AN OVERVIEW OF LASER SURFACE MODIFICATION OF DIE STEELS

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ABSTRACT

In recent years, surface modification using advanced heat source like laser has been replacing the conventional methods to produce amorphous microstructure via rapid solidification. Due to the benefits of laser to enhance the tribological and mechanical properties of materials' surface, several laser surface processing were developed including laser surface modification, namely laser alloying, transformation hardening, surface amorphization, shock hardening and glazing. In high temperature applications, the laser surface modification technique is beneficial to prolong the die life cycle, and also to improve the surface roughness of thermal barrier coatings (TBC). To produce the amorphous layer at a particular depth, laser parameter such as irradiance, frequency, and exposure time are controlled. Variations of parameter may result in modified microhardness properties of heat affected zone and transition zone. Nevertheless, works on laser glazing of bearings, railroad rails and TBC had proven the surface properties were enhanced through laser glazing to cope with excessive load, wear, fatigue, bending and friction demand.

KEYWORDS: Laser glazing, pulsed laser, microhardness.

1. LASER SURFACE MODIFICATION

For many years, works have been done to enhance the surface properties of materials in enduring the heat, wear and friction through coating or surface modification. Although various advanced materials with significant properties were developed, nevertheless when it concerns a particular surface engineering application, materials' property is only among the factors to be considered, apart from the practicality, cost and time consumption. For instance, die casting is increasingly operated to produce cast metals due to high surface quality of product, low manufacturing cost, and large quantity production. In spite of these advantages, the major problem lies on the costly dies preparation which includes tool design, material selection, its heat treatment, and casting process parameters, with the aim of maintaining the surface properties and prolongs the life cycle [1,2]. For that reason, using H13 tool steel in dies application would be no avail after thousands of cycles of aluminium castings or maybe shorter period for brass castings.

Due to the rapid advancement in the surface engineering field, conventional techniques for surface treatment like carburizing and flame hardening have been replaced by techniques using advanced heat sources such as plasma, laser, ion, and electron. Currently, high power lasers have become increasingly accepted as tools for many applications from cutting, to surface modification methods. Laser has also been proven to be capable of producing adherent, hard, wear, corrosion, fatigue and fracture resistant coatings on a diverse range of materials [3]. In other words, the crystal structure of metals' surface can actually be modified into very fine non-equilibrium microstructures as a result of rapid solidification (10^6–10^{12} K/s) via laser surface modification [4].

There are several methods of laser surface modification, namely laser alloying, transformation hardening, surface amorphization, shock hardening and glazing. These methods are different in terms of the composition changes on the material's surface and energy absorption rate on the materials and as shown in Figure 1. In comparing to other conventional methods for selective surface hardening, the benefits of laser surface processing technique include fine-grained and homogeneous microstructures, low thermal damage to the underlying substrate, reduced grain growth and distortion, non-equilibrium and amorphous structures; and extension of the solid solubility of alloying elements [4,5,6]. These benefit in turn enhance the tribological and mechanical properties, including hardness, strength, toughness, fatigue, wear and corrosion resistance while the bulk properties remain unaltered [4,5,6].

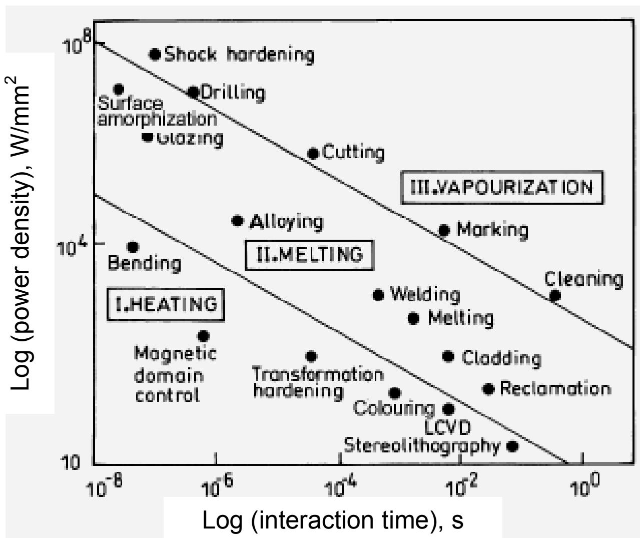

Figure 1: Schematic process map in terms of laser power density as a function of interaction time for different examples of laser material processing [7].

