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Optimization of hole quality characteristics in laser micro drilling of Polymethyl Methacrylate

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Abstract: *Polymethyl methacrylate(PMMA) is a polymer which is widely used in dental and biomedical applications owing to its biocompatibility and ease of manipulation. The fabrication requirements for biomedical applications make the processing difficult by conventional machining. Laser micro drilling is a thermal-based non-traditional machining process which removes material by ablation and finds its usage mainly in the aerospace, automobile, biomedical applications etc. In this work, Laser micro drilling on PMMA is performed using spot diameter, feed rate and sheet thickness as the process parameters. The hole characteristics, Heat Affected Zone (HAZ) and Hole circularity for the drilled holes are investigated. Regression Analysis was performed to predict the values of HAZ and circularity as a function of the process parameters. Further, Teaching Learning based Optimization is used to obtain the optimal values of the sheet thickness, spot diameter and feed rate to achieve minimal HAZ and maximum circularity.*
Keywords: *PMMA, Laser micro-drilling, Circularity, Heat Affected Zone(HAZ), Regression Analysis, Teaching Learning Based Optimization(TLBO)*

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I. Introduction:

An implant is a medical device which is used to support a damaged biological structure, replace a missing biological structure, or enhance an existing biological structure. Biocompatibility and bio-integration with the host tissue are important considerations for the manufacturing of bio-implants[1]. Polymethyl methacrylate is a non biodegradable polymer which is used for permanent mechanical bio-applications such as in bone tissue integration, dental implants etc[2]. PMMA is also used as a biomaterial for bone cement, drug delivery systems, bone substitutes, dental implants, contact and intraocular lens, vertebrae stabilization in osteoporotic patients, and filler material for skull defects and bone cavities. Ease of manipulation, mechanical properties, low cost, biocompatibility, aesthetics, low toxicity, excellent optical properties etc has made PMMA much more suitable for biomedical applications[3,4].

Machining the implants by conventional machining methods becomes difficult due to the material-specific and application-specific requirements[5]. Conventional machining methods like turning, drilling, milling etc can result in surface defects which can lead to faster degradation of the implants. Laser micro drilling is one of the widely used non-traditional machining processes, that can be used to fabricate features in the range of micro and nano ranges on almost any material [6]. In this process, a laser beam is used to produce a range of features like holes, periodic structures, channels etc by laser ablation. The excellent beam quality of the lasers results in material processing and high precision for micro-manufacturing. Other advantages of laser micromachining include high efficiency, compact installation size, easy integration and scalability[7]. Laser micro drilling finds its applications in fields like aerospace, automotive, biomedical, micro-via hole drilling etc. [8,9]. Laser drilling may be performed in different ways like trepanning, helical drilling, and laser percussion drilling in both continuous and pulsed modes depending upon the diameter of the hole, and sheet thickness[10].

The hole quality of laser micro drilling is affected by several process parameters like the thermal and optical properties of the material, process parameters like the feed rate, pulse repetition frequency, laser power, pulse width, pulse duration, lamp current etc. The investigation of the effect of process parameters on the hole quality has been carried out by many researchers. Mishra et.al [11] assessed the machinability of polymer matrix nanocomposites with different carbon fillers to achieve minimal HAZ and hole taper with cutting speed, pulse frequency, lamp current and air pressure as the parameters. Optimization is performed using Composite Response Surface Methodology(CRSM) and two different metaheuristic techniques. The results indicate more accurate results with the heuristic algorithms as compared to CRSM with an error of 12% and 15% respectively for hole taper and HAZ. Ghoochani et.al [12] developed a model to predict the microchannel characteristics like depth, width and profile with fluence, scanning speed, beam radius, pulse duration and the thermophysical properties as control variables during laser micro drilling of the biocompatible polymer Poly Ether sulfone using a CO_2 laser. The validation of the experimental and theoretical results showed an average deviation of 8.1%. Teixidor et.al [13] investigated the influence of the scanning speed, pulse repetition frequency, and Q-switch delay time on the depth and width of the microchannels during micro channelling of PMMA using a nanosecond laser. The study of the main effect plots showed a linear increase in the channel dimensions increasing Q-switch delay time, hence average power and non-linear increase with increased scanning rate. Stepak et.al [14] performed the cutting optimization of poly(L-lactide) (PLLA) and poly(L-lactide)/hydroxyapatite (PLLA/HAp) composite using femtosecond fibre laser to reduce the heat accumulation effects by considering three different fluence and ablation rates for rates. The results showed an increased cutting efficiency by using multiple, overlapped cuts. Prakash et.al [15] conducted underwater laser micro channelling on PMMA with Nd: YAG laser system to reduce the microcracking, HAZ zone and burr formation. RSM was used to develop a mathematical relationship between lamp current, pulse width, pulse frequency, cutting speed as input parameters to determine channel dimensions. The difficulty in achieving a surface finish with roughness less than ~1 µm Ra for the features obtained by laser micromachining due to the nature of light–matter interaction results in economical infeasibility of producing implants by LMM[16].

