Residual Stress and Surface Roughness Minimization in Laser Cutting of 304L Stainless Steel

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Abstract:

Laser cutting is a widely used process in industry for cutting metals, plastics, and other materials. However, it can result in residual stresses and surface roughness, which can affect the quality and performance of the final product. Thus, minimizing residual stress and surface roughness in laser cutting is an important research topic in the field of part manufacturing to enhance reliability and performance of machined parts. A virtual machining system for predicting and minimizing residual stress and surface roughness in laser cutting operations is developed using simulation and optimization techniques. The Stainless Steel Johnson Cook models are used to calculate the cutting temperature throughout laser cutting operations. The residual stress during laser cutting process is then calculated using the finite element approach. To minimize the Residual Stress and Surface Roughness in the operations, the Taguchi optimization technique is utilized to obtain the optimum cutting speed, laser power and beam size during cutting operations. Thus, using the optimized machining parameters, the residual stresses and surface roughness of the sample machined parts are decreased by 23.3% and 25.8%

respectively. Therefore, the developed virtual machining procedures can be an effective tool in enhancing reliability and performance of machined parts using laser cutting operations.

Keywords: Laser cutting operations, Residual Stress, Surface Roughness, Taguchi optimization, Steel Alloys

1- Introduction

Laser cutting is a widely adopted technique in the manufacturing industries due to its precision, speed, and versatility. During the laser cutting operations, a material is melted, evaporated, or burnt by utilizing a strong laser beam which is used for cutting a range of materials, including steels alloys. A computer-controlled system that directs the laser beam enables rapid and effective creation of accurate cuts and shapes. In the thermal cutting method such as laser cutting, the workpiece material is melted and evaporated using a strong laser beam. During the process, a powerful laser beam is used to pierce the workpiece materials, generally with the assistance of computer-controlled equipment. The laser beam is focussed through a lens, causing the material on the workpiece to melt and evaporate, leaving a tiny kerf or cut behind. Uneven contraction and expansion can result from a material which has been heated and then rapidly cooled due to there is a temperature differential across the material's thickness. So, the localized heating and rapid cooling during the laser cutting operations induce residual stresses which can lead to distortions and weakening of workpiece material. So, the workpiece material under load of working conditions may deform, fracture, or even break as a result of residual stresses. Therefore, it is important to understand and minimize residual stresses in laser-cut components to ensure the reliability and enhance fatigue life of machined parts.

Surface roughness is a common quality measure used in laser cutting operations which refers to the deviation of the actual surface from an ideal smooth surface. Laser cutting produces a relatively smooth surface with a low roughness value compared to other cutting methods such as plasma cutting as well as water jet cutting operations. However, achieving optimal surface quality remains a critical challenge during laser cutting operations. In laser cutting, the surface roughness can be affected by various factors, such as the laser power, the cutting speed, the beam diameter, and the assist gas used. As a result, minimizing both residual stress and surface roughness is crucial for ensuring the structural integrity and functional performance of laser-cutting operations in terms of accuracy as well as productivity enhancement of part production process.

In order to obtain the desired surface quality while minimizing thermal damage to the material, it is crucial to optimize the cutting process variables, including laser power, cutting speed, beam diameter, and assist gas. By optimizing the cutting parameters, such as raising the laser power, decreasing the cutting speed, or shifting the focus location, the roughness of the cut edge can be minimized. By boosting laser output, slackening cutting speed, and employing a smaller beam diameter, the roughness of the cut surface may be minimized. The quality of the cut edge can be impacted by these changes as well as increased heat damage and residual stress on the material.

Roughness of surface and residual stress reduction in laser cutting processes have been the subject of several investigations. Several methods have been suggested in the literature to reduce residual tensions during laser cutting. Utilizing a pulsed laser is one method that can lower the heat input and decrease material thermal distortion. A high-pressure gas jet is another technique that may be used to remove the molten material and lessen the heat-affected zone. Using various methods, surface roughness in laser cutting may also be reduced. To improve the cutting process, one method is to modify the laser beam's focal length, pulse width, and power density. Utilizing a protective gas is another way to stop oxidation and enhance the cut's quality. To further enhance the quality of a machined surface, post-processing methods like sanding, polishing, or shot blasting can be used.

