Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Parametric Analysis on Fiber Laser Surface Texturing of Hastelloy C-276

A. Sen*, B. Doloi, B. Bhattacharyya
Production Engineering Department, Jadavpur University, Kolkata-700032, India

Abstract

Hastelloy C-276 is a super corrosive resistance nickel based super alloy that is widely used in the field of power engineering such as heat exchanger, reactors, pressure vessels, etc. due to its outstanding performance at elevated temperatures. The surface finish of the components operating in this type of applications should meet the quality standards as most of the failures are initiated from surface defects. Only a few research works have been concentrated on machining corrosion-resistant super alloys, especially on Hastelloy C-276 and the results are not satisfactory. In the present research study, 50W ytterbium doped fiber laser system is employed for laser surface texturing on Hastelloy C-276 of thickness 1mm. Experiments have been carried out in order to find out the effect of four process parameters such as laser power, pulse frequency, scan speed and duty cycle on surface roughness criteria (R_a & R_z). In each experiment, transverse feed is kept constant at 8.4 µm between two successive scan tracks along with assist air pressure of 4 kgf/cm^2. In this context, the range of laser process parameters, i.e., scan speed from 1 mm/sec to 6 mm/sec, laser power from 7.5 W to 22.5 W, pulse frequency from 50 to 80 kHz, and duty cycle from 30% to 60% of pulse width have been considered. The higher and lower transverse overlap percentage between the two consecutive laser scan tracks for the present experimental study, are found to be 99.82% and 99.52% respectively.

Keywords: Fiber laser, Surface texturing, Hastelloy C-276, Surface roughness

1. INTRODUCTION

Laser surface texturing is one of the emerging areas of surface engineering, evolved through the past decade with the modification of the surface topological characteristics. Improvement of wear resistance, friction co-efficient by trapping of debris, wetting behavior in a liquid-solid interface are the key areas of surface texturing. Textured surfaces also provide high load carrying capacity of the machining component by improving stress distribution and concentration at the contact interfaces [1]. During laser irradiation on the workpiece surface at high temperatures, localized melting leads to material removal from the heated surface. The combination of controlled melting and surface evaporation generates either micro or nano pillars which in turn improve the surface hydrophobicity [2]. As a result, a significant tribological improvement on the workpiece surface is observed. Laser surface texturing is mainly utilized to generate various micro-structures in the form of cross grooves, linear grooves and dimple shaped impressions on metal and ceramic workpieces. Superalloys are characterized by high temperature materials. Over the years, nickel based superalloys have shown poor machinability compared to iron-nickel base superalloys under similar conditions of heat treatment [3]. The solid-solution strengthened nickel-base superalloys can be generalized as Hastelloy X and Inconel 625. Among various high temperature resistance and high corrosion resistant nickel based superalloys, Hastelloy C 276 is one of the key materials for the applications of various components in nuclear plants and chemical industries owing to the presence of high molybdenum and chromium contents.

Researchers over the years have utilized different inert gas conditions, predominantly nitrogen and argon for laser treatment of Hastelloy C 276 [2, 4]. Yilbas et al. [2] observed formation of high stress levels in the heated region of Hastelloy C-276 due to high temperature gradients in the heated region. On the contrary, the reports of Harrison et al [5] dealt with the improvement of corrosion and pitting potential in nickel based superalloy on the laser treated surface as compared to non treated surface. The previous observations were supported by the report of Georges et al [6] while introducing a thermo kinetic model on nickel superalloys. However, nanosecond pulsed fiber laser system is still to be utilized for the texturing of nickel superalloys, especially on Hastelloy C-276.

In the present research work, the effect of four process parameters, i.e., scan speed, laser power, pulse frequency and duty cycle on surface roughness values (R_a and R_z) have been studied.

