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# Investigation into the efficiency of a fiber laser in surface hardening of ICD-5 tool steel

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ABSTRACT

Surface transformation hardening is a vital final step in the manufacture of stamping and forming dies. An important requirement for the hardening process is minimizing the injection of heat into the precision machined component. The objective of this study is to find the parameters that govern the efficiency of utilizing a 500 W fiber laser for hardening of ICD-5 tool steel. It is shown that the heating part of the thermal cycle and complete dissolution of carbides in austenite has the controlling effect on the resultant microstructure and hardness. The surface hardness can be affected by as much as 100 HVN with increase in the power density or decrease in the travel speed. Hardening efficiency index (HEI) is defined for describing the efficiency of the process in terms of the average hardness increase times the volume of surface metal hardened over the incident laser energy per unit length scanned ($\Delta$HV.mm$^3$/J). It is established that square of laser power density over travel speed governs the hardening efficiency index. Thus, for control purposes, changes in the laser power density can be regulated with laser travel speed. It is also shown that surface hardening efficiency has a linear relationship with the ratio of the case width to the laser spot width at the component surface.



## 1. Introduction

Laser surface hardening can be considered as a relatively recent advancement, replacing more traditional processes such as flame hardening and induction hardening. Surface hardening is generally performed after machining of large molds/tools and in this regard a potential advantage of laser is the need for less heat injection into the component, which not only makes forced cooling unnecessary but also can decrease the risk of dimensional change in the precision machined component. Laser sources are rated by the power they deliver and distortion of the component is affected by the laser energy injected per unit area of the component hardened. Thus, in laser hardening it is important to optimize the process parameters including power density and travel speed, in order to use the laser power in the most efficient way.

Medium carbon low alloy tool steels in the form of castings are widely used for the production of large molds and laser hardening would be an attractive process for surface transformation hardening of such components. The process is based on raising the surface temperature of the material by the incident laser and transformation of the ferrite/pearlite/carbide phases in the cast material to an austenite phase and dissolution of carbides in austenite. By using an appropriate combination of process parameters, a layer at the surface is heated above the effective austenitization temperature but just lower than the melting temperature. Once the laser beam moves over, the heated surface layer is left to transfer its heat through conduction to the cold bulk material. When the component is thick enough and the steel has sufficient hardenability (usually a carbon content over 0.35 wt%) this can result in what is known as self-quenching i.e. a cooling rate higher than the critical cooling rate necessary for transformation of austenite to martensite without outside forced cooling. This method can improve hardness, wear resistance, corrosion resistance and resistance to initiation of fatigue crack at the surface due to local martensite formation which makes it applicable to surface hardening of dies, railroads, turbine blades and other engineering components [1–6].

The laser power density and interaction time at the surface are known as main process parameter which determine the thermal cycle, temperature profile and the case depth of hardening [7]. Thermal cycle in laser transformation hardening is relatively very steep, hence, metallurgical aspects of this process could be different compared to conventional methods. Austenite formation in laser hardening may not be homogenous due to fast transformation process and also limitation of carbon diffusion in solid state

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[1,6,8–10]. The initial state of austenite is of great importance for the development of the final microstructure and its mechanical properties [11]. Sehyeok oh et al [1] introduced effective carbon diffusion temperature (ECDT) and effective cooling time (ECT) to explain the effect of thermal cycle on carbon diffusion in laser transformation hardening and prediction of the hardness profile. Neil S. Bailey et al. [12] presented a model for residual stress in laser transformation hardening of AISI 4145 which predicts a strong compressive residual stresses in the hardened zone due to austenite–martensite transformation. Compressive residual stress delays initiation of fatigue crack which is a positive effect but it can also induce thermal distortion [5,13].

Sehyeok oh et al. [1] elaborated that obtaining the required hardness while minimizing thermal deformation in laser hardening is critical because complex components such as forming die require high dimensional precision. However, it is stated that minimizing thermal distortion while satisfying deformation requirements could be a challenge. Thus, it can be realized that it is highly important to use the laser energy for hardening the surface of such components in the most efficient way.

The term melting efficiency in fusion welding had been the subject of previous studies including laser cladding and laser welding [14,15]. The objective of this study is to investigate the process of laser hardening of ICD-5 tool steel. This material is widely used in fabrication of large molds for stamping and forming of car body parts. A 600 W fiber laser was used to investigate the governing aspects of the hardening process and make an effort to define a parameter describing its efficiency. Such approach is hoped to facilitate controlling the laser hardening process.

