scaled up to more powerful lasers and shorter times, enabling economical alloying to be carried out [Guy2002, Guy2003, Guy2004]. However, this technology requires rotating crank cases which may be a drawback in respect to the total processing time due to sequential instead of parallel processing. It has nevertheless brought laser alloying technology to a point where it is gaining attractiveness for industrial application in mass production.

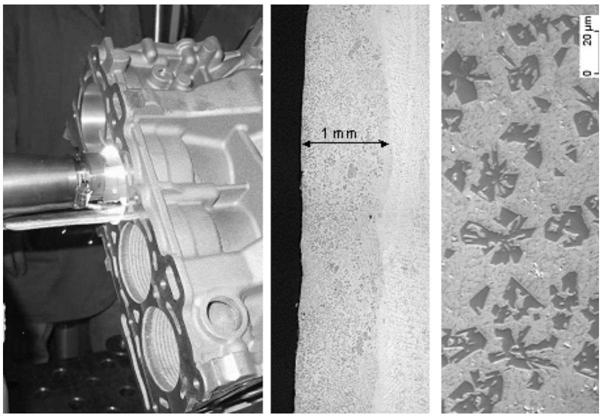

*Fig. 12:* *Laser alloying of an aluminum crank case using a 6 kW diode laser (left) and details of microstructure showing Si crystals (center and right)[Guy2004]*

# 6 Laser cladding

## 6.1 Process principle

The aim of laser cladding is the deposition of a cladding onto surfaces of work pieces in order to generate functional layers or regenerate the natural shape of parts.

The material is deposited by powder injection, pre-placed powder or by wire feeding. In combination with the laser beam generating a melt pool the additional material is melted. Today laser cladding is mostly done with powder injection.

A great variety of materials can be deposited on a substrate by powder injection. The deposition process generates the cladding track wise. By putting track beside track areas can be treated. Layer thicknesses range from 0.05 to 2 mm. Also multilayer cladding is possible to achieve higher cladding thicknesses.

The process is schematically shown in **Fig. 13**. The powder flow can be off-axis or co-axial. In both cases the powder travels some distance through the laser beam causing the particles to be preheated or even melted before they reach the melt pool. To protect the optical components a cross jet is usually applied in order to avoid damage caused by heated powder particles. For long running clad operations additional heat shield is used to protect the equipment (tubing) for excessive heat radiation.

Another characteristic of laser cladded surfaces is a comparably small dilution zone of substrate and clad material. In order to realise a low dilution zone the process parameters and material combinations have to be fitted to the geometrical boundary conditions of the work piece.

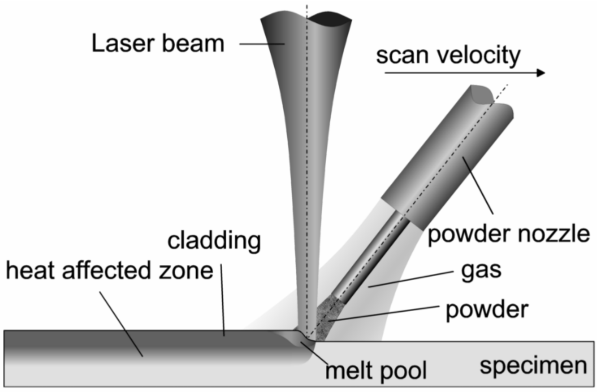

***Fig. 13:*** *Principle of laser cladding (BIAS)*

## 6.2 Process development

Industrial applications made a break through in 1983 in companies like Rolls Royce, Pratt&Whitney, Combustion Engineering, Fiat, GM, Rockwell and Westinghouse and others [Mac1983, Ebo1983].

The process development has been started with a two step process where a layer of the clad material was supplied on the substrate first and in the second step was molten by the laser. The clad material was supplied mostly as a paste which had the disadvantage of contraction at the edges of the track causing unevenness in case of overlapping tracks. Moreover, the process takes much more time compared to a one step process.

