Investigation on Laser Beam Machining of Miniature Gears

[1*]C Popa [1]K Gupta [1]A Mashamba [2]TC Jen

[1]Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Johannesburg-Republic of South Africa
[2]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg-Republic of South Africa

Abstract: Micro-machining has become a fast growing field in the global manufacturing sector due to increasing demand of miniature machines and devices. The trend involves the fabrication of precision miniature parts that have widespread applications in many areas such as, electronics, biomedical, aerospace, robotics, automobiles and consumer products. Miniature gears are essential components of miniaturised devices such as miniature motors and pumps, scientific instruments, medical equipment, timing devices, and robots etc. These gears are generally fine-pitched gears running at very high speed, mainly used for transmission of motion and/or torque. Therefore, minimum running noise, accurate motion transfer and long service life are the required qualities of these gears. Considering that a laser beam is capable of cutting complex shapes with great precision and little waste, motivates its use to machine small sized parts including miniature gears. This article reports on the fabrication of stainless steel miniature gears by laser beam machining (LBM) process. A total of twenty experiments have been conducted following one factor at a time design of experiment strategy on CO_2 laser machine. The fabricated gears have 9 mm pitch diameter, 10 teeth, and 4.5 mm thickness. The effects of laser machining parameters on surface roughness (mainly average roughness 'R_a' and mean roughness depth 'R_z') of gears have been analysed. The best quality miniature gear fabricated by LBM possesses 1.04 µm average roughness and 5.797 µm mean roughness depth at par with that obtained by conventional and other advanced processes of miniature gear manufacturing. Investigation reveals that LBM is capable to produce miniature gears of good surface finish and integrity ensuring their high functional performance and long service life. The outputs of this preliminary work encourage further exploration of LBM to establish it as an alternative process for fabrication of precision miniature gears.

Keywords: Laser; Miniature gear; Precision; Surface roughness

1. INTRODUCTION

Since last two decades there has been a rapid growth in demand of miniature products for aerospace, scientific, industrial, and domestic applications. To fulfill the growing demand, manufacturing sector is also busy in research and development to find the sustainable alternate of the conventional processes for manufacturing of miniature products. Electrochemical machining, electric discharge machining, photochemical machining, abrasive water jet machining, and laser beam machining are some of the advanced processes have been focused in recent past. Laser beam machining (LBM) is a nonconventional machining process where high-energy concentrated light beam is utilized to melt and vaporize the workpiece material which is further removed from the machining zone by the pressure of an assist gas [1]. LBM process employs photo-thermal energy in the machining process eliminating any mechanical contact with the workpiece. This represent a great advantages of the process as there is no tool involved, hence no tool wear. Furthermore, LBM process is applicable to a wide range of engineering materials, for macro, micro and nano-machining processes, producing simple to complex shapes with great accuracy and good machined surface quality.

The mechanism of an LBM process, depending on the application and type of material to be processed, can be a controlled fracture mechanism mostly applicable for brittle materials (ceramics), a melting and blow type of process, or a process where the material removal is done by evaporation (sublimation) [1]. For metallic and non-metallic materials the suitable mechanism is melting and blow that based on the type of the assisted gas can be a reactive process or a fusion process. In the reactive process the assist gas used is oxygen that reacts with the material constituents resulting in an exothermic energy as an addition to the laser energy, whereas the fusion process deals only with the laser energy as the assist gas used, usually nitrogen, is an inert gas. Major LBM applications are: cutting, drilling, marking, welding, sintering and heat treatment process. Laser cutting is the largest application of laser processes in metal working, for which CO_2 laser machine with high and NdYAG laser machine with short wavelengths are used [2].

As the cutting with laser presents evident advantages, the process is continuously being explored for a thorough understanding of the interaction of its parameters and the effect of these parameters on the cut quality in terms of surface roughness, kerf width, heat affected zone [3-8], dimensional accuracy [9] and surface topography [10]. The laser cutting parameters most often investigated are: laser power, cutting speed, and gas pressure [11]. Additional parameters considered are: focal position, nozzle diameter, and laser pulse frequency [12].