The study of the literature shows the necessity of optimizing the process parameters to achieve good dimensional accuracy and surface finish in order the make the LMM an efficient method for the fabrication of biomedical implants. In this present work, Laser micro drilling is performed on PMMA to evaluate the heat-affected zone thickness and circularity. A regression model is developed to predict the HAZ thickness and circularity as functions of sheet thickness, feed rate and spot diameter. The developed equation is used for further optimization using a Teaching learning-based optimization algorithm.

II. Experimentation:

PMMA is a non biodegradable polymer obtained from its monomer through free radical polymerization techniques. It is a transparent polymer from the family of acrylate. The structure of PMMA monomer and polymer are shown in figure-1:

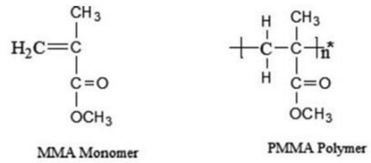

Figure-1 Structure of PMMA[17]

The physical and chemical properties of PMMA are listed in table-1:

Table-1 Properties of PMMA[18]

Property	Value
Thermal Conductivity (W/(m. K))	0.168
Density(kg/m3)	1170
Heat Capacity at Constant pressure(J/(kg.K))	1466
Emissivity	0.9
Latent Heat of Fusion(kJ/kg)	500

PMMA worksheets of three different thicknesses 0.2, 0.3 and 0.5mm are made using 3D printing using Prusa i3 bare upgrade. The machine uses a PMMA filament of 1.75 mm diameter and builds the sheets with a layer height of 0.07mm. The sheets are further used for laser micro drilling with Nd: Yag Femto second Laser Micro Machining system at Central Manufacturing Technology Institute(CMTI), Banglore. The micromachining set-up consists of a laser drilling system consisting of the delivery head, a worktable to position the workpiece and an optical system to achieve the focusing. The relative motion between the workpiece and the lasers is obtained by fixing the laser and movable worktable. The system utilizes nitrogen as an assist gas. A CNC drilling code is prepared with the required parameters to carry out the drilling of the holes in trepanning mode. The micromachining system is shown in Fig-2:

III. Input parameters levels:

In this experimentation, three parameters are considered-sheet thickness, feed rate and the laser spot diameter. The feed rate is considered the speed at which the laser beam interacts with the work material [19]. Feed rate is an important factor as it controls the time of irradiation, a higher feed rate results in low irradiation time, hence lowering the energy absorbed. This results in holes with low dimensional quality, channels with poor aspect ratio and with lower HAZ. Also, the surface roughness increases with increasing feed rate[20-23].

Fig-2: Femtosecond laser Micro Machining System at CMTI

Sheet thickness is another factor that affects the energy required for a laser beam to completely penetrate through the workpiece and also influences the focal setting required for the minimum kerf size and accuracy of the hole[24]. Also, an increase in the sheet thickness increases the depth of the drilled hole, thereby resulting in holes with a higher aspect ratio. High values of aspect ratio influence the power requirements, recast layer formation, penetration laser beam to produce the hole, taper formation of the holes etc[25]. The laser spot diameter directly affects the area irradiated by the laser beam on the workpiece. As the spot diameter increases, the area irradiated by the beam increases, and hence the amount of energy absorbed[26]. The spot diameter also has a significant effect on the specific material removal rate, which decreases with increasing spot diameter[27].