2. DIE STEELS AT HIGH TEMPERATURE

The in-service tool life is affected by thermal fatigue, which causes heat checks on the surface of the die, corrosion and soldering to the die surface, erosion due to melt flow, and catastrophic failures [1,2]. From previous works on hot working tool steel applications, Cr–Mo–V (H11) steel is widely employed in the manufacturing of forming tools for the hot working industry due to its high level of resistance to high temperature properties [8,9,10,11]. Therefore, many kinds of hot work dies, such as in forging, extrusion, and casting dies were produced using H13. The hardness of AISI H13 die steel varies with its application for the different type of dies. AISI H13 hardness recommended is at 43-52 HRC for extrusion dies, at 44-50 HRC for die-casting dies, and at 40-55 HRC for forging dies [12].

In die casting, the chromium-based (e.g. AISI H13) and tungsten-based (e.g. AISI H21) compositions [13] steels can withstand the relatively high working temperatures involved. When the temperature is above 600°C, the dies are easy to wear and collapse, so the die life at high temperature is not long enough [11]. Therefore, despite their good toughness and reasonable hardness obtained as a consequence of the tempering treatment at higher temperatures, these materials need to be surface treated in order to improve their mechanical and tribological properties, as well as their resistance to thermal crack initiation [14]. Various researches indicated laser surface treatment and coating are the effective way to protect die surfaces from thermal fatigue and extend die life by reducing the damage at contact surfaces [4,5]. Due to high temperature and cyclic running, premature failures of die-casting dies used in the metal casting industry occur excessively. These severe conditions will eventually lead to surface damage and die failures in the form of thermal fatigue, heat checking, erosion, stress corrosion, and soldering [4,5,15].

3. RECENT LASER GLAZING APPLICATIONS

In laser glazing, the heat energy from the laser beam is used to alter the properties of surface. Because of the rapid solidification rates, the use of laser-glazing technique is to produce an amorphous state on the surface of specimens under certain conditions [4,16]. Amorphous state is analyzed from the strength of x-ray diffraction (XRD) intensities of the glazed surface. Figure 2 shows the XRD curves of laser glazed surface with broad curve at low angles, which indicates the amorphous phase present in the microstructure [4,16]. Referring to previous work [5], laser glazing has the potential to seal the heat checks formed on the die surfaces and allow relaxation of surface stresses. In improving the plasma-sprayed TBC of gas turbine engines, laser glazed TBC has been revealed to have reduced surface roughness, increased microhardness, sealed porosity, reduced bending modulus of coating and generate a controlled segmented crack network on the coatings [17,18,19].

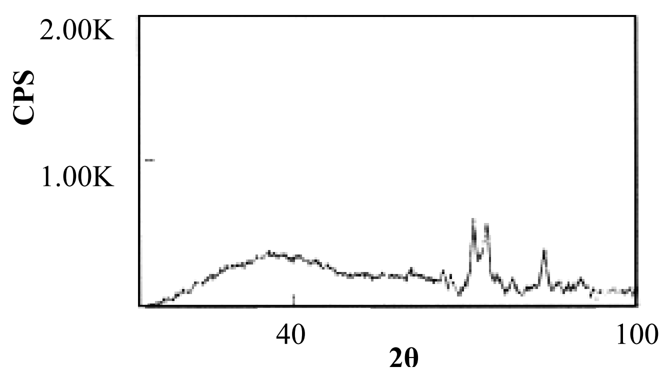

Figure 2: The X-ray diffraction curves of laser glazed specimens of FeCrPC alloy [16].

Other advantage of laser glazing surface treatment is referred to [20] in enhancement of rolling contact fatigue properties of bearings which result in a vast life improvement as much as 470% to 825% compared to the wrought counterparts. Further work on laser glazing is referred to [4] which were implemented in mitigation of the subsurface crack propagation in railroad rails. Though the two latter examples are not significant with the high temperature applications, the laser glazed surface is referred to have the metallic glass properties which are more resistant to fracture than ceramics, high hardness and also provide a combination of metallic high strength with polymer elasticity as shown in Figure 3.

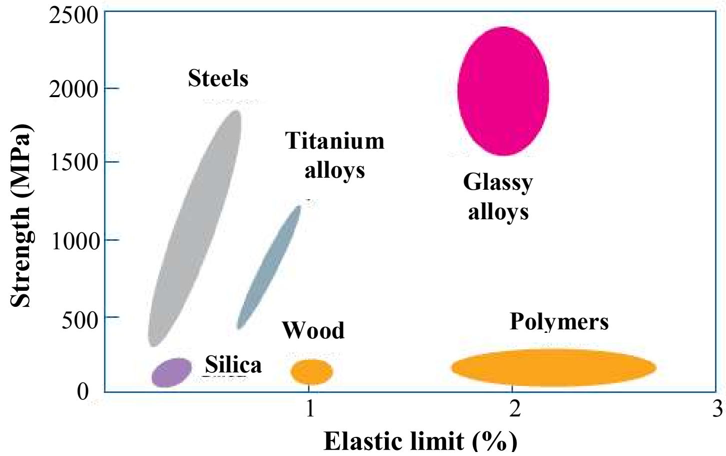

Figure 3: Amorphous metallic alloys combine higher strength than crystalline metal alloys with the elasticity of polymers [21].