Miniature gears are key components used in miniaturized systems such as miniature pumps and motors, medical equipment, scientific instruments, time measuring devices, etc. These gears are fine-pitched, running at very high speed and are made of aluminum, brass, bronze, stainless steel and plastic. Their purpose is mainly for motion transfer and their high quality determines the functional characteristics of the miniature devices. The major performance characteristics are minimum running noise, accurate motion transfer and long service life [13]. Besides micro-geometry parameters such as profile, pitch, and runout, the surface roughness parameters are also significantly important for smooth functioning and long service life of miniature gears [13, 14].

There has been some recent investigation on manufacturing of miniature gears by advanced machining processes [13-18]. Phokane et al. [14] has conducted experimental study on abrasive water jet machining of miniature gears of brass. Effects of abrasive water jet machining parameters on miniature gear surface roughness have been analysed and tribology parameters have been investigated. Gupta and Jain [15, 16] performed a systematic investigation on wire-EDM of miniature brass gears where extensive research has been conducted on analysis and optimization of micro-geometry and surface roughness of miniature brass gears. It was concluded that wire-EDM has potential to manufacture near net shape gears. Literature review reveals that there is a scarcity of work on LBM of gears, a few studies [18-20] do not focus on all the aspects of gear manufacturing by LBM and thus make insignificant contribution in the field.

The investigation reported in this paper aims to explore manufacturing of miniature gears by LBM and discusses the experimental study conducted on CO_2 laser with a range of machining parameters and their effects on surface roughness of miniature gears of stainless steel.

2. EXPERIMENTAL PROCEDURE

Miniature spur gears specimens from SS 304 plate were cut using a Trumph Lasercell 1005 CO_2 laser cutting machine. The fixed parameters are: machine nozzle to workpiece stand-off distance- 2.2 mm, focal length-5 inch (127mm) and nitrogen was used as the assisted gas. Table 1 presents the material composition and the specification of the miniature gears. The experimental set-up is shown in Figure 1.

Table 1. Composition of 304 Stainless Steel and specification of miniature gear

Material composition								
Carbon	Manganese	Phosphorus	Sulfur	Silicon	Chromium	Nickel	Nitrogen	Iron
0.08% max.	2.00% max.	0.045% max.	0.030% max.	0.75% max	18-20%	8-12%	0.10% max	Balance
Miniature gear specifications								
Type: external spur	Number of teeth: 10							
Outside diameter: 9.04 mm	Thickness: 4.5 mm							

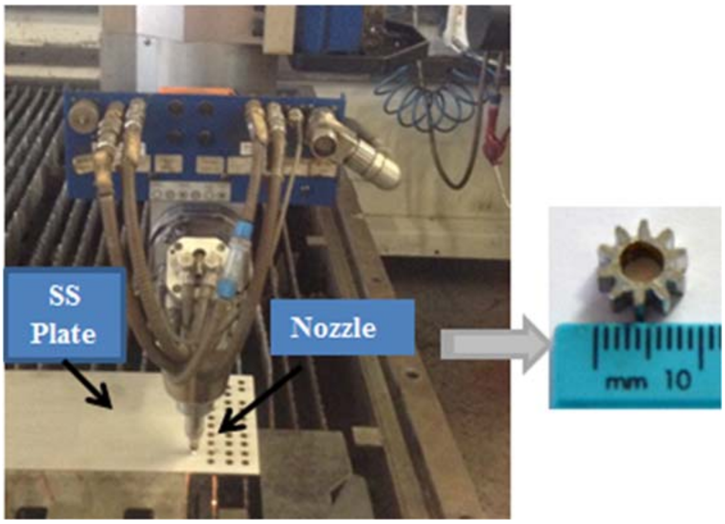

Figure 1. Experimental set-up and laser manufactured miniature gear

The input cutting parameters considered are laser power, cutting speed, focal position and gas pressure. The machining parameters and their levels selected are shown in Table 2. The levels of the parameters are selected based on machine admissible range for the thickness and type of material to be cut and on the supplier recommendation, machine operator experience, and literature review.

