Laser surface modification of Yttria Stabilized Zirconia (YSZ) thermal barrier coating on AISI H13 tool steel substrate

M S Reza¹, S N Aqida¹, I Ismail²

¹ Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
² Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

E-mail: ¹mdreza@ump.edu.my

Abstract. This paper presents laser surface modification of plasma sprayed yttria stabilized zirconia (YSZ) coating to seal porosity defect. Laser surface modification on plasma sprayed YSZ was conducted using 300W JK300HPS Nd: YAG laser at different operating parameters. Parameters varied were laser power and pulse frequency with constant residence time. The coating thickness was measured using IM7000 inverted optical microscope and surface roughness was analysed using two-dimensional Mitutoyo Surface Roughness Tester. Surface roughness of laser surface modification of YSZ H-13 tool steel decreased significantly with increasing laser power and decreasing pulse frequency. The re-melted YSZ coating showed higher hardness properties compared to as-sprayed coating surface. These findings were significant to enhance thermal barrier coating surface integrity for dies in semi-solid processing.

1. Introduction

Thermal barrier coatings (TBCs) are frequently used in die casting industry for insulation system which due to repetitive high temperature liquid flow and solidification process [1]. Rapid high temperature liquid flow produces erosion while high operating temperature gasses caused hot corrosion to metallic component which penetrated into ceramic coating. Erosion occurred due to repetitive rapid heating and cooling of die surface [2]. The cyclic process can cause premature failure in dies due to physical impingement of incoming liquid on die surface. Along with corrosion effect, oxygen diffusion occurred and was dominated in high porosity regions. Consequently, bond coat layer oxidized, and formed thermally grown oxide (TGO) layer [3]. Hence, decreasing porosity content in top coat layer is crucial to overcome TGO layer formation, as well as improving the coating surface integrity.

Previous studies on surface processing indicated laser modification is among the methods for improvement of plasma sprayed TBCs [4]. Laser treatment of YSZ TBCs was conducted to reduce surface roughness of top coat, increase surface hardness and seal open pores. Laser power, pulse duration and overlapping pulses were controllable parameters that can affect fracture strength of the ceramic coating layer [5]. In most TBC systems, substrate materials are super alloys or stainless steels coated using atmospheric plasma spraying technique. In this study YSZ coating surface was laser modified using pulse Nd:YAG laser processing to enhance TBC surface integrity and the substrate material was surface treated H13 tool steel. Effects of surface laser modification on surface roughness and hardness properties of plasma sprayed YSZ thermal barrier coatings were investigated.
2. Methodology
Coating layers were deposited by atmospheric plasma spray on cylindrical AISI H13 tool steel substrate of 10 mm (d) x 150 mm (l) dimension. Bond coat material was Praxair NiCrAlY (Ni 164/211 Ni 22% Cr 10% Al 1.0%Y) while top coat material was Praxair Ai-1075 yttria stabilized zirconia, YSZ (ZrO$_2$ + 8wt.% Y$_2$O$_3$). A 300W JK300HPS Nd:YAG laser with TEM$_{00}$ mode was used to modify the YSZ thermal barrier coating surface. In Table 1, laser power and pulse frequency were varied to produce constant residence time of 0.2 ms. Traverse speed of laser and sample rotation speed was constant at 2 m/min and 58 rpm respectively. The resulted laser energy range to melt the surface was between 0.03 and 0.07 J. Surface roughness of the lasered and without lasered YSZ TBC surface was measured using Mitutoyo Surface Roughness Tester. For cross sectional micrograph, metallographic study was conducted using IM7000 inverted optical microscope and cross sectional surface of microhardness were measured using MMT-X7 Matsuzawa Hardness Tester Machine with Vickers hardness scale.