The different levels of parameters used in the experimentation are shown in the table-3

Table 2: Parameter Levels

Parameter	Level-1	Level 2	Level-3
Sheet Thickness(mm)	0.2	0.3	0.5
Feed Rate(mm/s)	0.1	0.5	1
Spot Diameter(μs)	150	225	300

The hole diameters and the heat-affected zone thickness are measured using the Olympus 3D measuring laser microscope LEXT OLS4000 available at CMTI Banglore, which is designed for 3D measurement, nanometre level imaging, and roughness measurement. The magnification for the laser microscope ranges from 108x - 17,280x. In this study, the hole diameters are measured at the entry and exit of the hole. Two diameters d_1 and d_2 are measured at 90^0 intervals for each hole at the entry of the laser beam. Similarly, d_3 and d_4 are considered at the exit. The average diameters at entry and exit are calculated as:

$$d_{entry} = \left(\frac{d_1+d_2}{2}\right) \quad (1)$$

$$d_{exit} = \left(\frac{d_3+d_4}{2}\right) \quad (2)$$

In this work, two-dimensional quality aspects i.e., Heat Affected Zone (HAZ) thickness and hole circularity of the micro holes were considered. HAZ can be defined as the area surrounding the irradiated zone on the workpiece which undergoes microstructural changes as the beam propagated through the workpiece. The microstructural changes arise due to the repeating melting and solidification due to the pulsed mode of operation[28]. There tends to be a decrease in the HAZ as the pulse duration is decreased, which can be represented in fig 3:

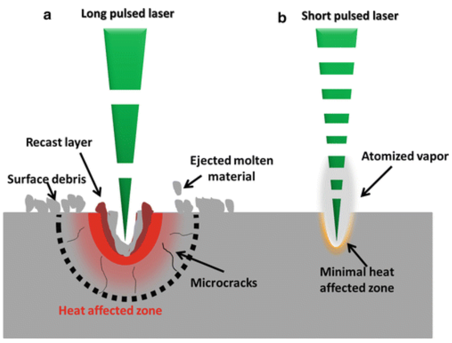

Fig -3: HAZ for different pulses[29]

To measure the HAZ thickness, the maximum diameter for each hole is measured as d_{max}. The HAZ thickness(h_t) at the entry of the hole can be calculated as:

$$h_t = \left(\frac{d_{max} - d_{entry}}{2}\right) \quad (3)$$

Another performance measure considered in this work is hole circularity. The laser beam used for industrial applications generally uses a Gaussian beam profile due to the greater penetrating capacity offered by them. The Gaussian beam generally results in tapered holes, with different diameters at the entry and the exit. The hole circularity is defined as the ratio of the minimum hole diameter to the maximum hole diameter.

$$C = \left(\frac{\min(d_{entry}, d_{exit})}{\max(d_{entry}, d_{exit})}\right) \quad (4)$$

Taguchi L9 Orthogonal array is used to design the number of experiments. Choosing Taguchi design makes the experimentation economical by reducing the number of experiments required to solve the problem and optimize the design. In this present work, the L9 array for 3 factors and 3 levels was chosen. Table-3 shows the obtained values of HAZ thickness and circularity:

Table 3: Obtained values of HAZ

Sheet thickness(mm)	Spot Diameter(μm)	Feed rate (mm/sec)	HAZ(μm)	Circularity
0.2	150	0.1	22.871	0.956671
0.2	225	0.5	49.389	0.949716
0.2	300	1.0	44.622	0.977989
0.3	150	0.5	47.750	0.441254
0.3	225	1.0	48.013	0.920726
0.3	300	0.1	43.526	0.981908
0.5	150	1.0	33.302	0.785474
0.5	225	0.1	47.500	0.910371
0.5	300	0.5	52.014	0.608321