Experiments have been designed and conducted based on one factor at-a-time approach. The surface roughness is measured with a Mitutoyo Surftest SJ-410 surface roughness tester.

Table 2. LBM parameters and levels

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Laser power [W]	1600	1800	2000	2200	2400
Cutting speed [m/min]	0.550	0.650	0.750	0.850	0.950
Focal position [mm]	-3.5	-2.5	-1.5	-0.5	+0.5
Gas pressure [bar]	11	13	15	17	19

3. RESULTS AND DISCUSSION

The responses measured were R_a and R_z. According to ISO 4287, Ra is the arithmetic mean deviation of the assessed profile. Graphically, the average roughness is the area between the roughness profile and its centre line divided by the evaluation length [15]. Although R_a does not differentiate between peaks and valleys and thus does not have a strong information character, it is by far the most used parameter in surface finish measurement. R_z is mean roughness depth and is evaluated as the average value of the five R_z values recorded over five sampling lengths. In other words, the mean roughness depth is the average of maximum peak to valley of five consecutive sampling lengths within the measuring length and has pronounced influence compared to average roughness on the performance of engineered surfaces [13, 14]. Table 3 presents the values of average roughness and mean roughness depth corresponding to all twenty experimental combinations. Figures 2-5 depict the variation of surface roughness of miniature gears with LBM parameters.

Table 3. Experimental results

Input parameters					**Responses**	
Run	**Laser power [W]**	**Cutting speed [m/min]**	**Focal position [mm]**	**Gas pressure [bar]**	**R_a**	**Rz**
1	1600	0.75	-1.5	15	1.309	6.564
2	1800				1.078	6.801
3	2000				2.308	8.735
4	2200				1.056	6.014
5	2400				1.04	5.797
6	2000	0.55	-1.5	15	3.089	18.369
7		0.65			1.06	8.358
8		0.75			2.308	8.8735
9		0.85			1.879	12.582
10		0.95			1.829	16.839
11	2000	0.75	-3.5	15	1.134	5.514
12			-2.5		1.603	8.673
13			-1.5		2.308	8.735
14			-0.5		1.058	8.039
15			0.5		4.519	12.354
16	2000	0.75	-1.5	11	2.474	15.188
17				13	2.484	14.798
18				15	2.308	8.735
19				17	1.392	7.395
20				19	1.75	18.344

The surface roughness behavior, with increase in laser power, follows a similar trend for Ra as for Rz, as shown in Figure 2. The lowest values of R_a and R_z are 1.04 μm and 5.797 μm respectively obtained at a laser power of 2400 W, with 0.75 m/min cutting speed, 15 bar gas pressure and 1.5 mm focal position below the upper workpiece surface. It is worth mentioning that laser machining at high power results in more power intensity at the focal point which needs to be matched with adequate cutting speed to prevent extensive HAZ and enough gas pressure to expel the molten metal without dross formation.

