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Laser Surface Transformation Hardening with High-Power Diode Lasers

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***Abstract*—Laser Surface Hardening (LSH) is an advanced technique applicable to a wide range of metals and alloys in modern industrial manufacturing, including the automotive sector. Among the various laser types used for hardening, CO_2, solid-state Nd: YAG, and fibre lasers have traditionally been the most common. However, with the development of high-power diode lasers (HPDLs), these have increasingly gained prominence in this field. In the LSH process, high-intensity laser radiation is focused on a localized area, rapidly heating and hardening the material's surface. The steep temperature gradients resulting from rapid heating and cooling induce structural transformations within the treated area. Additionally, the phase transformation from austenite to martensite occurs without the need for external cooling, simplifying the process. This review paper outlines the fundamental principles of laser hardening and its advantages over conventional hardening techniques. Key process parameters and influencing factors are discussed, along with a comparative analysis of LSH against other hardening methods. Furthermore, an overview of experimental research in this area is provided, with a particular focus on HPDL-based hardening. Various methods for analysing and evaluating laser-treated surfaces are also examined.**

***Keywords*— Austenite, High-Power Diode Laser, Laser surface hardening, Martensite, Phase Transformation.**

I. INTRODUCTION

Since its inception in the 1970s, laser technology has undergone rapid and exponential growth, with several scientific laboratories, researchers and scientists around the world working in this field today [1]. This growth is due to the unique properties of different types of laser sources, which are essential for modern industrial technologies. These properties include coherence, monochromaticity, high energy density in the processing area and a wide range of laser wavelengths, spanning from the ultraviolet to the infrared region of the electromagnetic spectrum. A prerequisite for this diversity is the different active media (gas, liquid, semiconductor and solid materials) for generating laser radiation with different wavelengths, output power levels and applications. The most used lasers in industry are CO_2, Nd: YAG, fibre lasers and diode lasers [1] – [4]. This diversity and these advantages form the basis for various industrial applications of laser technology, including machining, cutting, welding, drilling, ablation and marking/texturing (Fig. 1).

Surface modification methods such as laser texturing, laser hardening and laser cladding have found wide application in mechanical engineering, medical technology, aeronautics and military applications in recent years. It is well known that various techniques are also used by researchers to improve surface properties such as surface

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hardness, wettability, friction and wear resistance for laser surface treatment. With the advent of Industry 4.0, laser hardening technology is expanding and developing in new ways, including the use of artificial intelligence (AI).

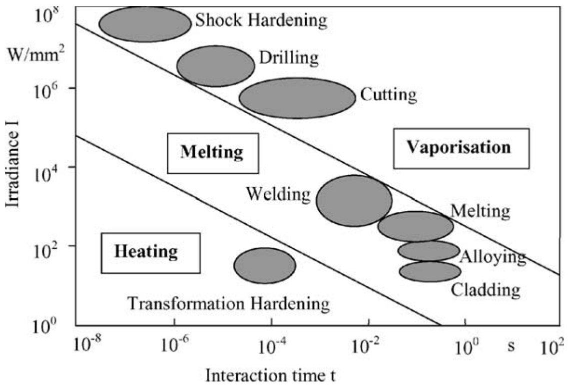

Fig.1. Possible industrial applications of lasers at different interactions of laser radiation with matter [5].

Laser surface hardening, an innovative technology, has become established because the process produces a hardened, wear-resistant outer layer without affecting the desired bulk properties such as toughness and ductility. Compared to other techniques such as induction, arc and flame hardening, the laser hardening process is characterized by short hardening times, easy automation and the ability to harden any part with complex geometry.

Surface hardening is essential for enhancing the performance and functionality of metal products across a wide range of industries. The use of laser technology to modify surface properties has unlocked significant potential for improving mechanical strength, wear resistance, corrosion protection, and even biocompatibility [6].

Recent advancements in laser hardening methods, particularly in surface engineering, have broadened the scope of applications. These innovations have yielded remarkable practical results and paved the way for exciting new possibilities in industrial and technological applications [7] – [13].