A regression model was developed to predict the values of HAZ thickness and circularity as functions of sheet thickness, spot diameter and feed rate using Minitab 17. The regression model helps to identify a relationship between the dependent and independent variables by hypothesizing the relationship and using the parameter estimates[30]. A general-order linear regression is given by

$$y = \beta_{0+} \sum_{i-1}^{n} \beta_0 X_i + \sum_{i-1}^{n} \beta_{ii} X^2{}_{i+} \sum_{i-1}^{n} \sum_{j-n+1}^{n} \beta_{ij} X_i X_j \quad (5)$$

Where Y is the dependent or the response variable, X is the predictor variable. β_is are the regression coefficients [31]. The method of least squares is used to obtain the coefficients of the regression equation[32]. The second-order regression equations developed for HAZ thickness and circularity for PMMA are as follows:

$$HAZ = 25.8 - (202 * t) + (0.287 * d) + (3.7 * f) + (278 * t^2) - (0.00035 * d^2) - (7.9 * f^2) + (0.022 * t * d) + (45.2 * t * f) \quad (6)$$

$$circularity = 0.715 - (3.11 * t) + (0.00727 * d) - (0.749 * f) + (3.01 * t^2) - (0.000014 * d^2) + (0.445 * f^2) + (0.00025 * t * d) + (0.856 * t * f) \quad (7)$$

An increase in the HAZ thickness tends to reduce the hole quality with greater microstructural changes around the irradiated zone on the workpiece. Also, uniformity in the hole diameter is desired at the entry and exit of the hole which requires the circularity of the hole to be close to one. Therefore, optimization of the process parameters is required to minimize the HAZ thickness and maximize hole circularity.

IV. Teaching Learning Based Optimization(TLBO):

Teaching learning-based Optimization Algorithm proposed by Rao et.al in 2011[33] for the optimization of design problems. The algorithm works based on a population of a group of learners in a classroom. The initial best learner is considered a teacher. The algorithm has two phases- the teaching phase and the learner phase. In the teaching phase, the learners learn from the teacher and in the learner phase the learners learn by interacting among themselves. The main idea behind the implementation of TLBO is that even though all the learners of a class have an equal chance to learn from the teacher, the different capabilities of the learners give rise to different probabilities of learning. The easy implementation, no requirement of specific algorithm parameters and faster convergence makes TLBO an efficient method to solve constrained, large-scale, multi-objective, and dynamic optimization problems[34]. The flow chart for the implementation of TLBO is shown in fig-4:

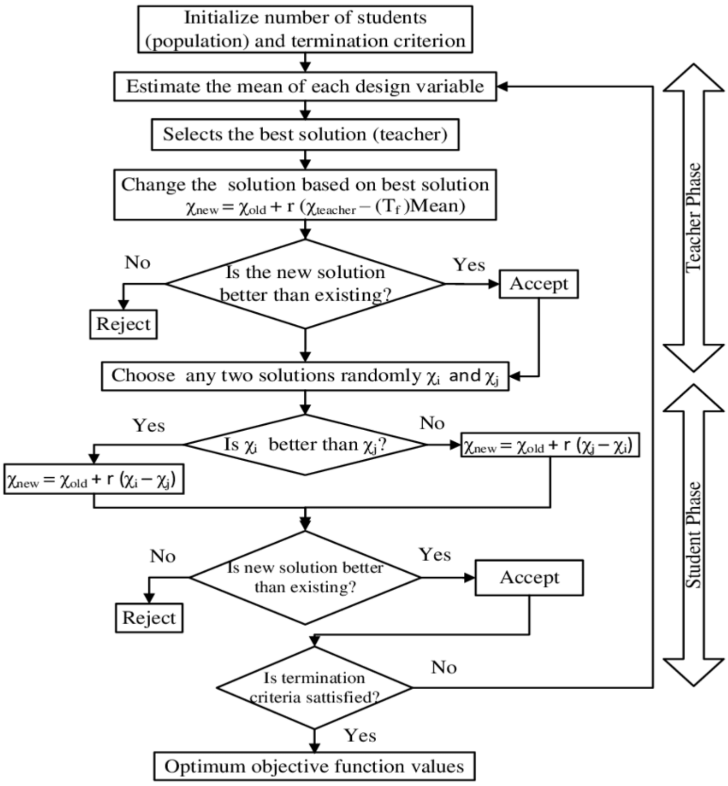

Fig-4: Implementation of TLBO[35]