One step processes feed the clad material continuously during the process, mostly as a powder transported by inert carrier gas. Initially lateral off axis powder delivery nozzles are applied. Today it is still common to take off axial powder feeding configurations for one dimensional process. Coaxial powder nozzles have been developed in order to be independent of the direction of motion. In [Lin1999] it was shown that the powder efficiency can be higher at off axial nozzles compared to the coaxial nozzles. Several nozzles have been developed for special purposes. Islam et al. [Isl2001] developed a multiple nozzle for manufacturing and repairing turbine blades. Jeantette [Jea2000] invented a coaxial nozzle which is used for the generation of complex shapes. This development has been licensed to Sandia Corporation. Keichner [Kei2001] has developed a multiple beam and nozzle system to increase the deposition rate. This design is licensed to Optomec Design Company. A combination of laser cladding and painting is described by Stiles et al. [Sti2004]. Shortly behind the clad nozzle a primer is sprayed over the cladding, having a temperature of some 150 °C. This protects the clad area because the original protective coating immediately near the clad track is removed by the high temperature. This one step process is of interest in shipbuilding components.

The lasers used for cladding were initially $CO_2$ lasers because of their high power and good efficiency of about 10 %. Currently also Nd:YAG and high power diode lasers HPDL are successfully used for laser cladding. Because their flexibility Nd:YAG lasers are applied in combination with optical fibres and robots. They become also available in high power rates although the wall plug efficiency is still poor (some 2 %). Also HPDL become available in high power rates. Besides the possibility to equip them with optical fibres, they can also be connected directly to a robot or Gantry system [Clu2004, Han2004, Sei2004]. The absorbtion of Nd:YAG and HPDL laser radiation at the melt pool is comparably high as $CO_2$ - laser radiation. The efficiency of about 35 % of HPDL is comparably high but the beam quality is comparable low. It was shown in [Hab2003] a HPDL is a useful tool for laser cladding. This is not a problem to obtain the required power density on the surface but it limits the ability to go into bores or other deep lying surfaces. No experience is known about the application of high power fibre lasers which are coming on the market now. They might be incorporated in mobile clad installations which are expected to be the next development for in-situ applications in repair laser cladding.

In order to improve the treatment time scales of laser cladding processes while simultaneously improving the process efficiency research activities are going on [Par2003]. The aim of this work is getting a process understanding of laser cladding processes with high scan velocities, laser powers and powder feed rates [Par2005].

## 6.3 Modeling

The models in the literature can be distinguished in steady state models, dynamic models, lumped models, flow models for the melt pool, flow models for the powder injection and models how the clad geometry is formed.

The process can be described in a few sequential steps. The laser beam reaches the substrate surface through a cloud of particles. The laser power is attenuated by the particles (absorption and reflection). The remaining power will develop a melt pool at the substate in which the particles are added. This part of the process is extensively described in the literature using the heat transfer equations for conduction and for convection caused by the moving beam [Rom1998, Rom1999a]. From such models it is concluded that the power density distribution over the surface should be adapted in a way that the depth of the meltpool is equal over the diameter. Especially deep melting in the center and subsequently mixture of substrate material in the pool should be avoided. Such modelling leads to power density distributions with higher intensities at the edges of the molten spot [Rom2000]. In practise such power distributions are hard to realise. In laboratories it was proved to work well, however in industry where the geometry of the clad tracks strongly depends of the product geometry it is not applied up to now.

The next group of models describes the flow in the melt pool. As a result of the temperature field there will be a surface tension gradient driving the fluid flow within the melt pool. Basically two flow patterns originate; eddy currents in the surface plane in shallow pools and in deeper pools also a circulation in depth. Both mechanisms will mix the powder particles rapidly in the melt pool. This mass convection involves a convective heat transfer which is taken into account only in a few numerical models up to now [Toy2005].

From the viewpoint of process control there is a need for precise dynamic models. An analytical model was developed by Bamberger et al. [Bam1998] for estimating the process parameters by direct injection of powder into the melt pool. It was applied to control the table speed as a function of the temperature of the melt pool. As a result the height of the clad was expressed as a function of the scan velocity. A more advanced model was reported by Kim et al. [Kim2000] who used a two dimensional, transient finite element technique.

Instead of theoretical models also empirical models for system identification have been developed. For laser hardening a system for identification of the dynamic model was described by Bataille et al. [Bat1992]. A stochastic based dynamic model has been developed by Römer et al. [Rom1998, Rom1999a, Rom1999b, Rom2001] using auto regressive (ARX) system identification techniques to obtain a dynamic model for laser cladding and alloying. With the table velocity and the laser power as inputs the melt pool area could be the output of the system. By measuring the melt pool area by a digital CMOS camera [Rom1997] the same system can be applied to control the table speed and the laser power for required area. Although such systems are available nowadays, they are not yet used in industry because of the nonlinearity of the process. Therefore a linearized model is used for a given operation point requiring a system identification for each type of application.