4. EFFECTS OF LASER PARAMETERS ON THE SURFACE PROPERTIES

To produce different depths of laser treated layer, the laser processing parameters were varied [22]. Some laser parameters are, laser beam wavelength, temporal pulse power (pulse length, peak power and pulse shape), repetition rate beam energy distribution, and beam geometry (focal spot size, depth of focus) [23]. Both continuous and pulsed wave lasers may be employed for surface modification. Specifically in pulsed laser treated surface, the properties are controlled by several independent laser parameters; pulse energy, pulse width, frequency and scan rate. The pulse energy and interaction time at the surface determine the temperature profile and also increase both width and depth of hardening as shown in Figure 4. The pulse energy determines the average and peak powers. In other words, as the pulse energy increases both the average and peak power increases, increasing the treated zone dimensions. Several variations of parameters from previous works on laser glazing are plotted in Figure 5. Compared to pulse laser spot, the obvious advantage of using continuous laser beam is that amorphous state can be obtained in a continuous process [16]. However, defects, such as porosity, bubbles or depressions, occur easily with a continuous wave laser [24,25]. A high-quality glazed layer is successfully produced using a pulsed laser [25]. The advantages of pulsed mode in laser processing are mainly [23]:

i. temporal limitation in energy coupling into the target, resulting in a very limited depth of heat conduction into it, often resulting in reduced heating of the work piece, and thus in higher quality.
ii. high pulse peak power and thereby high intensity, obtainable, resulting in improved light coupling in some materials, especially metals and thereby enables or improves the processing.

Further consideration in pulsed mode is the frequency of laser which controls the overlapping between laser spots. The overlapping technique with multipass is an effective method to enlarge the amorphous area of laser glazing treatment [16], but the sample surface roughness was also increased with the increase of crack density, as a consequence of the increase of beam scanning speed and overlap [16]. Increasing pulsing frequency would increase the overlapping area as referred to Kumar [26]. By studying the laser process parameters, the morphological defects on laser glazed surface can be avoided and properties such as microhardness, and surface roughness were improved.

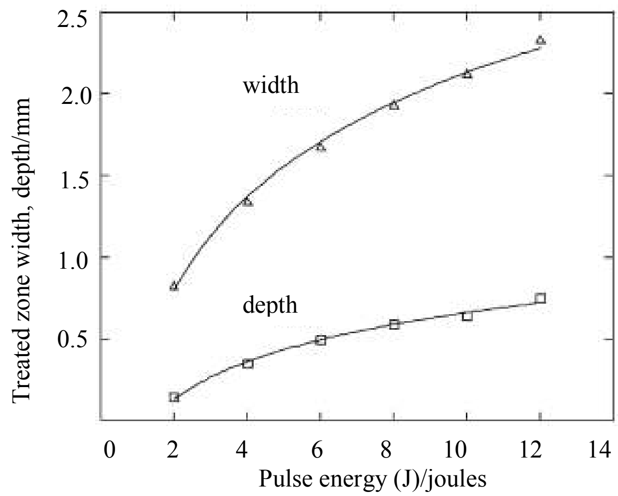

Figure 4: Variations of treated zone width and depth with increasing pulse energy for fixed values of pulse width (5 ms), frequency (30 Hz) and scan rate (5 mm s^{-1}) [26].

Nevertheless, in contrast to the continuous wave operation, pulsed beam offers several challenges owing to the higher number of operating variables and the complexity of optimizing the process parameters [26]. The cyclic temperature changes due to the use of pulsed laser sources was established in several fields such as welding, laser sintering and laser surface treatment [27], but very few papers have dealt with the influence of pulse frequency on the final material mechanical properties and microstructure; and these have not been found to be consistent [24]. Therefore the great potential of cyclic temperatures in laser hardening has not yet been realised [27].

