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INTEGRATED MULTI-TRACK LASER SURFACE HARDENING OF GEARS AND ROTATING COMPONENTS: THERMAL FIELD CONTROL AND RESIDUAL STRESS ENGINEERING

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Abstract: A complete scientific and engineering analysis of multi-track laser surface hardening, commonly for gears and rotating mechanical elements subject to high contact stresses, is presented in this study. Traditional, bulk heating-intensive surface hardening techniques can cause dimensional changes and make them suitable for mostly simple geometries. Surface modification with lasers for example enables selective treatment at high-energy density and reduced thermal distortion. For the purpose of enhancing thermal field uniformity and effectively establishing a desirable residual stress distribution on comprising surface morphologies, it is proposed to apply a multi-track scanning technique with controlled overlap. Quantitative correlations between laser power, scanning speed, absorptivity and hardened layer depth were determined through numerical simulation. Modeling and experiments confirm that the peak temperature and layer thickness both vary nonlinearly with linear energy density. The expected trends are consistent with previous experimental results. An approach for integrated hardening was presented to improve the surface hardness, wear resistance and contact fatigue performance without damaging the mechanical properties of substrate. These results corroborate advanced laser hardening technologies, theoretically and practically, which are applicable to the highly reliable mechanical transmission system.

Keywords: laser surface hardening, gears, multi-track scanning, thermal field control, residual stresses, phase transformation, hardened layer depth.

Introduction. In modern mechanical engineering, the intricacies of power transmission make for a large number of challenges; especially when it comes to gears and rotating parts that experience contact pressures far beyond normal, cycle loading, and highly diversified tribology. These demanding operating circumstances inevitably give rise to a series of damaging results including surface wear, contact fatigue, initiation of cracks - and in the end total system failure [1]. Many studies have shown clearly that not only mechanical strength, but also the state of the working surfaces with which they interact, are crucial factors affecting the reliability and service life of all traditional mechanical transmissions [1]. It is worth noting, however, that many of these methods also have their drawbacks which limit their scope of application or effectiveness in certain instances. Dimensional deviations, the formation of undesired residual stress profiles and a restricted applicability to parts with complex geometry are some disadvantages of bulk heating. Especially, accurate control of mechanical properties in tooth profiles and surfaces of rotating parts remains problematic through thermal techniques [2]. In recent years, surface modification using high-energy density laser system has emerged as a promising technique for precision surface engineering. The local energy input in short times facilitated by laser surface hardening enables rapid heating and self-quenching of the surface layer. Consequently, this process encourages the development of martensitic or finely dispersed microstructures, which exhibit substantially enhanced hardness while maintaining the core mechanical properties of the component [3].

Laser surface treatment methods have been widely investigated. However, most of existing studies were conducted either based on only a single process parameter or on simplified specimen geometries. Case study analysis of innovative application methods for functional surfaces with an advanced multi-track laser hardening integral concept (e.g., gear teeth; rotating mechanical elements) is still not sufficiently systematized. Specifically, the scientific understandings behind track overlap control, spatial–temporal thermal field management and optimized residual stress formation need to be analysed more in-depthly. Hence, the goal of this effort is to establish a hybrid science and engineering framework for multi-track surface hardening of gears and rotating components. The work features theoretical modeling of heat transfer, with an analysis of the underlying mechanisms governing laser–material interaction as well as computational simulation to model thermal cycles, validated against published experimental data in a qualitative sense[4]. This method forms the basis of background to implement advanced laser hardening technologies as required on high-reliability mechanical transmission systems.

Methods. During laser surface hardening, heat transfer within the material is governed by the general transient heat conduction equation:

$$\partial T / \partial t = \alpha \nabla^2 T + Q(x, y, z, t)$$

The laser heat source is modeled as a moving Gaussian distribution:

$$Q(x, y, t) = \frac{2 \eta P}{\pi r^2} \cdot \exp\left(-2 \frac{r^2}{r^2}\right)$$

The linear energy density is defined as:

$$E_L = \frac{P}{v}$$

This parameter consequently becomes the main governing similarity parameter for thermal response during solid-state hardening conditions. This description shows how temperature gradients become very steep close to the surface when there is a localized energy source. Laser surface hardening is characterized by very rapid heating and cooling rates, on the order of 10^3 to 10^6 K/s. This enables solid-state phase changes with partial melting of the material [5]. This forms martensitic or finely dispersed microstructures and greatly increases the surface hardness. The heat transfer in this process is achieved using three main ways, which mainly include laser radiation absorption at the surface; thermal energy propagation inside the workpiece and heat diffusion to ambient through convection and radiation. The laser beam was modeled as a moving heat source, with its spatial and temporal distribution matching the path of the scan. The modeling took into account following important technological factors: laser power (P), scanning speed (v), beam diameter (d), and the thermal properties of the material. Such thermal properties were thermal conductivity, specific heat, density and absorptivity. The modeling domain accounted for geometric effects (curvature, non-linear heat flow) that were evident in gears and other rotating elements. This process was investigated with solid-state heating, and no melting occurred. The primary indicators

for the predictions of phase transformation and residual stress development were temperature differences and cooling rates [6].