Modern high-power semiconductor lasers, due to their unique characteristics such as small size, high efficiency, are today an important factor in surface hardening technology. Laser hardening technology is increasingly being adopted in various industrial sectors including automotive, aerospace, defence and renewable energy systems such as wind turbines, etc. [14] [15].

The stable and successful development of laser surface treatments, including laser hardening, is based on several key advantages they offer compared to conventional technologies [16] – [22]:

- Precise temporal and spatial distribution of directed electromagnetic (laser) energy in the processing area.
- Energy-efficient and material-efficient processes.
- Flexibility to control and manage processing parameters - such as laser power, beam size, and laser scanning speed - to achieve the desired surface and subsurface characteristics.
- High-speed processing and high productivity.
- Minimal heat-affected area (HAZ) and distortion.
- Capability to achieve unique surface properties and a fine microstructure in depth.
- Environmentally friendly, green technology.

II. MATERIALS AND METHODS

Laser hardening is a surface treatment process in which a moving laser beam rapidly heats the laser-affected area above the critical solid-state transformation temperature but below the melting temperature, where the ferrite-to-austenite phase transformation occurs. As illustrated in Fig. 2, the material adjacent to the laser absorption area acts as a heat sink, rapidly cooling the surface through thermal conduction. This effect enables self-hardening, facilitating the transformation of austenite into martensite. As a result, the laser hardening process creates hard, wear-resistant regions on the metal surface while preserving mechanical properties such as strength and ductility [23] – [24].

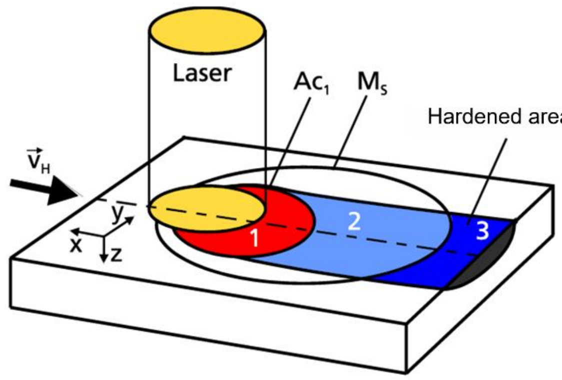

Fig.2. Principle scheme of laser hardening: V_H - the speed at which the laser beam moves; area (1) austenite structure; area (2) - austenite is supercooled; area (3) martensitic structure formation.

Austenite forms from an aggregate structure of pearlite-ferrite in hypoeutectoid steel or pearlite-cementite in hypereutectoid steel. During the heating phase, the body-cantered cubic (BCC) structure of α-iron transforms into the face-cantered cubic (FCC) structure of *γ*-iron.

In equilibrium transformation, austenite begins to form at temperature Ac_1 (723°C) in carbon steel and completes at the Ac_3 line (A_{CM}), as shown in Fig. 3 [25]. Due to the high heating rate in laser hardening, the transformation curve may shift significantly from the equilibrium state, causing the Ac_3 line to move toward higher temperatures. To achieve sufficient homogenization of austenite above the Ac_3 (A_{CM}) temperature, process parameters are typically adjusted to attain high peak temperatures. However, since a short thermal cycle can lead to insufficient carbon diffusion, the degree of carbon homogenization in the parent material significantly affects the carbon distribution within the martensite and the resulting hardness profile [26].

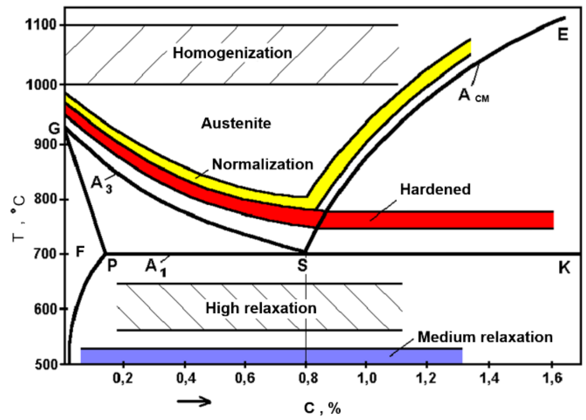

Fig.3.Diagram of surface hardening of steel [25]

Martensitic structure formation occurs exclusively through rapid cooling of austenite, necessitating that the material reaches the austenitization temperature during the heating phase. The thermal cycle in laser surface hardening is much shorter than in bulk hardening, as heating to the austenitization temperature takes place within fractions of a second. Consequently, the heated area must remain above the austenitization temperature long enough for carbon diffusion and austenite homogenization to occur, while ensuring that the surface temperature stays below the material's melting point [27].