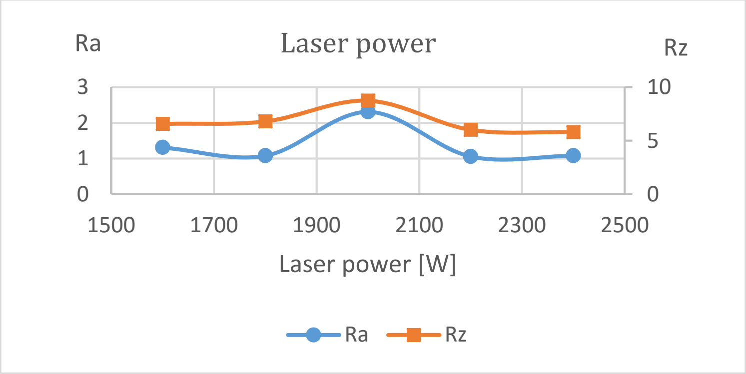

Figure 2. The effect of laser power on the surface roughness

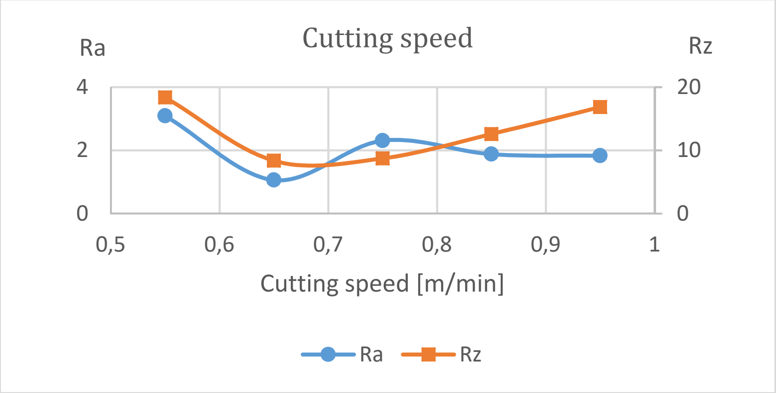

Figure 3. The effect of cutting speed on the surface roughness

When cutting speed is varied from 0.55 m/min to 0.95 m/min, the minimum values of R_a and R_z are found to be 1.06 and 8.358 respectively at a cutting speed of 0.65m/min. The results shows an increase in surface roughness as the cutting speed increases above the 0.65 m/min. Cutting speed have to be properly matched with the thickness of the material to be cut as the thicker the material, the slower the cutting speed would be.

The focal position is the point with highest power density and can be set up in the negative z direction within the thickness of the workpiece, on the surface or above the workpiece. The effect of focal position on R_a and R_z is shown in Figure 4, where it can be seen that both parameters follow a similar trend.

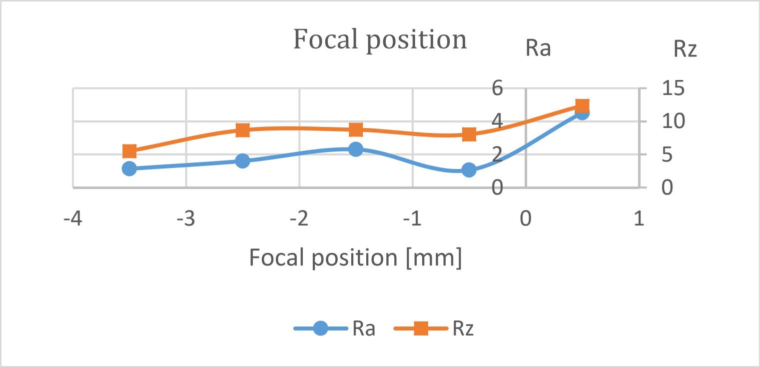

Figure 4. The effect of focal position on the surface roughness

The surface roughness has low values when the laser focal position is inside the workpiece, particularly at 0.5 mm below the surface where the average surface roughness has a lowest value of 1.058 µm. When the focal position is situated above the workpiece, the average surface roughness experiences a sudden increase to a value of 4.519 µm. In this case, the power intensity remains above the material and the thermal capacity required to melt the material in the cut zone is reduce by the effect of the Nitrogen that acts as a coolant.