Balbaa et al [1] experimentally determine the updated machining settings for Inconel 718 laser operations in order to achieve desired component qualities like residual stresses and surface roughness. The impacts of cutting variables, such as the strength of the laser beam and the speed of the nozzle's motion, are experimentally explored by Boujelbene et al. [2] to increase the quality of the surface of machined titanium parts using CO2 laser cutting. Residual stress and roughness of surface during the laser melted of AlSi10Mg is experimentally investigated by Schneller et al. [3] to analyze and increase fatigue strength of produced structures. the impact of AISI316L edge quality and operating cost on CO2 laser cutting process variables such as velocity of cutting and laser energy is experimentally analyzed by Eltawahni et al. [4] to improve component quality through the execution of optimized machining conditions. To enhance surface quality and decrease residual stress in laser shock peening operations, impacts of machining parameters such as peak pressure of laser shock wave and Hugoniot Elastic Limit (HEL) of workpiece is investigated by Dai et al. [5]. To estimate and reduce residual stress during laser bending operations, Kotobi et al. [6] presented an experimental and numerical examination of residual stress of laser-bent Ti materials. Reduction of surface roughness through laser shock peening of X12Cr steel turbine blades is investigated by Fameso [7] to improve the condition of the surface of the manufactured turbine blades by performing laser shock peening procedures. To enhance the surface functionality of machined elements produced through laser cutting techniques, Ninikas et al. [8] examined the effects of procedure variables on the precision of dimension and surface texture throughout CO2 laser cutting of PMMA thin sheets. to reduce the surface's roughness and continued stress when performing laser shock peening procedures, Attolico et al. [9] conducted a research investigation on the implications of laser shock peening on AA 7050-T7451. To improve surface finish during the laser shock wave planishing operations of LY2 aluminum alloy, the experimental investigations is proposed by Dai et al. [10].

To enhance the performances of machined components employing turning operations, Lakshmikanthan et al. [11] provided a multi-objective optimization of machining parameters using response surface methods on aluminum alloy metal matrix composites. Nemati et al. [12] implemented multi-objective optimization of electrochemical finishing to maximize the rate of material removal while achieving a predetermined level of surface roughness and dimensional precision in the hole-making procedure. In order to improve surface quality and geometric accuracy of machined parts, Das and Chakraborty [13] present the application of the grey correlation-based EDAS technique for parametric optimization of the photochemical machining process, the laser-assisted jet electrochemical machining process, and the abrasive water jet drilling process. To improve the mechanical characteristics and strength of dissimilar welding of titanium grade 2 and aluminum 3105-O alloy, Shehab et al.[14] discussed the effect of welding speed on the microstructure and mechanical properties of the welded components using a high-energy laser instrument. Experimental and numerical study of laser assisted machining operations of ceramics is implemented by Roostai et al. [15] to enhance the machinability of hard-to-cut materials.

To minimize residual stress during powder mixed near-dry electric discharge machining operations, optimized machining parameters is presented by Sundriyal et al. [16]. Azari and Aali [17] proposed an experimental research work of the impact of CO2 laser machining on the electrical conductivity and magnetic characteristics of PMMA/MWCNT composite to improve and assess the mechanical properties of machined components under real-world operating circumstances. To calibrate and tune a Laser Assisted Micro-Machining (LAMM) process with two correlated outputs, Khalaj et al. [18] provide statistical modification and calibration of laser machining operations. Ghasemzadeh et al. [19] have established a road plan for the application of Building Information Modeling in infrastructure sectors to ensure the appropriate execution of infrastructure projects. Karimi Ghaleh

Jough and Beheshti Aval [20] have implemented an adaptive neuro-fuzzy inference system based on fuzzy C-means algorithm to develop a seismic fragility curve for an SMRF structure in order to reduces uncertainties related to seismic loads and structural modeling.