2. FIBER LASER SURFACE TEXTURING

50 W ytterbium doped multi-diodes pumped fiber laser system of 1064nm wavelength has been utilized to generate different scanning patterns on Hastelloy C276 (thickness of 1mm) to alter the surface conditions for improving the tribological properties. A fiber laser beam of spot diameter 21µm, at focused condition is irradiated on the work surface with predefined patterns with the aid of CNC programming to obtain a rectangular scan area. The workpiece moves in X and Y directions with a relative motion to scan on the surface to obtain the desired scan area. Overlap between two consecutive lasers scan tracks is called as transverse overlap. The transverse feed is kept constant at 8.4 µm between two following scan tracks. Transverse feed governs the amount of transverse overlap factor in laser texturing process. The schematic representation of laser beam scan pattern along with transverse overlap and lateral overlap is shown in the figure 1. Study of lateral overlap has not been considered in the present research work. The mathematical relationship between the laser spot diameter and the transverse overlap is given in equation 1 [7].

$$\text{Transverse overlap } (O_T) = \frac{D - D_T}{D} \times 100\% \qquad (1)$$

ISBN: 978-93-80689-28-9

Here, D is the spot diameter of the laser beam at focused zone in mm; D [illegible] ap distance in mm.

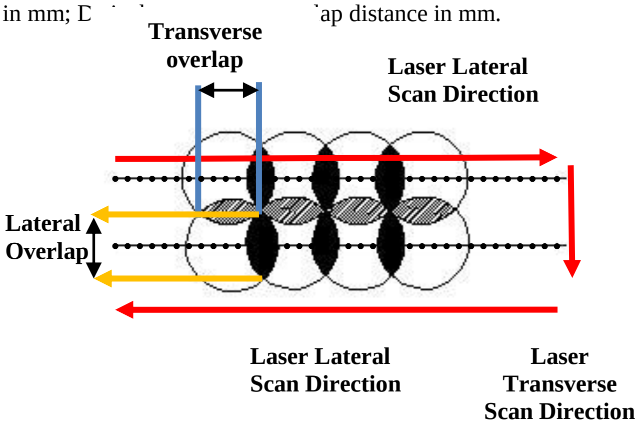

Fig. 1. Schematic view of laser scanning strategy showing lateral and transverse overlap

3. EXPERIMENTAL PLANNING

The ranges of the process parameters have been selected with the aid of pilot experiments. Mitutoyo SJ 410 surface roughness tester with Gaussian filter is utilized to measure the aforesaid surface topological characteristics. For the measurement of surface roughness, arithmetic mean height (Ra) and maximum peak height (Rz) have been considered. On the fiber laser generated rectangular textured surfaces, surface roughness are measured at 5 regions to determine the average values of Ra and Rz. For the analysis of 3D surface topology, Talysurf CCI non-contact surface profiler system is utilized further.

4. RESULTS AND DISCUSSIONS

A total of 24 experiments has been carried out and the results are given in the table 1. The effects of the various process parameters on the surface roughness have been discussed.

4.1 The effect of scan speed on the surface roughness

The effects of scan speed on the surface roughness have been shown in the figure 2 while keeping the other process parameters as constants such as 15 W of laser power, 80 kHz of pulse frequency, 50 % of duty cycle and 4 kgf/cm^2 of assist air pressure.

The heat transfer varies due to multiple laser scan tracks in the textured rectangular area, which eventually changes the rate of cooling in the surface vicinity. As a result, self annealing effects are induced in the textured surfaces without the high thermal stress levels [2]. From the figure 1, it can be observed that with the increment of scan speed, initially the variation of both the surface roughness values (R_a and R_z) are very less up to the scan speed of 5mm/sec. After the scan speed of 5mm/sec, both the aforesaid output responses have increased. When the scan speed is low, laser material interaction time is more and the subsequent cooling time is also more. On the contrary, with the increment of scan speed, the molten material doesn't have the enough time to cool down to melt and vaporize the metal. In addition to this, there is also a non-uniform removal of material due to the less percentage of spot overlap which causes in the increment of surface roughness value.