In this work, the following parameters were chosen to obtain the optimal parameters of sheet thickness, feed rate and spot diameter to achieve minimal HAZ thickness and hole circularity ratio close to one:

- The lower bound and the upper bound were taken respectively as LB=[0.2,150,0.1] and UB=[0.5,300,1] for the chosen parameter levels.
- number of variables m=3;
- population size n=50
- The maximum number of iterations is taken as Maxiter=50;

The regression equations obtained for HAZ thickness and circularity were considered as the objective functions for TLBO. Optimization is performed using MATLAB R2021.Table-4 shows the optimal values of the parameters obtained:

Table- 4 Optimal values obtained from TLBO

Thickness (mm)	Spot Diameter (µm)	Feed Rate (mm/s)	HAZ Thickness (µm)	Circularity
0.4	284.19	0.18	50.3	0.84

The corresponding values of HAZ thickness and circularity for the optimal parameter as obtained from the regression analysis were 48.94 µm for the HAZ thickness and 0.789 for circularity. The results show an error of 2.8% and 8.7% between the optimization and regression values.

V. Conclusions:

The following are the conclusions made from the present work:

- Laser micro drilling is performed on PMMA with laser spot diameter, feed rate and sheet thickness as parameters.
- L9 orthogonal array was considered for experimentation with Heat affected zone thickness as the performance measure.

- The teaching Learning based algorithm for the obtained results shows that the minimal HAZ occurs for thickness 0.4mm, spot diameter 284.19μm and feed rate 0.18 mm/sec. The obtained value of HAZ thickness as per PSO is 50.3μm and circularity is 0.84
- The corresponding value of HAZ and circularity as obtained by regression analysis is 48.94 μm and 0.789 resulting in an error of 2.8% and 8.7% respectively.

References:

[1]. A. Ralls, P. Kumar, M. Misra, and P. L. Menezes, "Material Design and Surface Engineering for Bio-implants," JOM, vol. 72, no. 2, pp. 684–696, Feb. 2020, doi: 10.1007/s11837-019-03687-2.

[2]. O. S. Manoukian et al., "Biomaterials for Tissue Engineering and Regenerative Medicine," in Encyclopedia of Biomedical Engineering, R. Narayan, Ed. Oxford: Elsevier, 2019, pp. 462–482. doi: 10.1016/B978-0-12-801238-3.64098-9.

[3]. M. S. Zafar, "Prosthodontic Applications of Polymethyl Methacrylate (PMMA): An Update," Polymers, vol. 12, no. 10, p. 2299, Oct. 2020, doi: 10.3390/polym12102299.

[4]. R. Q. Frazer, R. T. Byron, P. B. Osborne, and K. P. West, "PMMA: an essential material in medicine and dentistry," J. Long. Term Eff. Med. Implants, vol. 15, no. 6, pp. 629–639, 2005, doi: 10.1615/jlongtermeffmedimplants.v15.i6.60.

[5]. D. Axinte, Y. Guo, Z. Liao, A. J. Shih, R. M'Saoubi, and N. Sugita, "Machining of biocompatible materials — Recent advances," CIRP Ann., vol. 68, no. 2, pp. 629–652, 2019, doi: 10.1016/j.cirp.2019.05.003.

[6]. B. Bhattacharyya and B. Doloi, "Machining processes utilizing thermal energy," in Modern Machining Technology, Elsevier, 2020, pp. 161–363. doi: 10.1016/B978-0-12-812894-7.00004-9.