Characteristics of HPDLs

The properties of modern high-power diode lasers (HPDLs) make them particularly suitable for use in the technological hardening process. This is due to the following characteristics that this type of lasers has Fig. 4.

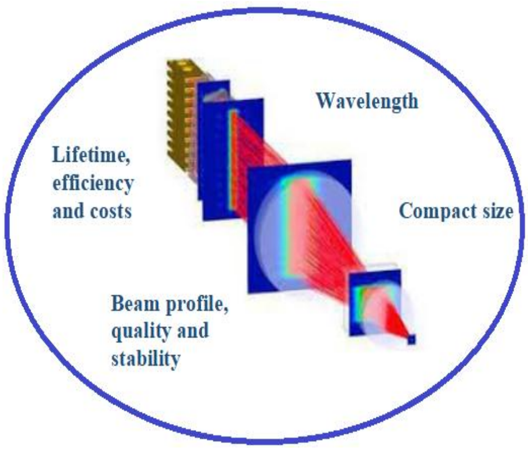

Fig.4. Specific properties of high-power diode lasers (HPDLs) that make them useful for the laser hardening process.

The wavelength λ of the laser radiation generated by most industrial HPDLs is between 800 and 940 nm. These wavelengths λ for most lasers in this range have a lower reflectivity than the surface of the processed metals (see. Fig. 5) Due to their shorter wavelength λ, this type of lasers has a significantly higher degree of absorption already at the start of the laser interaction with the substance.

For example, comparisons of HPDL λ = 800 nm with CO2 lasers λ = 10.6 µm and Nd: YAG lasers λ = 1.06 µm show a significantly higher absorption rate of approximately 1.2 – 13 % when processing various metals [29].

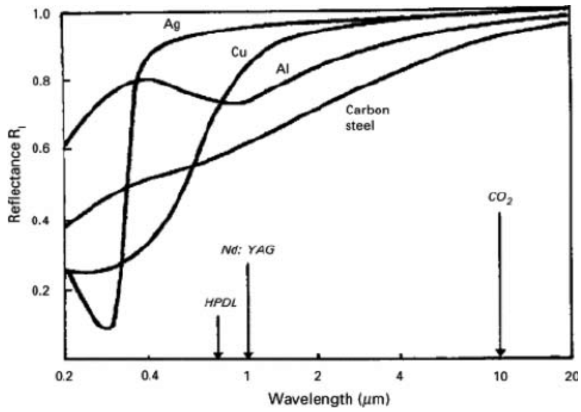

Fig.5. Reflectivity as a function of wavelength for various materials.[28].

According to analyses by World Star Tech - industry-leading laser, the typical laser diode lifetime is between 25,000 and 50,000 operating hours, which is a good indicator of an industrial laser system. The maintenance and operating costs of HPDL are also less than those of competing laser types.

According to analyses by World Star Tech, a leading laser manufacturer, the typical diode life is between 25,000 and 50,000 operating hours, which is a good indicator for an industrial laser system. The maintenance and operating costs of HPDLs are also lower than those of CO_2 and Nd: YAG lasers. While for these lasers the maintenance period varies between 1000 and 200 hours, HPDLs are virtually maintenance-free [30].

The diode laser is the most efficient of all laser types, its typical electrical to optical efficiency is 50 – 65 %, as compared to 10 – 15 % for CO_2, 4 – 5 % for Nd: YAG (arc-pumped) lasers, and 13 – 15 % for Nd: YAG diode-pumped lasers [31] – [33]. The capital costs of HPDLs are also currently lower than CO_2 and Nd: YAG lasers of equivalent power (see Fig. 6).