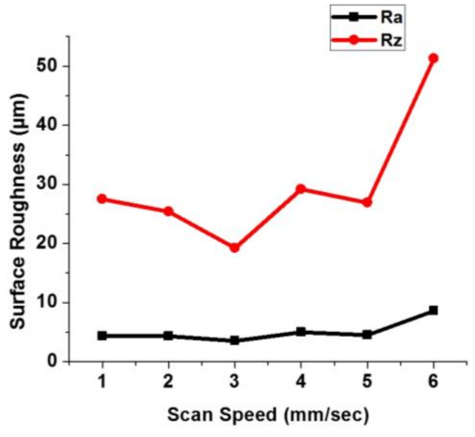

Fig. 2. The effect of scan speed on surface roughness

3.2 The effect of laser power on surface roughness

Figure 3 shows the effects of laser power on the surface roughness when the other process parameters are kept at 3mm/sec of scan speed, 80 kHz of pulse frequency, 50 % of duty cycle and 4 kgf/cm^2 of assist air pressure.

It is observed from the graphical plot (figure 3) that with the increment in laser power, the surface roughness increases. This is due to the fact that with increase of laser power, the peak power of the beam is also increasing according to equation 2. Thus, the material from the laser irradiated zone gets adequate heat energy to melt and evaporate instantly. In addition to this, the laser output power intensity distribution of the irradiated spot is Gaussian [2]. Thus, the peak intensity reaches at the irradiated spot center and the power intensity reduces towards the irradiated spot edges. Simultaneously, melting phenomenon can be observed in the region of spot edges at the surface while evaporation of the surfaces may occur in the irradiated spot center [2]. As a result, the machined surface shows irregularities which in turn increase the surface roughness of the textured profiles.

$$Peak\ power(P_P) = \frac{Average\ power(P_A)}{Pulse\ frequency(F_P) \times Pulse\ duration(\mu)} \quad (2)$$

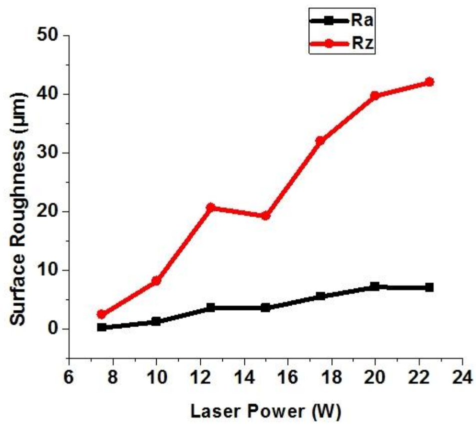

Fig. 3. The effect of laser power on surface roughness

4.3 The effect of pulse frequency on surface roughness

The effects of pulse frequency on the surface roughness of the textured surface have been shown in the figure 4 with the combination of fixed process parameters of 3mm/sec of scan speed, 15 W of laser power, 50 % of duty cycle and 4 kgf/cm^2 of assist air pressure.

The combination of sufficient pulse energy with an acceptable pulse frequency range is favorable for a good surface roughness [8]. Soveja et al.[8] found that a good correlation between the pulse energy and the pulse frequency reduces the melted layer thickness. Increment of pulse frequency results in reduction of both pulse width (from 100 ns to 66.67 ns) and laser fluence (from 173.23 J/cm^2 to 115.49 J/cm^2). Figure 4 shows that the effects of pulse frequency on the surface roughness values (R_a & R_z). Both the surface roughness values have shown a gradual decrease in their values (up to 65 kHz of pulse frequency), but the phenomenon reversed back with the more increment in pulse frequency. The increment of pulse frequency with the combination of moderate laser scan speed results in increase of overlap percentage of the textured surface. A thin melted layer, formed on the textured surface, helps to obtain a surface less disturbed by the liquid displacement. This happens due to under the action of recoil pressure, formed during the laser–material interaction [8]. As a result, smooth textured surfaces can be observed at a low pulse frequency. With the more increment of laser pulse frequency, number of laser pulses will be more, i.e., number of laser shots will be more during the laser irradiation on Hastelloy C-276. In addition to this, pulse energy reduces with the increment of pulse frequency. The distortion in the poor textured surface is observed at a high pulse frequency. This is due to the fact the delivered laser energy is insufficient for material removal by evaporation, but surface melting is induced instead. Thus, high pulse frequency parameters are not suitable for producing the desired texture [9].