[7]. U. Klotzbach, A. F. Lasagni, M. Panzner, and V. Franke, "Laser Micromachining," in Fabrication and Characterization in the Micro-Nano Range, vol. 10, F. A. Lasagni and A. F. Lasagni, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 29–46. doi: 10.1007/978-3-642-17782-8_2.

[8]. L. Li, "2 - The challenges ahead for laser macro, micro, and nano manufacturing," in Advances in Laser Materials Processing, J. Lawrence, J. Pou, D. K. Y. Low, and E. Toyserkani, Eds. Woodhead Publishing, 2010, pp. 20–39. doi: 10.1533/9781845699819.1.20.

[9]. G. Chryssolouris and K. Salonitis, "Fundamentals of laser machining of composites," in Machining Technology for Composite Materials, Elsevier, 2012, pp. 266–287. doi: 10.1533/9780857095145.2.266.

[10]. K. L. Dhaker and A. K. Pandey, "Particle Swarm Optimisation of Hole Quality Characteristics in Laser Trepan Drilling of Inconel 718," Def. Sci. J., vol. 69, no. 1, pp. 37–45, Jan. 2019, doi: 10.14429/dsj.69.12879.

[11]. L. Mishra, T. R. Mahapatra, D. Mishra, and S. R. Parimanik, "Investigation of laser micro-drilling machinability and performance optimization of polymer nanocomposites reinforced with different carbon allotropes," Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng., p. 09544089231158898, Mar. 2023, doi: 10.1177/09544089231158898.

[12]. D. E. Ghoochani, F. R. Biglari, and H. Pazokian, "Pulsed laser micro-machining of polymer for micro-channel fabrication: Theory and experiment," Infrared Phys. Technol., vol. 102, p. 103068, Nov. 2019, doi: 10.1016/j.infrared.2019.103068.

[13]. D. Teixidor, J. Ciurana, T. Thepsonthi, and T. Özel, "Nanosecond Pulsed Laser Micro-Machining of PMMA-based Microfluidic Channels," presented at the Transactions of the North American Manufacturing Research Institution of SME, Jun. 2012, vol. 40.

[14]. B. Stepak, A. Antonczak, and K. Szustakiewicz, "Optimization of femtosecond laser micromachining of polylactide and PLLA/HAp composite," Feb. 2018, p. 70. doi: 10.1117/12.2296433.

[15]. S. Prakash, B. Acherjee, A. S. Kuar, and S. Mitra, "An experimental investigation on Nd:YAG laser microchanneling on polymethyl methacrylate submerged in water," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 227, no. 4, pp. 508–519, Apr. 2013, doi: 10.1177/0954405412472178.

[16]. E. Kažukauskas, S. Butkus, P. Tokarski, V. Jukna, M. Barkauskas, and V. Sirutkaitis, "Micromachining of Transparent Biocompatible Polymers Applied in Medicine Using Bursts of Femtosecond Laser Pulses," Micromachines, vol. 11, no. 12, Art. no. 12, Dec. 2020, doi: 10.3390/mi11121093.

[17]. "PMMA." http://www.mit.edu/~6.777/matprops/pmma.htm (accessed Dec. 06, 2021).

[18]. "TSD 0021 Material Properties Web.pdf." Accessed: Jun. 21, 2022. [Online]. Available: https://www.bangslabs.com/sites/default/files/imce/docs/TSD%200021%20Material%20Properties%20Web.pdf

[19]. H. Lavvafi, "EFFECTS OF LASER MACHINING ON STRUCTURE AND FATIGUE OF 316LVM BIOMEDICAL WIRES," phd, CASE WESTERN RESERVE UNIVERSITY, CLEVELAND, Ohio, 2013.

[20]. N. Rajaram, J. Sheikh-Ahmad, and S. H. Cheraghi, "CO2 laser cut quality of 4130 steel," Int. J. Mach. Tools Manuf., vol. 43, no. 4, pp. 351–358, Mar. 2003, doi: 10.1016/S0890-6955(02)00270-5.