Due to the nature of the design and their compact size**,** HPDLs can be relatively easily integrated into conventional machining centres or on robot arms. This is mainly due to the reduced cooling requirements of diode lasers compared to other types of lasers, i.e. HPDLs are significantly more compact than CO_2 and Nd: YAG lasers [30].

The beam profile of an HPDL is typically a rectangular spot due to the nature of the beam and the laser generation process. The typical beam quality of, for example, a 4 kW high-power diode laser (HPDL) when collimated with fibres is about 20 – 30 mm/mrad. HPDLs with specialized beam shaping optics can reach 4 – 10 mm/mrad, but this comes at the expense of a higher cost. One of the main differences between HPDL systems and other laser sources is the number of laser beams generated at the output. In CO_2

and Nd: YAG active medium laser systems, only one beam is generated at the output. In this type of laser, small variations in the excitation time of the laser active medium lead to intensity fluctuations, visible as uneven peaks in the beam profile. In the HPDL system, we have many superimposed laser beams, which compensates for fluctuations in the individual beams, giving the combined beam exceptional modal stability [34].

III. FACTORS INFLUENCING THE PROCESS

The production of a martensitic structure requires a temperature-dependent transformation of the crystal structure of the steel, which redistributes the carbon content during the thermal cycle. Since martensite is obtained exclusively by rapid cooling of austenite, the austenitization temperature must be reached already in the heating phase. The thermal cycle in laser surface hardening is much shorter than that of bulk hardening, heating to the austenitization temperature occurs in fractions of a second. A specific feature here is that the heated area must be maintained above the austenitization temperature for a relatively long enough period to allow carbon diffusion and homogenization of the austenite. The heated surface must be maintained below the melting point of the material [23], [27].

The realization of this extremely complex process depends on the interrelationship between three groups of factors shown in Fig. 6. The factors related to the laser source, the technological process, and the optical and thermophysical properties of the material as a function of the temperature and wavelength of the laser radiation.

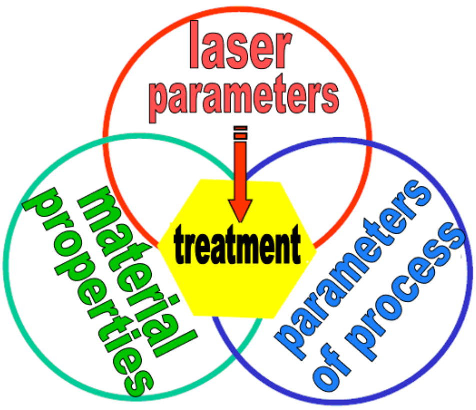

Fig.6. The factors influencing the process of transformation hardening under laser treatment.

A. Wavelength

Fig. 5 provides a clear comparison of the absorption characteristics of different metals as a function of wavelength. The graph shows that CO_2 laser treatment ($\lambda = 10.6$ μm) has relatively low efficiency, with absorption rates of approximately 2 – 5 %. To mitigate this limitation during hardening, a special coating is often applied to the surface before treatment to enhance laser energy absorption [35], [36].

B. Laser Power and Laser Power Density

Studies have shown that the laser power required for surface hardening varies from a few watts to several kilowatts, depending on the material type and processing speed. The laser power density used in hardening typically ranges from 10^3 to 10^5 W/cm² [37], which is relatively low compared to other laser-based processing techniques (see Fig. 7).

For steels with high hardenability, a lower laser power density combined with a longer interaction time is recommended to achieve a uniform hardened layer with significant depth. In contrast, for steels with low hardenability, a higher laser power density and shorter interaction time are preferred to ensure the rapid cooling necessary for martensite formation, albeit at the cost of a shallower hardened layer [38], [39].