Another mathematically model approach from the thermodynamically point of view was investigated by Cho et al. [ChoC2004]. In this model the latent heat was taken into account. It came out that this effect has a significant influence on the result of the calculation being close to experimental results.

An interesting part of modelling laser cladding is the calculation of temperature distributions. Jendrzejewski et al. [Jen2004] has calculated the temperature distribution for multi layer claddings. To get closer to applications Palumbo et al. [Pal2004] has modelled the laser cladding process on ring geometries for the treatment of valve seats in engines. An interesting combination of various modelling techniques was done by Toyserkani et al. [Toy2003], including fundamental work of Picasso et al. [Pic1994]. Another attractive model was realized by Sameni et al. [Sam2004]. In this model the clad height was calculated by a fuzzy logic based model.

Further models for laser cladding are e.g. numerical FEM models, being developed in order to predict the metallurgical and the mechanical properties of laser clad layers on a substrate.

## 6.4 Materials properties

Two main classes of material combinations are distinguished, clad materials on ferrous and on non-ferrous substrates.

Most cladding is done to improve surface properties of relatively heavy and cheap substrate materials. Therefore the ferrous substrates forms are now the majority.

- Ferrous substrates

*Cobalt base powders*

Cobalt base superalloys (trade name ‘Stellites’) are popular to improve the wear resistance of mechanical parts in hostile environments.

Those powders are mixtures of cobalt and other elements like nickel, chromium, tungsten, carbon and molybdenum. Chromium is added to form carbides and to provide strength to the cobalt matrix as well as to enhance the resistance against corrosion and oxidation. Tungsten and molybdenum have large atomic sizes and give, therefore, additional strength to the matrix. They also form hard brittle carbides. Nickel is added to increase the ductility. The carbide is mostly the chromium rich $M_7C_3$ (M=metal) type. These carbides (2200 HV) are responsible for the hardness of the clad (~ 550 HV) and for the wear resistance. In low-carbon alloys other carbides such as $M_6C$ and $M_{23}C_6$ are found. The hardness and the wear resistance for a given cobalt-base powder mixture can be further improved by adding hard particles, such as carbides, nitrides and borides directly to this mixture. An example is the addition of tungsten carbide ($WC/W_2C$) to a cobalt base powder in order to enhance the abrasive wear resistance. Acker et al. [Ack2005] investigated the influence of the WC distribution in laser cladded metal matrix composites on the wear resistance. Tungsten carbide allows no plastic deformation, the thermal expansion is low and the wet ability by molten metals is good, especially cobalt. Tungsten carbide is dissolved by molten cobalt. The dissolution increases with the temperature of the melt and the interaction time. Depending on the carbon concentration in the melt, dissolved tungsten carbide crystallizes to WC, or with low carbon concentrations, to $W_2C$ or brittle phases such as $Co_3W_3C$ and $Co_6W_6C$. The temperature of the melt should be as low as possible to prevent the formation of these phases.

*Nickel base alloys*

Nickel base alloys are used for applications in aggressive atmospheres at high temperatures.

They have a good high temperature corrosion and oxidation resistance. Nickel base alloys can also be used as a substitute for cobalt.

Elements that can be mixed with nickel are chromium, boron, carbon, silicon and aluminium. The formation of hard borides and silicon carbide improves the wear resistance and hardness but these hard phases make the coating brittle. Hard particles can also be mixed with the clad powder. Addition of tungsten carbides to a mixture of Ni-B-Si gives a nickel rich structure with fine distributed $Ni_3B$ and dissolved tungsten. The addition of boron and silicon improves the wetting behaviour resulting in very smooth surfaces. Aluminium can be added to further increase the hardness by the formation of intermetallic phases ($NiAl_3$ and $Ni_2Al_3$) or oxides ($Al_2O_3$).

*Iron base alloys*

Mixtures of iron, chromium, carbon and manganese or tungsten show a good wear resistance due to the formation of carbides.

The carbides are of the type $M_6C$ instead of $M_7C_3$, as found in cobalt base clad materials. Another application is the cladding of austenitic corrosion resistant layers on top of low carbon steels. The corrosion resistance can be further improved by increasing the molybdenum content.

- Non-Ferrous substrates

*Nickel base substrates*

Nickel base alloys retain their mechanical properties up to high temperatures in combination with a good corrosion resistance.