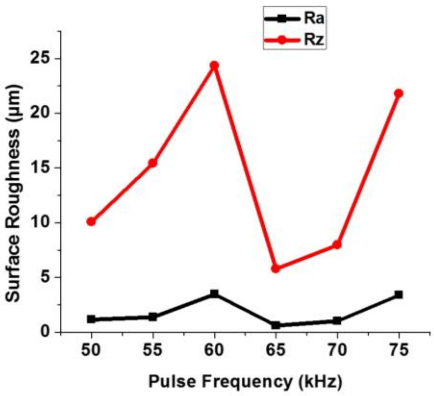

Fig. 4. The effect of pulse frequency on surface roughness

4.4 The effect of duty cycle on surface roughness

Figure 5 shows the effect of duty cycle on surface roughness when the other process parameters are kept constants such as 3mm/sec of scan speed, 15 W of laser power, 80 kHz of pulse frequency, and 4 kgf/cm^2 of assist air pressure.

From the figure 5, it can be observed that both the surface roughness values (R_a & R_z) have a tendency to gradually decrease with the increment of duty cycle. When the duty cycle increases, the laser beam penetration rate decreases gradually, although average laser power increases simultaneously. However, pulse energy remains constant. As a result of which, more amount of molten material is removed from the textured surface. With the combination of high pulse frequency and moderate scan speed, the cooling time of the molten material increases. As a result, the molten material can be uniformly removed from the rectangular scan region. The effect of cooling rate and thermal gradient determine the triboligical properties of the textured region. At a particular constant laser power, the variation in cooling rate is more significant than the thermal gradient. An increase in duty cycle results in a decrease of thermal gradient throughout the laser treated zone.

Figure 6 (a) shows the 3D topology of the textured region at the parametric condition of 15 W of laser power, 65 kHz of pulse frequency, 50% of duty cycle and 3mm/sec of scan speed. The textured region shows up to 27.5 µm depth from the top face for the length of 0.8mm. 3D topology of the textured region shows homogeneity throughout the scan area. The corresponding surface roughness profile has been shown by the figure 6 (b).

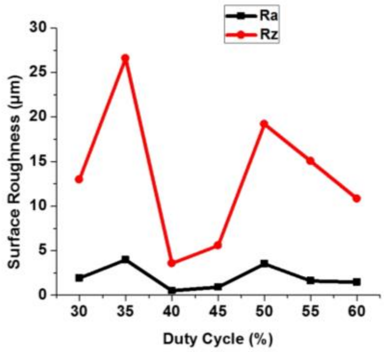

Fig. 5. The effect of duty cycle on surface roughness

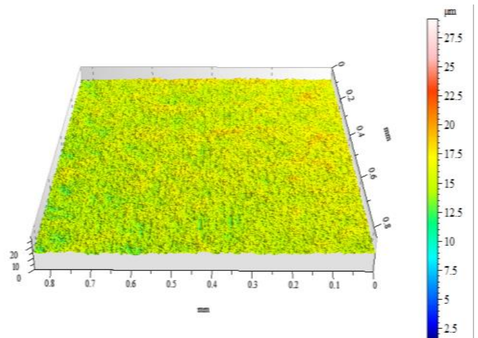

Fig. 6 (a). 3D topology of the textured area at the parametric condition of 15 W of laser power, 65 kHz of pulse frequency, 50% of duty cycle and 3mm/sec of scan speed

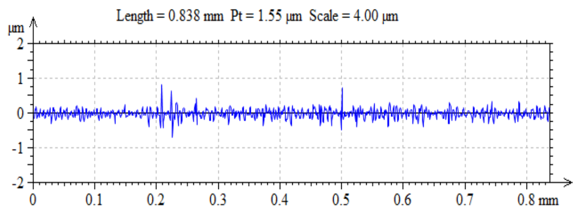

Fig. 6 (b). The surface roughness profile of the textured region of Hastelloy C276