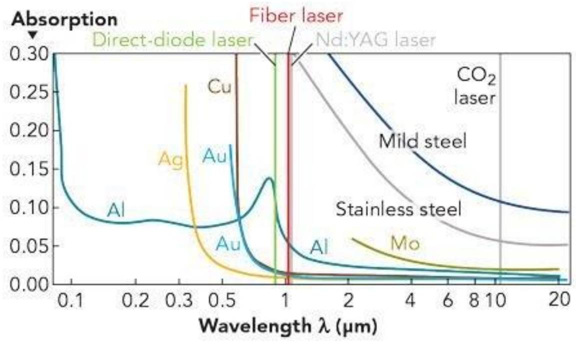

Fig.7. Radiation of laser absorbed varies the wavelength for different metals [40].

C. Different Laser Beam Geometry and Power distribution

Distribution The shape of the heated area in the material usually resembles the function of the intensity distribution in the cross section after the exit of the focusing optics. For example, if the power distribution is Gaussian, then such an effect usually creates a hemispherical hardened area in the material. When working with a rectangular laser beam formed by the optics, a uniform power distribution is created on the surface of the material, and the hardened section also has a rectangular shape with rounded edges. For a given power density and traverse speed, there is an optimal range of beam widths that can produce a large, hardened width without surface melting [41].

A variety of optical solutions can be used to meet specific customized requirements in the practice of laser hardening. Many engineering solutions in design use rotationally symmetric laser beams, which are created by defocusing optics. Shaping optics are also used to provide various shapes of hardened sections with desired high coverage levels (see Fig. 8)

The aspect ratio (ratio of width to length) can be varied to obtain the desired thermal cycle and cross-sectional geometry. A high aspect ratio results in a fast thermal cycle and a wide hardened track. Uniform power distribution across the beam profile includes maximum depth of hardening, depth uniformity, and degree of coverage. Ring and Gaussian beam profiles minimize distortion, but the latter can cause melting in the centre.

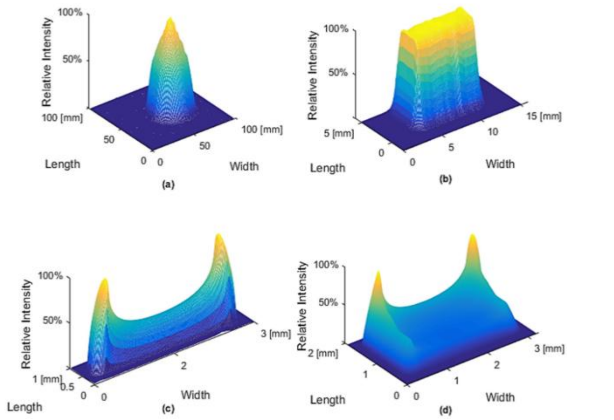

Fig. 8. For laser hardening, four intensity profiles are commonly used. The defocused round top-hat profile (a); the rectangular top-hat profile (b); the intensity profile generated by a harmonic oscillation of a scanning mirror (c) as well as the optimized intensity profile which was calculated by Burger [42].

The optimal power distribution across the heating pattern should include a leading edge with high power density, with power decreasing toward the trailing edge. This is beneficial to the hardening process because it provides a thermal cycle with sufficient time for microstructural homogenization, while also providing a cooling rate high enough to form martensite. This model also minimizes the energy required per unit volume of hardened section [43], [44].

D. Process Parameters in Laser Hardening

a) PROCESS SPEED: The laser irradiation time is inversely proportional to the speed of travel over the material surface. A laser power density in the range of 10^3–10^5 W/cm², with a typical interaction time of 0.1–0.3 seconds, can produce a martensite structure in steel. The speed is a critical parameter that is finely adjusted to achieve the desired hardening depth and homogeneity of the treated surface. Knowing the laser spot diameter and the travel speed, the interaction time can be easily calculated. Additionally, by understanding the power density and exposure time, the hardening process can be accurately modelled and optimized [45].

b) PROCESS GAS: During laser hardening, surface oxidation can significantly increase the absorption of laser energy. This effect was observed by the authors [46] when comparing the hardening of steel in argon and air. Argon and nitrogen are commonly used as process gases. The gas is typically directed at the material surface at a flow rate of approximately 20 L/min through either a coaxial or external nozzle [36], [37]. The process gas serves two primary functions in laser transformation hardening:

- Protection against oxidation – Prevents excessive absorption, which could lead to overheating or melting.
- Optical system protection – Shields the laser optics from contamination during processing.