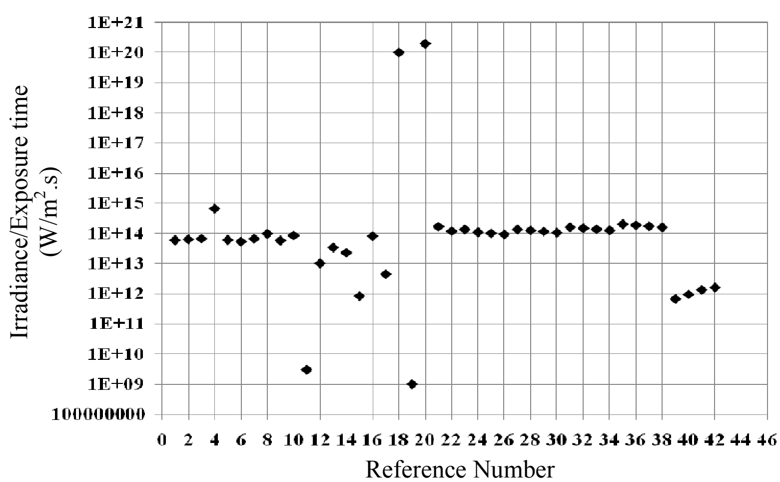

Figure 5: Variations of parameter used in previous laser glazing works. Each reference number on the x-axis represents a data point of one of the following references [4,5,7,16,17,20,28,29,30,31,32].

Micrograph in Figure 6 indicates the cross section of laser glazed railroad rail surface which consists of 3 zones; glazed zone, transition zone and base metal. The transition zone shows the intimate bonding between the glazed zone and the base metal which provide less microhardness gradient between the glazed zone and base metal. The effect of laser glazing on microhardness is referred to Jiang and Molian [5] and Biggs [32] where the microhardness of laser glazed H13 surface and transition zone increased more than 200% and 100% respectively compared to the substrate, at a given laser glazing process parameter [32].

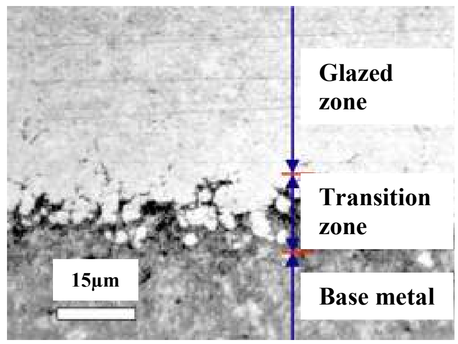

Figure 6: Micrograph of cross sectional view of laser glazed railroad rail [34].

Referring to the advantage in reducing the surface roughness of TBC, the successful results of laser glazing process signify a surface roughness improvement from 9 µm to 4 µm [18]. The experimental results showed that the surface roughness was controlled by varying the laser irradiance and number of pulses as shown in Figure 7. On the other hand, by increasing beam scanning speed and overlap, the surface roughness is consequently increased [5,17].

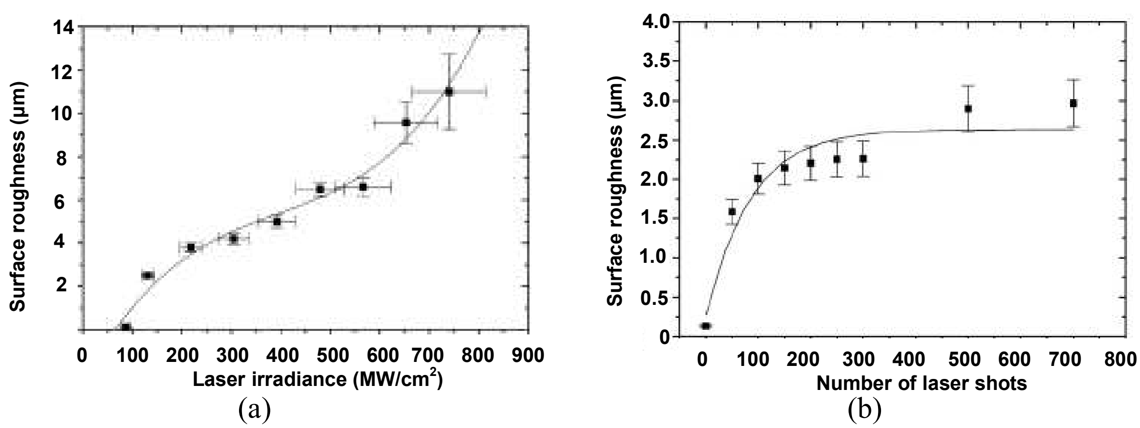

Figure 7: Dependence of surface roughness on (a) laser irradiance and (b) number of laser shots (laser irradiance is 125 MW/cm^2) in laser ablation process [35].

5. CONCLUSION

The future of sustaining die application depends on the success of laser hardening process design. With proper control of laser parameters such as irradiance, exposure time and laser frequency, as well as right composition of material, an amorphous layer with excellent properties combination of metallic and glass can be developed. Works on laser glazing of bearings, railroad rails and TBC had proven the surface properties were enhanced through laser glazing to cope with excessive load, wear, fatigue, bending and friction demand. Nevertheless, from the results of metallographic study, microhardness, and surface roughness there are more to be explored in this field which compatible with the necessity of high temperature applications.

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