Table 1 shows the results of the experiments

Ex No:	Peak Power	Pulse Width	Transverse Overlap (%)	Surface Roughness (μm)	
	KW	ns		R_a	R_z
1	3	62.5	99.94	4.357	27.476
2	3	62.5	99.88	4.309	25.391
3	3	62.5	99.82	3.513	19.206
4	3	62.5	99.76	4.972	29.173
5	3	62.5	99.70	4.497	26.880
6	3	62.5	99.64	8.592	51.256
7	1.5	62.5	99.82	0.214	2.393
8	2	62.5	99.80	1.181	8.114
9	2.5	62.5	99.80	3.527	20.611
10	3.5	62.5	99.80	5.513	31.971
11	4	62.5	99.80	7.123	39.658
12	4.5	62.5	99.80	7.040	41.997
13	3	100	99.70	1.157	10.073
14	3	90.90	99.74	1.379	15.420
15	3	83.33	99.76	3.457	24.333
16	3	76.92	99.78	0.601	5.780
17	3	71.42	99.79	1.022	7.967
18	3	66.67	99.80	3.391	21.784
19	5	37.5	99.82	1.923	12.976
20	4.28	43.75	99.82	3.974	26.596
21	3.75	50	99.82	0.502	3.562
22	3.33	56.25	99.82	0.911	5.578
23	2.72	68.75	99.82	1.605	15.039
24	2.5	75	99.82	1.456	10.838

5. CONCLUSIONS

In the present research work, experimental investigation and analysis of the fiber laser surface texturing on Hastelloy C276 of thickness 1 mm have been made. The effects of four process parameters, i.e., scan speed, laser power, pulse frequency and duty cycle are analyzed of the textured profiles in the form of surface roughness values (R_a & R_z). From the experimental results, the following conclusions can be drawn.

(a) Initially surface roughness values have decreased with the scan speed, but later both the surface roughness values have shown a tendency to increase with the higher scan speed.

(b) High laser power in the textured region produces rough surfaces. Rate of increase in R_a value is more than that in R_z value with the increase in laser power.

(c) A gradual decrease in the surface roughness values is observed at low pulse frequency, but a higher number of laser shots have produced coarse textured on Hastelloy C276.

(d) High cooling time and low thermal gradient with the combination of with the higher duty cycle (60%) has produced uniform and smooth textured region on Hastelloy.

The experimental results of the current research will be useful guidelines for further work for analyzing other topological characteristic features such as waviness and also tribological characteristics, i.e., wear, micro-hardness etc.

Acknowledgement

The authors acknowledge the financial support and assistance provided by CAS Ph-IV program of Production Engineering Department of Jadavpur University under University Grants Commission, New Delhi.

References:

[1] Y. Xing, J. Deng, X. Feng, S. Yu, Effect of surface texturing on Si3N4/TiC ceramic sliding against steel under dry friction, Materials and Design, **52**(2013) 234-245, DOI:10.1016/j.matdes.2013.05.077.

[2] Yilbas B. S., & Ali H., Laser texturing of Hastelloy C276 alloy surface for improved hydrophobicity and friction coefficient. *Optics and Lasers in Engineering*, **78** (2016) 140-147.

[3] Donachie, J.M, & Donachie, J.S. *Superalloys A Technical Guide: ASM International*,. San Francisco, U.S.A., 2nd Edition, 439 p., 2002.

[4] Hashim M., Babu K. S. R., Duraiselvam M., & Natu H., Improvement of wear resistance of Hastelloy C-276 through laser surface melting. *Materials & Design*, **46** (2013) 546-551.

[5] Harrison N. J., Todd I., & Mumtaz K., Reduction of micro-cracking in nickel superalloys processed by selective laser melting: a fundamental alloy design approach. *Acta Materialia*, **94** (2015) 59-68.

[6] Gordani G. R., ShojaRazavi R., Hashemi S. H., & Isfahani, A. R. N., Laser surface alloying of an electroless Ni–P coating with Al-356 substrate. *Optics and Lasers in Engineering*, **46** (2008) 550-557.

[7] Vora H. D., & Dahotre N. B., Surface topography in three-dimensional laser machining of structural alumina. *Journal of Manufacturing Processes*, **19** (2015) 49-58.

[8] Soveja A., Cicală E., Grevey D., & Jouvard J. M., Optimisation of TA6V alloy surface laser texturing using an experimental design approach.*Optics and Lasers in Engineering*, **46**(2008) 671-678.

[9] Tshabalala L. C., & Pityana S., Surface texturing of Si 3 N 4–SiC ceramic tool components by pulsed laser machining. *Surface and Coatings Technology*, **289** (2016) 52-60.