## 2. Experimental

Cast ICD-5 tool steel with the composition shown in Table 1 was used for the study. The samples were in fully annealed condition and had a predominantly pearlite microstructure with an average hardness of 340 HVN. This material is applicable to trimming parts of forming dies in the production of car body components. In order to ensure consistency in laser absorption, surface contaminations and oxides were removed by grinding (#600). The size of the test coupons for laser hardening were 50 mm × 100 mm with a thickness of 20 mm.

The laser machine was model YFL-600, a single mode fiber laser (1080 nm, continuous wave) with a maximum power of 600 W and Gaussian beam profile. The minimum spot size of the laser beam was 0.2 mm at the 100 mm focal distance. Fig. 1 illustrates the schematic of the laser transformation hardening process set up used in this study. The laser power was set near the maximum at 500 W and the process variables studied were "laser travel speed" and "laser spot size". The default laser spot size of 4.2 mm was chosen after performing some initial tests using the power of the available fiber laser at 500 W and varying the beam spot size (by changing the defocus distance) and travel speed to establish the tolerance box of the process. The initial test runs mainly included visual examination and surface hardness measurements. The choice was based on achieving the highest level of tolerance on travel speed. This power density provided a useful beam travel speed range of almost 1.5 to 7 mm/s, i.e. not too high to cause melting and at the same time enough to reach the surface temperature required for transformation hardening.

After the initial test runs, in the first set of experiments, beam travel speed was fixed at 5 mm/s, and the effect of power density variation (28–81 W/mm$^2$) was studied by changing the defocus distance from 50 mm to 90 mm which resulted in laser spot diameters from 2.8 mm to 4.7 mm, see Table 2. In the second set of experiments the effect of beam travel speed (from 2.3 to 6.5 mm/s) was studied while the laser spot diameter was kept at 4.2 mm. This was achieved by employing a constant defocus distance of 80 mm. Thus, for the second set of experiments the power density was fixed at 35 W/mm$^2$. This power density in combination the beam travel speed range chosen (1.5–7 mm/s) kept the laser process almost in what was required for transformation hardening for the ICD-5 tool steel.

It should be noted that all experiments were performed at fixed laser power (500 W) and the irradiated zone was shielded coaxial by pure Argon gas at 25 L/min flow. Between the hardening runs, the samples were allowed to cool. As a matter of comparison and

**Table 1**
Chemical composition (wt%) of ICD-5 tool steel investigated for laser hardening.

| | Fe | C | Si | Mn | Cr | Mo | V | Ni | P | S |
|---|---|---|---|---|---|---|---|---|---|---|
| ICD-5 | Bal | 0.57 | 0.9 | 1.0 | 1.0 | 0.4 | 0.3 | 1.1 | 0.02 | 0.02 |

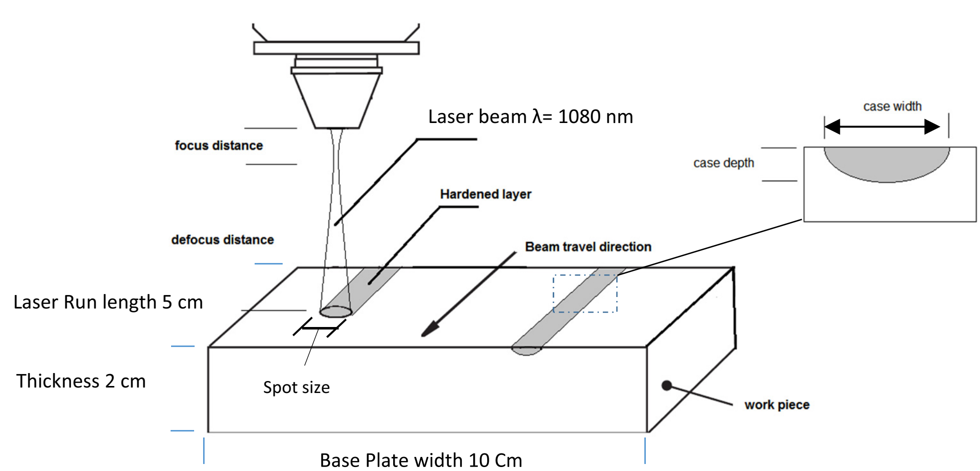


**Fig. 1.** Schematic illustration of laser transformation hardening process and measurement of case dimension.