To determine machining variables' impacts such laser power, speed of cutting, , depth of cut and rate of feed on the surface roughness of machined components, Khatir et al. [21] conducted an experimental analysis of surface imperfections in laser-assisted hard turning of AISI 4340. To improve the functionality of machined components produced utilizing selective laser melting procedures, Lesyk et al. [22] conducted a study experiment on the impacts of mechanical treatment of the surface on surface elevation, porousness, robustness, and residual stress. To assess and enhance the durability of machined elements produced by selective laser melting techniques, Zhang et al. [23] conducted experimental research on the quality of surfaces, residual stress, fatigue properties of 304L stainless steel. Surface roughness prediction using artificial neural networks during laser cutting operations of thin thermoplastic plates is investigated by Kechagias et al. [24] to analyze and enhance quality of machined component surfaces using the laser cutting operations. During laser shock peening, the impacts of residual stress and surface abrasiveness on a nickel aluminum bronze alloy's fatigue life are evaluated by Gao et al. [25] to improve the durability of manufactured parts using laser peening operations. Experimental investigation of the impact of centrifugal shot peening on the surface characteristics of laser-cut C45 steel parts is presented by Skoczylas et al. [26] to enhance the surface quality of produced items. Residual stress determination on selective laser melting operations of Al Alloy using XRD is experimentally investigated by Chen et al. [27] to reduce residual stress through utilization of laser melting operations. To analyze and enhance fatigue behavior of produced Ti-6Al-4V parts with a curved surface using laser peened operations, residual stress distribution is experimentally investigated by Praveenkumar et al. [28]. To analyze and optimize performance of 3D printing processes, the Taguchi's design approach is studied and implemented by Kechagias [29]. Taguchi and full factorial design in turning operations of Ti6Al4V ELI alloy is implemented by Kechagias et al. [30] to analyze and minimize cutting forces and surface roughness in machining operations of difficult to cut materials.

To assess and improve CNC machining in simulated environments, virtual machining techniques are applied by Soori et al. [31-34]. To increase the longevity of the cutting tools utilized during machining operations, Soori and Arezoo [35] investigated several tool wear prediction methods. Soori and Asamel [36] explored the utilization of virtual machining technology to reduce residual stress and displacement inaccuracy during milling operations of turbine blades. To reduce displacement error while machining impeller blades using five axes milling machines, virtual milling techniques were developed by Soori and Asmael [37]. Measurement and reduction of residual stress in machining processes was discussed by Soori and Arezoo [38]. Soori and Arezoo [35] studied multiple techniques for predicting tool wear to extend the life of cutting tools throughout the machining procedure. Soori and Arezoo [39] employ the Taguchi optimization approach during the grinding processes using Inconel 718 to optimize the machining parameters, decrease residual stress, and maintain the surface integrity.

Soori and Arezoo [40] examined how coolant affected tool wear, cutting temperatures, and surface quality during turning operations utilizing Ti6Al4V alloy. To minimize cutting wear of cutting tool in drilling operations, Soori and Arezoo [41] designed a virtual machining system. To improve product quality created through abrasive water jet machining, Soori and Arezoo [42] roughness of surface minimized and residual stress. Deformation errors are assessed and reduced by Soori [43] to raise precision while machining turbine blades.

Previous research works in laser cutting operations has predominantly relied on experimental methods to analyze and optimize surface roughness and residual stress, which are both costly and time-consuming processes. The study introduces a novel approach by developing and utilizing a virtual machining system specifically designed to predict and minimize residual stress and surface roughness in laser cutting of 304L stainless steel. This approach in application of virtual machining systems for laser cutting operations not only reduces the dependency on extensive experimental trials but also provides a robust framework for improving the quality and reliability of laser-cut components. Thus, a virtual machining system which can optimize the machining parameters in order to minimize the surface roughness and residual stress of machined parts during laser cutting operations can provide a key tool in terms of productivity and accuracy enhancement of part manufacturing process.

To predict and minimize surface imperfections and residual stress throughout laser cutting operations, a virtual machining system is created. This system can use advanced computational modeling techniques and simulations to predict the behavior of the material during the laser cutting process. Once the virtual model has been created, simulation software can be used to predict the residual stress and surface roughness that will be produced by the laser cutting process. This can be done by running simulations of the virtual model with different input parameters and analyzing the resulting outputs. A thermal model of the laser cutting procedure is developed using finite element analysis (FEA). The model can consider the parameters of laser's power and speed of cutting during FEM calculation. This model can simulate the heat transfer process and predict the temperature distribution and thermal history of the material during cutting. Thus, generated residual stress while using a laser cutter are predicted using the proposed virtual machining procedure. Also, the virtual machining system can predict surface imperfections after the laser cutting process. This can be done using a presented surface roughness model that takes into account the cutting variables and the mechanical properties of workpiece materials. To minimize residual stress and surface imperfections while employing laser cutter, optimized machining parameters of laser power and cutting speed are obtained using the Taguchi optimization approach. Using the simulation results, the virtual machining system can then optimize the laser cutting parameters to minimize surface integrity and residual stress. To get the required results, it could be required to optimize the speed of cutting, power of laser and beam size. After optimizing the laser cutting variables, the virtual machining system can verify the results using experimental data. The validation processes involve running physical tests of the laser cutting process using the optimized parameters and comparing the results to the simulation predictions. Thus, virtual machining system can be an effective tool for assessing and minimizing residual stress and roughness of surface in laser cutting operations. It can save time and resources by allowing for simulations and optimizations to be done before any physical cutting is implemented.