[21]. K. A. Ghany and M. Newishy, "Cutting of 1.2mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser," J. Mater. Process. Technol., vol. 168, no. 3, pp. 438–447, Oct. 2005, doi: 10.1016/j.jmatprotec.2005.02.251.

[22]. J. P. Davim, N. Barricas, M. Conceição, and C. Oliveira, "Some experimental studies on CO2 laser cutting quality of polymeric materials," J. Mater. Process. Technol., vol. 198, no. 1–3, pp. 99–104, Mar. 2008, doi: 10.1016/j.jmatprotec.2007.06.056.

[23]. S. Bhandari, M. Murnal, J. Cao, and K. Ehmann, "Comparative Experimental Investigation of Micro-channel Fabrication in Ti Alloys by Laser Ablation and Laser-induced Plasma Micro-machining," Procedia Manuf., vol. 34, pp. 418–423, 2019, doi: 10.1016/j.promfg.2019.06.186.

[24]. C. Karatas, O. Keles, I. Uslan, and Y. Usta, "Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation," J. Mater. Process. Technol., vol. 172, no. 1, pp. 22–29, Feb. 2006, doi: 10.1016/j.jmatprotec.2005.08.017.

[25]. V. Nasrollahi, P. Penchev, T. Jwad, S. Dimov, K. Kim, and C. Im, "Drilling of micron-scale high aspect ratio holes with ultra-short pulsed lasers: Critical effects of focusing lenses and fluence on the resulting holes' morphology," Opt. Lasers Eng., vol. 110, pp. 315–322, Nov. 2018, doi: 10.1016/j.optlaseng.2018.04.024.

[26]. K. Ding and L. Ye, "Physical and mechanical mechanisms of laser shock peening," in Laser Shock Peening, Elsevier, 2006, pp. 7–46. doi: 10.1533/9781845691097.7.

[27]. M. Chaja, T. Kramer, and B. Neuenschwander, "Influence of laser spot size and shape on ablation efficiency using ultrashort pulse laser system," Procedia CIRP, vol. 74, pp. 300–304, Jan. 2018, doi: 10.1016/j.procir.2018.08.119.

[28]. A. Jain, B. Singh, and Y. Shrivastava, "Analysis of heat affected zone (HAZ) during micro-drilling of a new hybrid composite," in Proceedings of the Institution of Mechanical Engineers, Part C, Sep. 2019. doi: 10.1177/0954406219877911.

[29]. R. Agrawal and C. Wang, "Laser Beam Machining," in Encyclopedia of Nanotechnology, B. Bhushan, Ed. Dordrecht: Springer Netherlands, 2016, pp. 1739–1753. doi: 10.1007/978-94-017-9780-1_101020.

[30]. "https://www.britannica.com/science/statistics." https://www.britannica.com/science/statistics

[31]. H. Guo and A. Mettas, “Design of Experiments and Data Analysis,” in 2012 Annual RELIABILITY and MAINTAINABILITY Symposium, 2012.
[32]. K. L. Dhaker and A. K. Pandey, “Particle Swarm Optimisation of Hole Quality Characteristics in Laser Trepan Drilling of Inconel 718,” Def. Sci. J., vol. 69, no. 1, pp. 37–45, Jan. 2019, doi: 10.14429/dsj.69.12879.
[33]. R. V. Rao, V. J. Savsani, and D. P. Vakharia, “Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems,” Comput.-Aided Des., vol. 43, no. 3, pp. 303–315, Mar. 2011, doi: 10.1016/j.cad.2010.12.015.
[34]. X. Chen, B. Xu, K. Yu, and W. Du, “Teaching-Learning-Based Optimization with Learning Enthusiasm Mechanism and Its Application in Chemical Engineering,” J. Appl. Math., vol. 2018, p. e1806947, May 2018, doi: 10.1155/2018/1806947.
[35]. S. R. Salkuti, “Solving optimal generation scheduling problem of microgrid using teaching learning based optimization algorithm,” Indones. J. Electr. Eng. Comput. Sci., vol. 17, p. 1632, Mar. 2020, doi: 10.11591/ijeecs.v17.i3.pp1632-1638.

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