Effect of laser parameters on surface roughness of laser modified tool steel after thermal cyclic loading

Annie Lau Sheng¹, Izwan Ismail¹, ², Syarifah Nur Aqida², ³

¹ Faculty of Manufacturing Engineering, University Malaysia Pahang, Malaysia
² Automotive Engineering Centre, University Malaysia Pahang, Malaysia
³ Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia

izwanismail@ump.edu.my

Abstract. This study presents the effects of laser parameters on the surface roughness of laser modified tool steel after thermal cyclic loading. Pulse mode Nd:YAG laser was used to perform the laser surface modification process on AISI H13 tool steel samples. Samples were then treated with thermal cyclic loading experiments which involved alternate immersion in molten aluminium (800°C) and water (27°C) for 553 cycles. A full factorial design of experiment (DOE) was developed to perform the investigation. Factors for the DOE are the laser parameter namely overlap rate (η), pulse repetition frequency (f_{PRF}) and peak power (P_{peak}) while the response is the surface roughness after thermal cyclic loading. Results indicate the surface roughness of the laser modified surface after thermal cyclic loading is significantly affected by laser parameter settings.

1. Introduction

Die casting is a process that can produce geometrically complex parts with closer dimensional tolerances by using permanent metallic moulds. This process generally has a high production rate that produce as fast as 200 parts per hour and 300,000 parts per batch. Molten aluminium that temperature of 670-710°C is injected into the mould at velocities of 30-100 m·s⁻¹ and injection pressure of 50-80 MPa [1]. Extreme working conditions in form of thermal cyclic loading lead to surface failure of the die casting mould. The mould usually affected by corrosion, soldering, erosion, oxidation and thermal fatigue which occur on the die surface [2]. To prolong the tool life, die repair process is performed on the failed surface. The repair process involves grinding, surface recovering by welding and machining [3]. This process is unreliable as chances of repeated failure is high. Alternatively, improving the surface properties by laser surface modification technique was proven to tackle this problem [4]. The surface is irradiated by high power laser beam that generate austenitizing temperature and rapidly self-quenched to produce hard surface of the tool steel. The self-quenching process was due to high-speed heating and cooling which is also known as thermal cyclic loading [4]. Surface roughness of the laser modified tool steel was tailored for specific purpose. However, the surface roughness might be altered when the modified surface slides with molten aluminium in cyclic manner. This paper presents the experimental study that try to explain the effect of laser parameters on surface roughness of laser modified tool steel after thermal cyclic loading.
2. Methodology

Properties of the AISI H13 tool steel used in this study are shown in Table 1. Test specimen of the AISI H13 tool steel was cut into desired dimension and shape by using milling machine. Figure 1 shows dimension of the samples with four side of test surface. Four samples were prepared to be lasered. The surface the test specimens were then treat with laser surface modification process by using Nd:YAG laser with pulse mode.

Table 1. Typical chemical compositions of the AISI H13 tool steel used in the experiment. [4]

| Element | C  | Mn | Si  | Cr  | Mo  | V  | P   | S   | Fe  |
|---------|----|----|-----|-----|-----|----|-----|-----|-----|
| wt%     | 0.36 | 0.38 | 0.96 | 4.82 | 1.19 | 0.86 | 0.017 | 0.004 | Bal. |

To produce small number of test specimen block, each surface of test specimen was lasered with two different laser parameters setting. Therefore, eight sample surfaces were prepared for each test specimen block. The laser parameter settings were designed using $3^3$ full factorial design of experiment (DOE). The factorial design produced 28 different parameter setting. Three parameters of the DOE are (a) overlap rate, (b) pulse repetition frequency and (c) peak power while the response is the surface roughness after cyclic loading experiment. The specification of the laser processing is shown in Table 2. The overlap rate is set between 30% to 70%. The PRF is set between 50 Hz and 70 Hz. Meanwhile, the peak power is set between 1700 W and 2500 W.
Table 2. Summary of specification of laser surface modification process.

| Laser specification | Value      |
|---------------------|------------|
|                     | Low        | High       |
| Peak power          | 1700 W     | 2500 W     |
| PRF                 | 50 Hz      | 70 Hz      |
| Overlap rate        | 30 %       | 70 %       |
| Pulse width         | 0.6-1.2 ms |            |
| Energy              | 1.4-2.0 J  |            |
| Spot size           | 0.7 mm     |            |

The lasered samples were treated with thermal cyclic loading by conducting alternate immersion of test specimens in molten aluminium and water bath. The cyclic immersion test was used to imitate the process of aluminium die casting [1]. Temperature of the molten aluminium and the water bath was controlled at 800°C and 27°C respectively. Cycle time was set constant at 31 s with 11.2 immersion time in both molten aluminium and water. The average surface roughness (RA) was measured using contact surface profilometer. The evaluation length and measurement speed were set to 4.0 mm and 0.6 mm/sec respectively.