Heating analysis and temperature prediction of laser cutting is presented in section 2. The modified Jonson-Cook model of steel alloys is presented in section 3. Surface roughness in laser cutting operations is described in section 4. Taguchi optimization approach of laser cutting operations is explained in section 5. Virtual machining system to calculate and minimize roughness of surface and residual stress in laser cutting operations is proposed in section 6. Section 7 presents modeling and verification of the study. Section 8 of the research presents the output results.

2- Heating analysis and temperature prediction of laser cutting operations

When laser cutting is implemented, the transitory condition is connected to the laser heating process. An appropriate transient heating model for laser processing is necessary for the heat transfer investigation. The transient heat transfer model can be expressed in Cartesian coordinates as follows,

$$\rho \frac{DE}{Dt} = (\nabla(k\nabla T)) + S_0 \tag{1}$$

where E is the substrate material's energy absorption and S_0 is source of volumetric heat. It is assumed that the source of laser heating is Guassian at the surface (x, z)-plane with the Guassian diameter “a”. Also, the surface area is where the beam becomes absorbed in the y-axis absorption thickness. Therefore, the volumetric source is,

$$S_0 = I_0\delta(1-r_f)e^{-\delta y}e^{(-(x^2+z^2/a^2))} \tag{2}$$

Where, I_0 is intensity of laser peak, δ is depth of absorption, r_f is radiance of the surface, and x and z are axes of cutting operations.

$$\rho\frac{DE}{Dt} = \rho\frac{\partial E}{\partial t} - \rho U\frac{\partial E}{\partial z} \tag{3}$$

Or

$$\rho\frac{DE}{Dt} = \rho\frac{\partial (C_p T)}{\partial t} - \rho U\frac{\partial (C_p T)}{\partial z} \tag{4}$$

So, by combining Eq. (1) and Eq. (3),

$$\rho\frac{\partial (C_p T)}{\partial t} = (\nabla(K\nabla T)) + \rho U\frac{\partial (C_p T)}{\partial z} + S_0 \tag{5}$$

where ρ is the density, C_p is specific capacity of heat, k is conductivity of thermal effects, and U is speed of sample part along the Z-axis. Since the cutting region catches the internal reflection, the laser beam's reflection from the cut edges is not taken into consideration in the cutting analysis. As a consequence, the laser beam's radiation reflection loss solely affects the substrate material's free surface. Additionally, the convective boundary is assumed at the workpiece's free surfaces and the boundary constraints for convection and radiation are taken into account at the workpiece's reverse side. So, the surface with radiation damage has the following boundary condition,

$$\frac{\partial T}{\partial z} = \frac{h}{k}(T_s - T_{amb}) \tag{6}$$

Also, the rear side of surface is,

$$\frac{\partial T}{\partial y} = \frac{h}{k}(T_s - T_{amb}) + \frac{\varepsilon\sigma}{k}(T_s^4 - T_{amb}^4) \tag{7}$$

$$\frac{\partial T}{\partial z} = \frac{h}{k}(T_s - T_{amb}) \tag{8}$$

where h is heat transfer variables associated with natural convection, and T_s and T_{amb} are temperatures of the workpiece's surface and surrounding areas respectively, ε is the emissivity which is considered as ε=0.9, σ is constant of Stefan–Boltzmann (σ=5.67×10−8 W/m2 K). At a far boundaries (the outside limits of the solution region), as $x = \infty, y = \infty, z = \infty$, boundary of constant temperature is assumed T=293 K. It is expected that the base material will initially stay at room temperature before laser cutting, i.e., T=Tamb, that can be recognized as Tamb=293 K. To calculate the substrate material's thermal field, Eq. (5) is computed numerically with the required boundary conditions. To study the phase change issue, a non-linear instantaneous thermal investigation utilizing the enthalpy technique is performed. In order to take into consideration for the evolution of latent heat during phase shift, the energy equation includes the material's enthalpy as a function of temperature. Temperature and stainless steel (duplex) laser cutting parameters have the following relationships [44],

$$Temp = 338 + 53.5\text{speed - }1.064\text{power + }533\text{focal length - }52.35\text{speed + } \\ 0.4525\text{speed} * \text{power - }0.625\text{power} * \text{focallength} \tag{9}$$

3- Jonson-Cook model

Due to high precision and theoretical simplicity of the Johnson-Cook approach, it is used to determine how much stress is distributed throughout a material regarding to the different strain inputs, influences of cutting temperature, and strain rate. The three variables describe how the flow stress of the components during plastic strain is affected by hardening by strain, hardening via strain rate, and heat relaxation. Due to its versatility in FEM investigation, the method is utilized to gauge the distortion predispositions of various substances. The Johnson–Cook methodology can be presented as [45].