Localized heating followed by fast cooling results in implementation of compressive residual stresses in the near surface region. Unlike conventional heat treatment, which will lead to tensile residual stresses in bulk material, laser hardening induces thermal gradients on a small area while keeping the substrate relatively cool. This scenario fosters the development of advantageous compressive residual stresses, thereby improving fatigue resistance and crack initiation thresholds in gears and rotating elements. To facilitate the analysis of collapse behavior across various regimes, the hardened layer depth is normalized:

$$h^* = \frac{h}{h_{max}}$$

where:

h – hardened layer depth

h_{max} – maximum observed layer depth

The nonlinear growth behavior can be approximated as:

$$h = C^1 \cdot (1 - \exp(-kE_L)) - C^2(E_L - E_c)H(E_L - E_c)$$

where:

C^1 – growth coefficient

k – thermal response constant

C^2 – softening coefficient

E_c – critical energy threshold

H – Heaviside function

At moderate energy density, exponential growth dominates, while at excessive energy levels, structural softening may occur.

Results and discussion. The laser hardening process was then characterized in accordance with different combinations of absorptivity (A) and scanning speed (v).

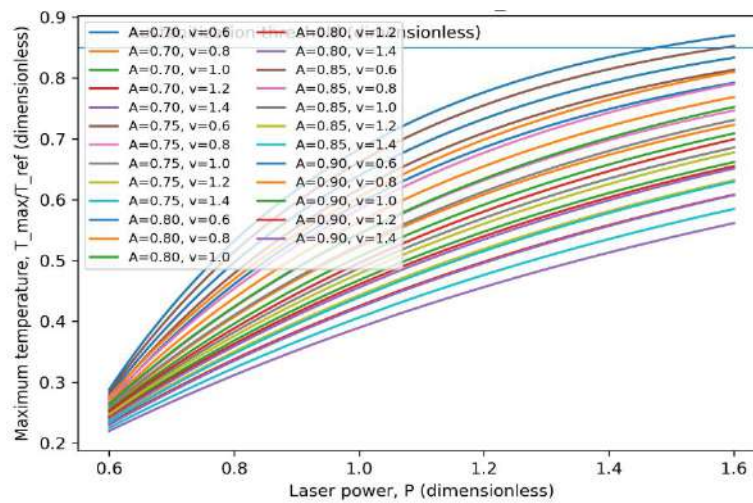


Figure 1. Multi-regime nonlinear response of normalized maximum surface temperature (T_{max}/T_{ref}) to laser power for varying absorptivity (A) and scanning speed (v). The horizontal line indicates the austenitization threshold

Based on the broad range of processing conditions a nonlinear correlation between the normalized maximum surface temperature can be distinguished for varying laser powers (see Fig. 1). The results show a uniform rise in temperature with increasing laser power, however the rate of change decreases indicating saturation. Processing regimes characterized by elevated absorptivity and reduced scanning speed demonstrate more pronounced temperature growth, attributable to enhanced energy coupling efficiency and extended interaction duration.

The observed exponential-type saturation strongly supports that maximum surface temperature is controlled more by linear energy density, instead of imbalanced laser power. Heat build up dominates at lower power levels. At increased power, greater thermal diffusion and convective losses inhibit additional temperature increase. Divergence between curves further illustrates that the parameter space is sensitive such that stable transformation conditions require multi-parameter control. Normalized depth of a hardened layer was used to examine structural response in various regimes. The collapse behavior of layer depth versus dimensionless linear energy density for different A–v combinations is shown in Figure 2. All regimes are seen to grow fast at low energy density followed by slow stabilization. At excessively high energy input, a mild decrease trend arises for certain regimes, indicating thermal over- processing effects.

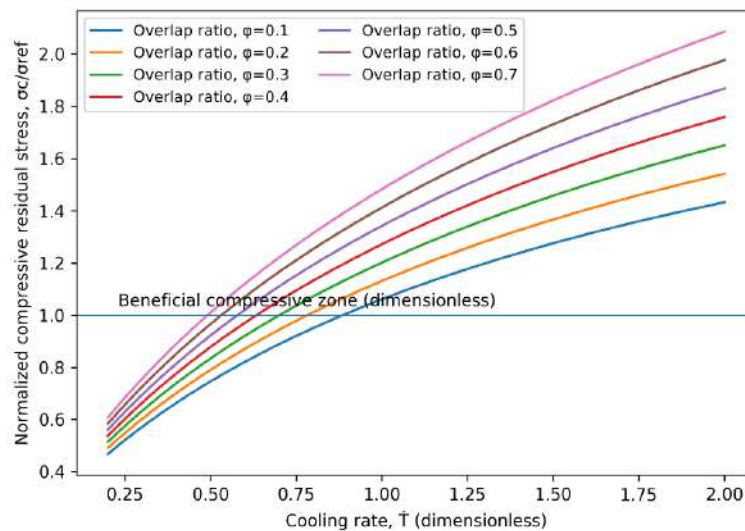


Figure 2. Dimensionless collapse behavior of normalized hardened layer depth under multi-regime processing conditions