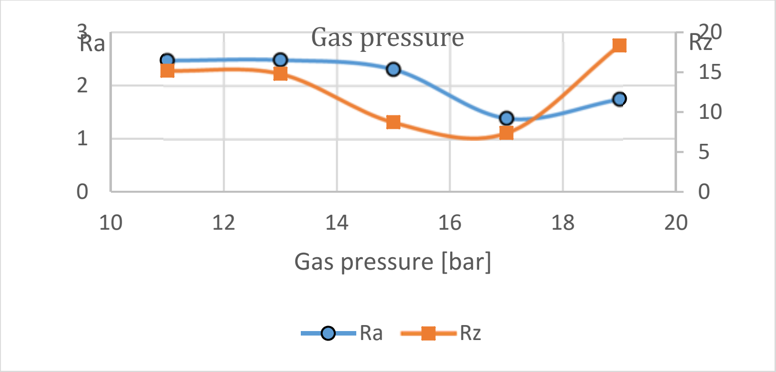

Figure 5. The effect of gas pressure on surface roughness

In LBM, the commonly used gas for cutting stainless steel is Nitrogen due to its inert properties which make it safe for cutting process, provide functionality to cool the workpiece at the cut zone and to assisting in the removal of molten material from the cut. When the gas pressure is not enough, the molten material does not remove in a laminar fashion; therefore the resulting cutting edge produced with a poor quality [22]. The results of gas pressure variation as shown in Figure 5 display a decrease in average surface roughness with the increase of gas pressure. The lowest value of the average surface roughness is 1.392 µm recorded at 17 bar.

Laser cutting is a thermal process that affects the microstructure of the region near the cut surface resulting in a hardening zone directly at the cut edge and an adjacent heat affected zone. These changes in microstructure are associated with undesirable effects such as surface cracking and fatigue resistance [23]. The main parameter of laser cutting that affects the microhardness of the thermally affected zone is the laser power [23, 24]. Vickers tests with low load application are very good to characterize the microstructure gradients and determine the surface hardness [25].

The microhardness of the gear with minimum surface roughness was examined by pushing a diamond body, shaped ii Vickers pyramid, as seen in Figure 6, at three different loads applied for a duration of 10 s. The sample preparation included the sectioning of one tooth, and grinding and polishing by appropriate metallographic techniques. Innova Test Falcon 500 was used to create three indents for each load, 1 mm apart

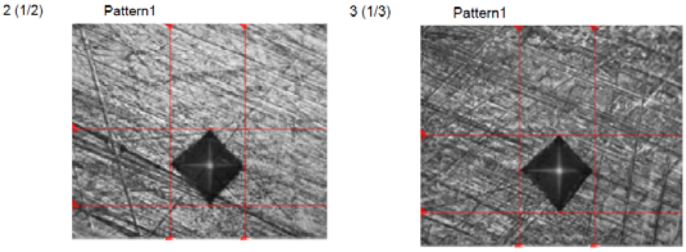

Figure 6. Vickers microindentation

Table 4. Vickers hardness results

Load [gf]	Minimum	Maximum	Average HV	Standard deviation
50	221.68	229.02	226.18	3.21
100	186.97	190.63	188.8	1.5
200	166.20	170.92	168.04	2.07

The hardness values shows a dependence on the applied indentation load, as the load is increased, the HV value decreases as shown in Figure 7. That is expected at low-load Vickers microindentation However, the low standard deviation values indicate a very small variation in the microhardness for the same load. That shows that the in bulk of the material the increased hardness is almost constant suggesting the absence of HAZ. The results confirm that laser cutting is one of the thermal cutting techniques that generates a minor HAZ, with a thickness ranging to hundred microns [24, 25]. As observed in Figure 6, the microindentations did not produce any cracking at corners

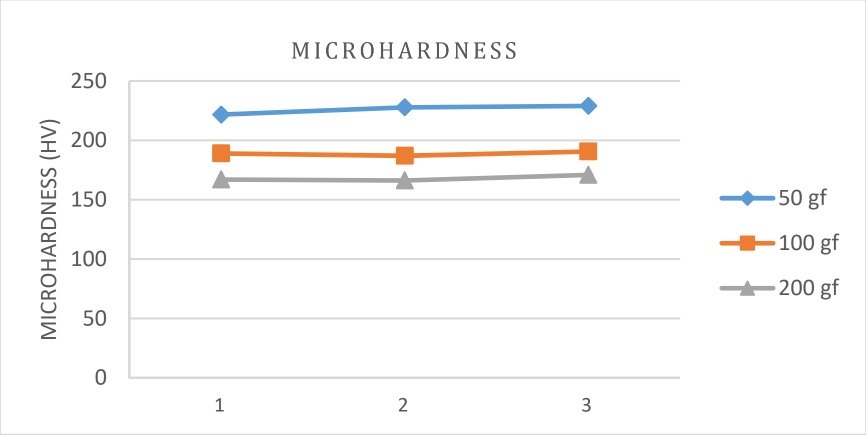

Figure 7. Variation of microharness with applied load

Although the surface roughness on the flank of the gear tooth have good measured values, a closer look at the macro-geometry of the gears , see Figure 6, shows that there hole presents a tapper and there are deviations from the profile geometry. The deviations are visible on the flank, at the tip and at the base of the teeth in an uneven distribution, that may be due to fluctuations of the laser power and/ the gas pressure.