They are especially useful for applications exposed to corrosion and wear at high temperatures like diesel exhaust valves as well as for jet engine turbine blades. The wear properties of the nickel base alloys are not very good but they can be improved by using cobalt base clads, by protective oxide layers such as chromium oxide or by the addition of hard particles in a binder alloy. Beside their hardness, oxide layers also form a thermal and chemical barrier to the harsh environment. A problem with ceramic layers is the often poor adherence to the coating. Elements as hafnium and yttrium can improve this adherence.

A typical application of a cobalt based clad alloy is laser cladding of notches of jet engine turbine blades.

*Aluminium and titanium base substrates*

Aluminium and titanium alloys are popular for parts in aerospace and automotive industry because of their low weight and high strength.

At high temperatures, however, the mechanical properties and the wear resistance are poor but this can be improved by a nickel base clad layer combining the advantage of light weight with a high temperature wear resistance. Nickel, titanium and aluminium are known to form brittle intermetallic compositions as $Al_3Ni$, $Al_3Ni_2$ and AlNi which are sensitive to cracking. Sandwich layers like Ni-Al bronze can prevent this. Well bonded aluminium oxide layers could be obtained by cladding aluminium alloys with a mixture of aluminium and silicon oxide. Then the following reaction will occur: 2Al+3/2SiO2=Al2O3+3/2Si. The presence of silicon in the oxide layer is favourable for the wetting by liquid aluminium. The hardness of an aluminium or titanium alloy can also be increased by the injection of a mixture of hard particles and an aluminium respectively titanium alloy. Especially silicon carbide and titanium carbide seem to be useful hard particles. An application is a clad layer of a very hard cubic boron nitride and Ti6Al4V mixture on a Ti6Al4V compressor blade.

## 6.5 Applications

Laser cladding is applied for coating, repair and refurbishment, rapid prototyping and rapid tooling.

*Wear resistant layers*

Probably the most cladding applications are in the domain of wear resistant layers on machine components.

An example of a new product is the cladding of hydraulic cylinders in heavy roof supports in Australian coal mines by UNS-S43100 on 4140 Alloy Steel. This improved the lifetime considerably compared to the previously applied hardchrome on steel. Examples of repair are components of heavy coal trucks by the same company, [And2002].

In sheet metal forming especial in deep drawing tools are made of high grade nodular cast iron, materials that has a good impact and wear resistance, but it is difficult to cast without inclusions or porosity. Also the machinability can be improved. An application of laser cladding in this area is to produce tools of alternative materials like low grade cast iron and apply a laserclad layer as high-grade surface. Masen [Mas2004] has tested several materials and coating in deep drawing experiments. He found a wear reduction better than a factor of three compared to untreated nodular cast iron. The wear was found to be only 4 104 µm3 N-1 m-1, which is the same as what could be obtained with more expensive titanium nitride coatings.

Examples of wear resistant clad layers are given in **Fig. 14.**

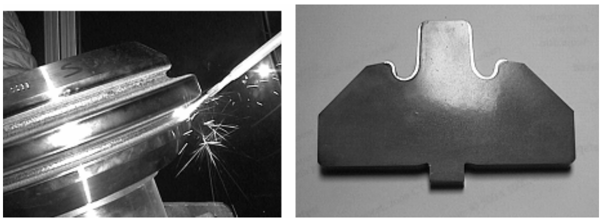

***Fig. 14:*** *Laser cladding tool for sheet metal rolling (Photo courtesy NedClad)*

Another possibility to achieve strong wear resistant layers is taking carbides as powder particles in addition to the conventional cladding powder.

For the hard particles $Cr_3C_2$ – Co powder was taken. This was combined with a NiBSi matrix filler material. This two powder compositions were treated in one process to generate a clad metal matrix composite MMC.

In order to avoid high local changes in the material properties the hard particles concentration was changed during the multi layer process. By this technology a gradient of hard particles concentration pointing perpendicular to the surface was build up. At the surface $Cr_2C_3$ concentrations of 70 vol% were realized [The2003].

*Corrosion resistant layers*

Corrosion resistant layers are applied in marine applications, new as well for repair as well in high temperature applications in industrial furnaces but also in aircraft engines. The regeneration of valve seats can be realized by laser cladding, **Fig. 15**.