3. Results and Discussion

Design of experiment analysis indicates variation in the parameter effect on the surface roughness of the lasered surface after thermal cyclic loading. Figure 2 (a) and (b) depicted the effect of peak power and PRF on the surface roughness at 30% and 70% beam overlap percentage respectively. It can be seen that, the surface roughness relationship with peak power and overlap are inversed at low and high PRF. At low PRF (50 Hz), the surface roughness after thermal cyclic loading is high at combination of high peak power and large overlap. This finding was opposite at high PRF (70 Hz) where the surface roughness is increase with decreasing of both PRF and overlap. The inverse trend at low and high PRF indicates contrast contribution of the factor. Higher PRF will increase surface energy density. This behaviour allows surface hardening to be occurred at low peak power and overlap.

Figure 2 (c) and (d) show the effect of overlap and PRF on surface roughness at peak power of 1700 and 2500 W respectively. Similar inverse trend also depicted here. At low peak power, the surface roughness is increase with increasing PRF and decreasing of overlap. While at high peak power the relationship is inversed. It was notice that, there are no significant changes of Ra at any value of overlap when the PRF and peak power at lowest magnitude. This behaviour was due to domination of peak power and PRF as contributed factor to material properties of laser modified sample. By providing low frequency and low peak power, the energy intensity bombarded on the sample surface is reduced. Low energy intensity makes the surface temperature reduced which the rapid cooling process from austenitic temperature is not happened. The consequence of this behaviour is the hard surface is difficult to achieve and erosion due to cyclic thermal cyclic loading is prone to be happened.

Effects of peak power and PRF on surface roughness are shown in Figure 2 (e) and (f). When overlap is at 50%, combination of low peak power and low PRF failed to show significant changes of Ra. While at larger overlap (70%) the behaviour changed. The combination of low peak power and high PRF is failed to show significant surface roughness.

Analysis of variant (ANOVA) of the data shows the model of two factor interaction (2FI) is significant with the model F-value of 2.69. The chance of noise to influence the response is 4.24% which is relatively low. The terms are significant with prob>F is less than 0.05. The result of ANOVA test also indicates acceptable value of lack of fit 3.46 which is not significant, there for the model is fit.
Figure 2. The effects of laser parameters on surface roughness (Ra) after thermal fatigue loading.
Final model equation produced by statistical analysis is shown in equation 1.

\[
Ra_{tl} = -36.86 + 0.01P_{peak} + 0.87f_{PRF} + 0.07\eta - 2.83P_{peak}f_{PRF} + 1.17P_{peak}\eta - 5.13f_{PRF}\eta
\]  

(1)

Where, \(Ra_{tl}\) is the surface roughness after thermal cyclic loading, \(P_{peak}\) is the Peak Power (W), \(f_{PRF}\) is the Pulse Repetition Frequency, PRF(Hz), and \(\eta\) is Overlap (%).

The average surface roughness of test specimen increase after thermal fatigue test which is from 3.238 μm increase to 3.922 μm. This increasing of surface roughness occurs on laser modified surface due to entrap of oxides and carbides which possibly initiates the thermal fatigue failure [5].

The surface roughness of laser modified AISI H13 tool steel depends on the overlaps efficiency [6]. The overlap rate is the most important factor to affect surface roughness before thermal loading process. However, the surface roughness after thermal loading has different relationship with the laser parameter due to produced thermal wear resistance properties. Sliding action between molten aluminium and laser modified surface at high temperature induced the changes of surface roughness. The wear mechanism involved during the thermal loading experiments is a friction wear at high temperature. Oxide accumulated due to oxidation process on the surface of test specimen led to increase of surface roughness.

4. Conclusion

Surface roughness of laser modified AISI H13 tool steel surface was significantly influenced by laser parameters. Relationship between the any two parameters and surface roughness was found to be inverse when the third parameters at the lower and the higher value. Finding of this study leads to further investigation on the wear mechanism of laser modified sample in thermal cyclic environment.

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