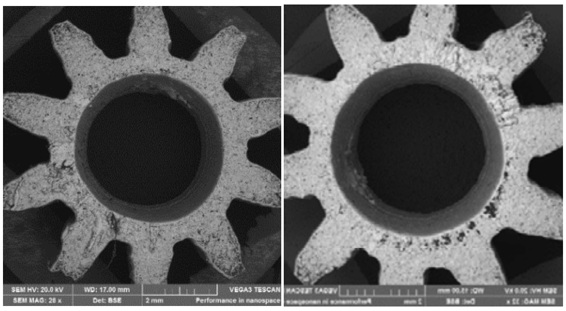

Figure 6. SEM Micrographs of laser machined miniature gear

4. CONCLUSIONS

The following conclusions can be drawn from the current investigation:

- The least average surface roughness 1.04 μm and maximum roughness 5.797 μm have been obtained at a power of 2400 W, 0.75 m/min cutting speed, 1.5 mm below top surface focal position, and 15 bar gas pressure. This level of surface finish is acceptable for miniaturized applications and at par with the finish obtained by other conventional and advanced processes of miniature gear manufacturing as reported in the literature.
- The investigation shows that micro-parts with complex geometry and good surface integrity can be machined by laser process and further quality improvement can be explored.
- The results of current investigation indicate significant potential in laser beam machining for manufacturing of quality gears.
- The finding of current investigation encourages future research in the area to establish the field further.

The following points highlight the scope of future research:

- A more detailed investigation on analysis and optimization of important laser process parameters and their interaction to obtain high quality of miniature SS gears.
- Investigations on geometric accuracy in terms of profile, pitch, and runout of laser machined miniature gears.
- Study on functional testing i.e. roll testing, noise, and vibration testing etc. of miniature gears fabricated by laser beam machining.
- Laser beam machining of gears made of other materials such as brass, bronze, aluminum, and plastic etc.