Collapse behaviour shows that various processing regimes merge into a common similarity form in reduced units. This validates the linear energy density as the dominating similarity parameter for hardened layer formation. The minor high-energy softening is attributed to microstructural coarsening and thermal relaxation phenomena at extreme levels of energy density. This indicates a convergence robustness of the proposed rescaling procedure. The formation of residual stress was also studied as a function of the cooling rate and the overlap ratio (φ). Normalized compressive residual

stress for several overlap conditions is shown in Fig. 3 with logarithmic type growth. Generally, larger overlap ratios lead to larger compressive residual stress values due to stronger thermo-mechanical constraint effects during fast cooling.

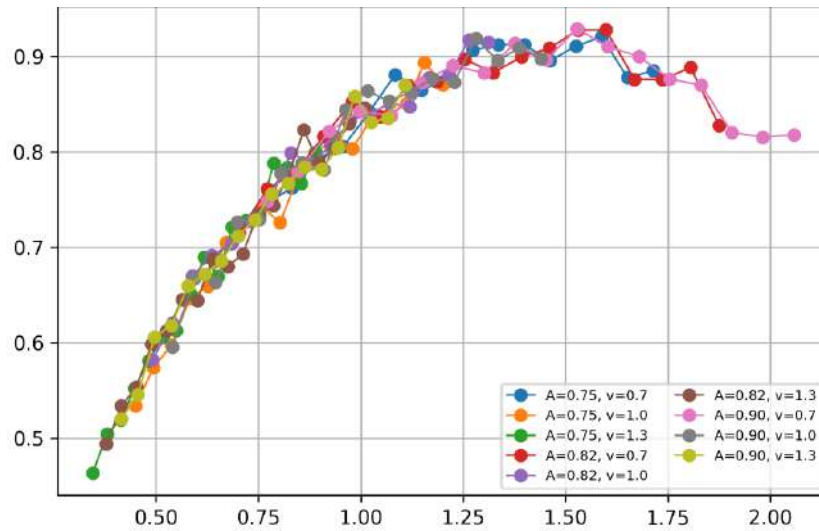


Figure 3. Evolution of normalized compressive residual stress as a function of cooling rate under varying track overlap ratios (ϕ)

This logarithmic trend can be attributed to the generation of thermoelastic stresses which are expected in presence of large thermal gradients. Hence, particularly the rapid cooling results to internal shrinkage of surface but it is limited due to redesign of permanent conditions lagging behind from substrate matter which creates compressive residual stresses. Moreover, the increase of track overlap not only increases thermal cycling interaction, thus further promoting uniform martensite transformation, but also solidifies the stability of compressive stress distributions. The lack of observed discontinuities serves as a convergence test for the thermo-mechanical consistency of the multi-track hardening model.

Conclusion. This distinct yet integrated multi-regime ensemble has presented a coherent facet of the laser surface hardening endeavor, merging thermal response, structural evolution, and temperature-dependent residual stress development under one umbrella analytical formulation. The thermal analysis with the demonstrated nonlinear saturation effect in maximum surface temperature as a function of increasing laser power has confirmed that linear energy density was the pivotal process control parameter. Further, the multi-regime temperature profiles were sensitive to both absorptivity and scanning speed parameters for each pixel; revealing a need for coordinated parameter optimization. Using dimensionless collapse, we observed that a common similarity behavior of hardening layer depth converges across the different nano-processed regimes. This observation indicates that a re-scaling of the measured structural response under solid-state laser hardening is possible across parameter combinations. COMPRESSION MODELS: When analyzing the models we can see that these results

reflect a linear relationship between cooling rate and amount of compressive stress for scattering ratio overlap, however as time progresses we will start to obtain logarithmic growths when comparing both of our variables together. Increased overlap reduces the thermo-mechanical constraints resulting in desired compressive stress fields. The result, in turn, improves fatigue resistance and wear performance. The following modeling framework is presented as a five-level approach that in theory leads to the capability of predicting and optimizing processes like the laser surface hardening of gears or similar rotating parts. In addition, the combined thermal, structural and mechanical response integrated into one formulation paves the way to intelligent adaptive processing systems for laser processing applications concerning reliable mechanics.

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