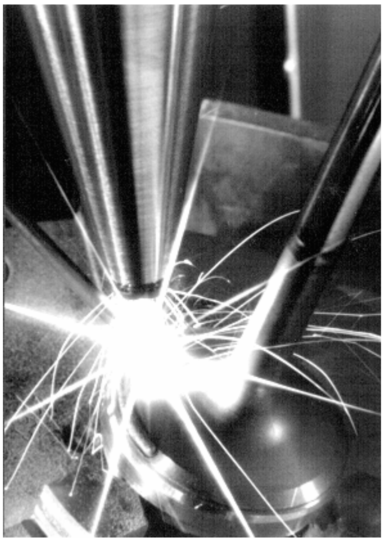

***Fig. 15:*** *Laser cladding of a diesel engine intake valve. (Photo Univ. Twente)*

*Others*

Other applications are found in several domains. An example is the surface texturing of roller mills for the transportation of cow skin for collagen extraction in difficult environmental conditions. By the application of laser cladding several 100,000 tracks of hard clad were cladded on the outer surface of the mill to obtain a good track with slippery material. It is expected that more of such application will follow.

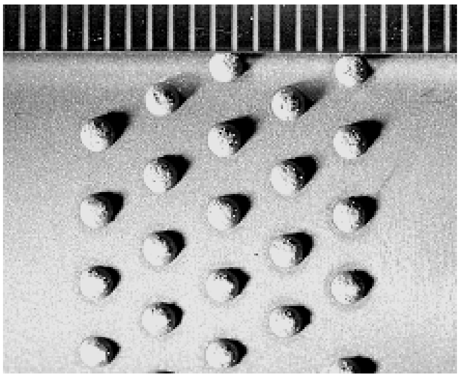

***Fig. 16:*** *Detail of transportation tracks on miller rolls, with a mm scale on top. (Photo courtesy NedClad)*

In the domain of prototyping and tooling the applications cover a wide area from spare parts and dies in the heavy machine industry to small dedicated dental inserts. An example of refurbishment of engine parts is given in **Fig 17**.

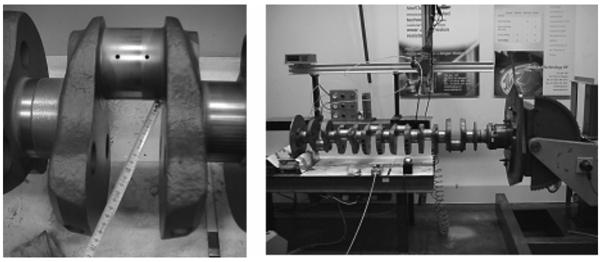

***Fig. 17:*** *Repair of a diesel engine crankshaft (Photo courtesy NedClad)*

Today optimization is still going on in order to make the processing even better. Bremer [Bre2004] has shown a strategy in order to handle the huge amount of parameters and data. A detailed comparison between laser cladding repair welding on aerospace materials and conventional TIG welding was shown by Sexton et al [Sex2002].

## 7 Conclusions

All the laser surface modification techniques have a great potential to cover a large amount of demands on surface properties. Some representative values are given in **Tab. 1**.

***Tab. 1:*** *Overview of surface treatment processes*

| | | **typical values** | | |
|---|---|---|---|---|
| **method** | **laser type** | **treated material** | **average laser power [kW]** | **treated area per time [cm²/min]** |
| **Shock hardening** | Excimer,<br>Nd:YAG,<br>Nd:Glass | aluminium,<br>titanium,<br>steel | 0.04 – 0.16 | 0.3 - 60 |
| **Transform. hardening** | Diode,<br>Nd:YAG,<br>$CO_2$ | heat treatable steel | 0.5 – 5 | 20 - 100 |
| **Remelting** | diode,<br>Nd:YAG,<br>$CO_2$ | aluminium, bronze,<br>steel,<br>cast iron | 0.1 – 5 | 0.5 - 150 |
| **Alloying** | Diode,<br>Nd:YAG,<br>$CO_2$ | aluminium, titanium,<br>steel | 2 - 6 | 10 - 50 |
| **Cladding** | Diode,<br>Nd:YAG,<br>$CO_2$ | aluminium,<br>steel,<br>super alloys | 0.2 - 5 | 1.5 - 50 |

Researchers all over the world are working on optimisation and process development in order to increase the field of applications even more. The computational modelling is very important in this development.

Deeper process understanding and process optimisation e.g. in terms of efficiency and process speed will help to get a wider application in industry for the laser surface treatment technologies.

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