REFERENCES

1. J.P. Davim (ed), Nontraditional machining processes-Chapter 2, Springer 2013.
2. A. Sharma, V. Yadava, R. Rao, Optimization of kerf quality characteristics during Nd:YAG laser cutting of nickel based superalloy sheet for straight and curved cut profiles, Opt. Lasers Eng. 48 (2010) 915–925.
3. B.S. Yilbas, Effect of process parameters on the kerf width during the laser cutting process, Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. 215 (10) (2001) 1357–1365.
4. C.B. Yang, D.S. Deng, H.L. Chiang, Combining the Taguchi method with artificial neural network to construct a prediction model of a CO2 laser cutting experiment, Int. J. Adv. Manuf. Technol. 59 (9) (2011) 1103–1111.
5. M. Madić, M. Radovanović, M. Manić, M. Trajanović, Optimization of ANN models using different optimization methods for improving CO2 laser cut quality characteristics, J. Braz. Soc. Mech. Sci. Eng. 36 (1) (2014) 91–99.
6. M Madića , J.Antuchevicieneb, M. Radovanovića, D. Petkovića , Determination of laser cutting process conditions using the preference selection index method, Optics and laser technology, 89(2017) 214-220
7. N. Rajaram, J. Sheikh-Ahmad ∗, S.H. Cheraghi, CO_2 laser cut quality of 4130 steel, International Journal of Machine Tools & Manufacture 43 (2003) 351–358
8. A. Lamikiza, L.N. Lo´pez de Lacallea, J.A. Sa´ncheza, D. del Pozob, J.M. Etayoa, J.M. Lo´peza, CO2 laser cutting of advanced high strength steels (AHSS), Applied Surface Science 242 (2005) 362–368
9. Z. Durukan, A.R. Motorcu, A. Güllü, Modeling of the effects of parameters on dimensional accuracy in laser cutting of AISI 304 steel with different geometries, J. Fac. Eng. Archit. Gazi Univ. 29 (3) (2014) 505–515.
10. M. Harničárová, J. Valíček, M. Kušnerová, R. Grznárik, J. Petrů, L. Čepová, A new method for the prediction of laser cut surface topography, Measurement Science Review Volume 12, No.5, 2012
11. M. Radovanovic, M. Madic, Experimental Investigations Of Co2 Laser Cut Quality: A Review, Nonconvetional Technologies Review no.4/2011
12. M. Madića, M. Radovanovića, M. Gostimirovićb, ANN modeling of kerf taper angle in CO2 laser cutting and optimization of cutting parameters using Monte Carlo method, International Journal of Industrial Engineering Computations 6 (2015) 33–42
13. T.C. Phokane, K. Gupta, (2017), "Sustainable Manufacturing of Precision Miniature Gears by Abrasive Water Jet Machining-An Experimental Study," Proceedings: 15th International Conference on Manufacturing Research (ICMR) 2017, 05-07 Sept. 2017, London, UK.
14. TC Phokane, K.Gupta, M. K. Gupta (2018), "Investigations on Surface Roughness and Tribology of Miniature Brass Gears Manufactured by Abrasive Water Jet Machining", Proc. IMechE, Part C: Journal of Mechanical Engineering Science (Sage).
15. Kapil Gupta, N K Jain (2014), "Analysis and Optimization of Surface Finish of Wire Electrical Discharge Machined Miniature Gears" Proc. IMechE, Part B: Journal of Engineering Manufacture (Sage), 228 (5), 673-681.
16. Kapil Gupta, N K Jain (2014), "Analysis and Optimization of Micro-Geometry of Miniature Gears manufactured by Wire Electric Discharge Machining", Precision Engineering (Elsevier), 38 (4), 728-737.
17. Kapil Gupta, N K Jain, RF Laubscher (2015), "Spark-Erosion Machining of Miniature Gears: A Critical Review", The International Journal of Advanced Manufacturing Technology (Springer), 80 (9-12), 1863-1877.
18. H. Liess, J. Heinzl Manufacturing of micro-ridges and micro-gears by laser ablation, in: Proceedings of ASME 7th biennial conference on engineering systems design and analysis, Manchester, England, 2004, July 19-22, 3: 305-309.
19. P. Yang, G.R. Burns, J.A. Palmer, M.F. Harris, K.L. McDaniel, J. Guo, et al., Microfabrication with femtosecond laser processing (A) laser ablation of ferrous alloys, (B) direct-write embedded optical waveguides and integrated optics in bulk glass. Sandia National Laboratories Report-5625, 2004.
20. C.G. Khan, Malek, W. Pfleging, S. Roth, Laser micromachining of polymers, in: A.D. Campo, E. Arz (Eds.), Generating Micro- and Nanopatterns on Polymeric Materials, Wiley, Hoboken, NJ, 2010.
21.
22. X. Dong, F. Chen, S. Chen, Y. Liu, Z. Huang, H. Chen, S. Feng, L.Zhao, Z. Wu, X. Zhang, Microstructure and microhardness of hot extruded 7075 aluminumalloy micro-gear, Journal of Materials Processing Technology 219 (2015) 199–208
23. C. Wandera, V. Kujanpaa, Characterisation of the melt removal rate in laser cutting of thick sections stainless steel, Journal of laser applications 22, 62(2010)
24. I.Miraoui, M. Boujelbene, E. Bayraktar, Analysis of cut quality of sheet metals obtained by laser machining: thermal effects, Advances in material and processing technologies, Vol 1 2015, 633-642.
25. I.Miraoui, M. Boujelbene, M.Zaied, High-power laser cutting of steel plates: Heat affected zone analysis, Advances in material science and engineering, 2016
26. G.F. Vander Voort, R. Fowler, Low load Vickers microindentation, Advanced materials and processing, 2012, 28-33