IV. Results and Discussion

Analysis of laser hardened area is essential for assessing the efficiency and overall effectiveness of the technological process. By studying the microstructural and tribological properties of engineered surfaces, valuable insights can be obtained into the relationship between structural and functional [47]. These insights inform solutions aimed at optimizing the laser hardening process. This section highlights the main characterization methods used to evaluate this innovative technology and allows for comparison with conventional techniques (Fig. 9 and Fig. 10).

A. Micro-structural analysis

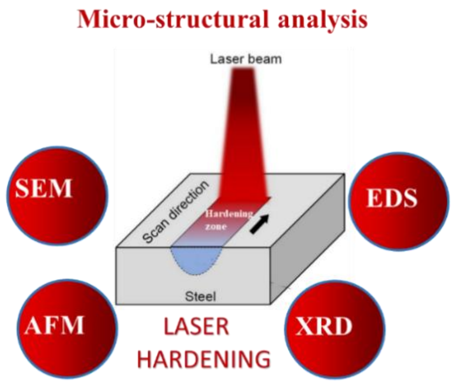

Fig. 9. Different methods for micro-structural analysis of laser transformation hardened area.

Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS) Analysis

Scanning electron microscopy (SEM) is a widely used technique for surface microstructural analysis, offering high-resolution images that reveal details of grain structures and phase transitions in the hardened area. To further enhance the analysis, energy-dispersive X-ray spectroscopy (EDS) can be integrated with SEM, allowing the investigation of the elemental composition in the laser-treated surface. This powerful combination provides a comprehensive set of tools for in-depth analysis of laser-treated area. SEM provides important morphological information, helping to understand the relationship between microstructure and material properties. EDS complements this by identifying and quantifying the elemental composition, which is particularly valuable for optimizing post-laser cooling processes in the treatment area. Together, these techniques provide a holistic understanding of the morphology, composition, and overall characteristics of samples after laser treatment, offering insights that are essential for refining and optimizing the laser hardening process [48].

X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) is a vital tool for analysing the phase composition and crystallographic structure of the laser-treated area. By examining the diffraction patterns produced by X-ray radiation, detailed insights into the crystal lattice and atomic arrangement within the treated surface are obtained. XRD enables the identification of phases present in surface-modified layers and provides an evaluation of their structural characteristics.

Through XRD analysis, the crystal structures in the laser-treated area and their relative proportions can be determined. By comparing the diffraction patterns with established crystallographic databases, the specific phases formed during the laser treatment process are identified. Additionally, XRD offers valuable information on structural defects, residual stress, and the quality of crystal growth in the laser-hardened area.

This data is essential for understanding the relationship between surface structure and physical properties, providing a foundation for optimizing the laser surface hardening process to achieve enhanced material performance [49].

Atomic Force Microscopy Analysis

Atomic Force Microscopy (AFM) is a powerful tool for analysing surface topography at the nanoscale. It operates by using a sharp probe that scans the surface and measures the forces between the probe tip and the sample, generating high-resolution topographic images. This methodology is particularly effective in quantifying changes in surface characteristics, such as roughness, following laser processing.

Complementary modes of Atomic Force Microscopy, such as Kelvin Probe Force Microscopy (SKPM) and Magnetic Force Microscopy (MFM), can also be employed. These modes provide additional information about surface potential and magnetic properties, respectively. AFM is widely used in various fields of scientific research and industry. By measuring surface characteristics at the nanoscale, it offers essential insights into material surface properties, helps assess quality, and ultimately contributes to optimizing processes like laser hardening [50] – [52].

B. Analyses of mechanical and tribological characteristics

Surface profilometry

It plays a crucial role in various industries, including automotive, aerospace, and microelectronics, specifically roughness measurement. It is effectively applied in scenarios where precise control of surface properties is essential. Surface profilometry is a technique used to measure surface roughness and evaluate variations in the height of a sample. Most devices employ either a stylus or optical methods (often using a laser beam) to scan the surface and record the profile.