| Sample | Pulse frequency (Hz) | Peak power (W) | Energy (J) | Residence time, T (ms) |
|--------|----------------------|----------------|------------|------------------------|
| 1      | 70                   | 2              | 0.04       | 0.2                    |
| 2      | 73                   | 3              | 0.05       | 0.2                    |
| 3      | 76                   | 4              | 0.06       | 0.2                    |
| 4      | 79                   | 5              | 0.07       | 0.2                    |
| 5      | 82                   | 2              | 0.03       | 0.2                    |
| 6      | 85                   | 3              | 0.04       | 0.2                    |
| 7      | 88                   | 4              | 0.05       | 0.2                    |
| 8      | 91                   | 5              | 0.06       | 0.2                    |

3. Results and discussions
Figure 1 shows micrograph of cross-sectional surface of coated laser modified surface H13 tool steel which comprised of laser surface modification of YSZ top coating [A], YSZ top coating [B], NiCrAlY bond coating [C], laser modified surface of substrate H13 [D] and substrate H13 tool steel [E]. Lasered surface modification of top coating layer thickness average from 10 to 30 micron. Whereby, YSZ top coating layer thickness average from 180 to 360 micron, while bond coat NiCrAlY thickness average from 100 to 150 micron. Laser modified surface of substrate H13 tool steel thickness average from 20 to 30 micron.

Figure 1. Micrograph of cross-sectional surface of laser modified YSZ H13 tool steel
Figure 2 shows results of surface roughness (SR) measurement for lasered YSZ TBC surface and without lasered YSZ TBC surface. Based on Figure 2, reduction of SR, $R_a$ was measured on all samples which were laser modified after YSZ coating deposition. Sample 2 exhibited the lowest surface roughness with highest surface roughness reduction of 42% after laser surface modification. While, the lowest SR reduction occurred in sample 8 of 7%. Comparing between sample 2 and sample 8 SR result, sample 2 has lower SR value than sample 6 with similar pattern exhibited for sample 4 and sample 8. For other samples comparison between sample 1 and sample 7 SR result, sample 1 has lower SR value than sample 5. While, similar pattern exhibited too for sample 3 and sample 7.

According to table 1, where laser power was constant by 3W, sample 2 laser energy setting was set higher than sample 6 and as for sample 4 and sample 8 the energy setting was also set higher for sample 4 than sample 8 but with laser power constant by 5W. Similar pattern to sample 1 and sample 5, where higher laser energy was set for sample 1 with constant laser power of 2W and as if for sample 3 and sample 7, higher laser energy for was set for sample 3 with constant laser power of 4W. All the comparison between sample 1 and 5, sample 2 and 6, sample 3 and 7 and sample 4 and 8, generally showed the pattern of lower pulse frequency leads to lower surface roughness.

Effects of higher laser energy setting, explains the phenomenon where laser beam that was radiated on the surface, remelting it by high heat creation. When the laser beam passed through the molten area, this zone was solidified rapidly [4]. These remelting and re-solidification phenomena resulted in the reduction of surface roughness of plasma sprayed coating. Reduction in the surface roughness leads to the improvement of corrosion as it is due to the reduction of specific surface area of the laser layer. The corrosion reaction of the molten salts of semi-solid liquid in die with the top coat will be reduced as compared with the coatings in the as-sprayed condition [5].

![Figure 2. Surface roughness (SR) of laser surface modification of YSZ layer](image)

Figure 2 illustrates the variation of micro-hardness of cross sectional surface of laser modified H13 tool steel as a function of depth from top laser surface modification to the substrate. In general the laser surface modification has improved the hardness of specimen for all incident energies. The micro-hardness initially increases with laser power and pulse energy and begins to decrease at a certain parameters. The micro-hardness of the irradiated area is larger than the non-irradiated area, by reason of that the grains after laser irradiated become smaller and closer compared with raw materials under the action of the temperature gradient [5].
4. Conclusion
Higher laser pulsed energy and lower pulse frequency parameter setting leads to decrease in surface roughness. Increase in micro-hardness of specimen for all incident energies was also obtained. Thus, lead to the improvement of the resistance to corrosion of YSZ thermal barrier coating of H13 tool steel.

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