This technique provides quantitative data on parameters such as average roughness (*Ra*), maximum height (*Rz*), and area roughness (*Rq*). Surface profilometry is widely utilized for surface quality control and the optimization of various processes in surface engineering, including laser hardening [54] – [55].

Hardness testing

Several common hardness tests are used in practice, all of which measure the resistance of a material to indentation or penetration. These include the Rockwell hardness test, the Vickers hardness test, and the Brinell hardness test, each employing specific techniques to measure indentation and determine the material's hardness.

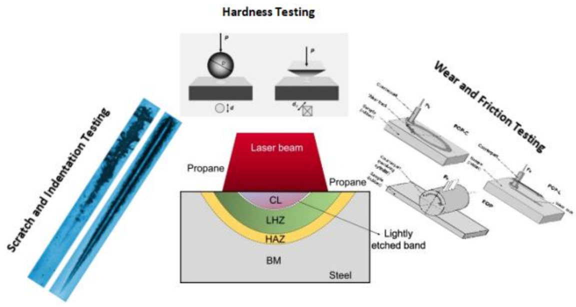

Fig. 10. Types of methods for mechanical and tribological analysis of laser hardened area

The information obtained from these measurements is particularly important in laser surface hardening, as it aids in optimizing the process's technological parameters. This ensures the desired wear resistance and durability of components subjected to mechanical stress [56] – [58].

Scratch and indentation testing

Measurements obtained through scratch and indentation testing of laser-hardened surfaces help evaluate a material's ability to resist wear, withstand mechanical stress, and maintain its functional properties. These tests can determine critical properties such as hardness, modulus of elasticity, bond strength, and resistance to deformation. The data gathered provides valuable insight into the mechanical integrity and performance of the laser-hardening process [59].

Wear and friction testing

To evaluate the tribological performance of surface-engineered areas after laser surface hardening, it is essential to conduct wear and friction tests. Techniques such as pin-on-disk, ball-on-disk, and reciprocating sliding tests are commonly used to simulate contact and sliding conditions under real-world scenarios. These tests provide valuable information on parameters such as wear rate, friction coefficient, and surface resistance. Wear and friction testing allows researchers to assess the performance and durability of surface-engineered materials under various operating conditions. By quantifying wear rate, friction coefficient, and surface damage, these tests facilitate comparative analysis of different laser processing techniques and surface modifications. This, in turn, helps optimize the laser hardening process, achieving the desired engineering outcomes of enhanced wear resistance, reduced friction, and extended surface life [60] – [62].

V. CONCLUSIONS

1. Laser Surface Transformation Hardening (LSTH), particularly when implemented with High-Power Diode Lasers (HPDLs), has proven to be a transformative technique in modern materials engineering. The study

highlights the significant advantages HPDLs offer over traditional hardening technologies, including precise energy control, minimal thermal distortion, high processing speed, and energy efficiency. These attributes not only improve the surface hardness and wear resistance of treated components but also maintain the base material's toughness and ductility—an essential factor in sectors such as automotive, aerospace, and heavy engineering.

2. The experimental and analytical evaluations discussed in this review affirm that HPDLs are highly suitable for the treatment of 42CrMo4 steel and similar alloys. The results show that appropriate tuning of process parameters such as laser power density, beam profile, and traverse speed can result in a uniform martensitic layer with excellent mechanical properties and microstructural uniformity.

3. Additionally, the integration of advanced characterization techniques—including SEM/EDS, XRD, AFM, and various tribological tests—has enabled a deeper understanding of the process–structure–property relationships in laser-hardened surfaces. These methods not only confirm the microstructural transformations but also support optimization efforts for industrial-scale implementation.

4. Overall, this research reinforces the value of HPDLs as a practical and sustainable solution for surface engineering in high-performance applications. Future directions may include further automation, the use of AI for process monitoring, and expansion into dual-use technologies where structural durability and multifunctionality are paramount.

VI. ACKNOWLEDGMENTS

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