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\frac{\overset{\circ}{\varepsilon}}{\overset{\circ}{\varepsilon}_0})\left[1 - (\frac{T - T_0}{T_m - T_0})^m\right] \tag{10}$$

Where ε is identical plastic rigidity, $\overset{\circ}{\varepsilon}$ and $\overset{\circ}{\varepsilon}_0$ are the identical and principal rates of plastic strain, T, T_m and T_0 are the cutting area temperature, point of melting and temperatures of experimental environments respectively. The m is heat-softening index, while the index of strain hardening is N. The material's rates of yield strength, strain, and strain sensitivity are denoted by letters A, B, and C, respectively.

According to the Johnson-Cook theory, the three influencing factors of tension, strain magnitude, and heat are entirely independent of one another, eliminating any influence factor's cumulative impact. It is challenging to predict such strain rate dependency when applying the common Johnson-Cook approach. The developed Johnson-Cook model can introduce additional parameters to better capture the material behaviour. These parameters could account for specific phenomena like strain hardening, thermal softening, sensitivity of strain rate and strain rate dependency [46]. The upgraded Johnson-Cook model is presented by Lin et al. [47] to solve the weaknesses of Johnson-Cook as Eq (13),

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_1 \ln \varepsilon^{\circ}) \exp\left[(\lambda_1 + \lambda_2 \ln \varepsilon^{\circ})(T - T_{ref})\right] \quad (11)$$

Where, A_1, B_1, B_2, C_1, λ_1 and λ_2 are material characteristics, and the values of the other parameters are identical to those in the Johnson-Cook method. T_{ref} is temperature of experimental room. The modified Johnson–Cook model for the steel alloys is obtained as Eq. (12) [48].

$$\begin{aligned} \sigma &= (32.76109 + 270.75562\varepsilon + 452.3822\varepsilon^2)(1 + 0.14759 \ln \frac{\varepsilon^{\circ}}{\varepsilon_0^{\circ}}) \\ &\times \exp\left[(-0.0051 + 0.0091 \ln \frac{\varepsilon^{\circ}}{\varepsilon_0^{\circ}})(T - 1173)\right] \end{aligned} \quad (12)$$

4- Surface roughness in laser cutting operations

The surface quality of the cut edge is an important consideration in laser cutting operations, particularly for applications where the cut edge will be visible or require further processing. The edge quality will depend on a variety of factors, including the laser power, speed of cutting, assist gas, and type of steel being cut. Equation (13), which depicts the correlation between roughness of surface and variables of laser cutting for stainless steel alloys, includes linear, square, and nonlinear variables as [44],

$$\begin{aligned} Ra &= 18.7 - 3.54\text{speed} - 0.0156\text{power} + 0.12\ \text{focallength} + 0.338\text{speed} * \text{speed} \\ &+ 0.00163\text{speed} * \text{power} + 0.00075\text{power} * \text{focallength} \end{aligned} \quad (13)$$

5- Taguchi optimization approach of laser cutting operations

The Taguchi methodology is an effective and powerful optimization approach that can greatly improve process performance with a small number of experiments. By figuring out the best values for the objective functions, the optimization process reduces the costs associated with cycle time and production in manufacturing processes. The flowchart for Taguchi optimization approach is shown in Figure 1.

The signal-to-noise ratio (S/N) for each control element is determined to assess the impact of EDM settings on the response characteristic. The signals show how the influence on average answers has changed over time. The noises estimate the effect of noise components on deviations from average responses while taking into account how sensitive the experiment's outcome is to noise. The response analysis method employs a variety of quality standards, including the nominal-the-better, the lower-the-better, and the higher-the-better. In order to reduce the response during the optimization process, the S/N ratio is chosen using the lower-the-better criteria. The following is a representation of the smaller-is-better S/N ratio [49].

$$S/N = -10\log\frac{1}{n}(\sum_{i=1}^{n} yi^2) \quad (14)$$

where, n indicates the number of times the experiment was carried out and yi is the experimental data's mean measured value i.

The selection of laser cutting parameters such as cutting speed, power of laser and beam size for optimization process is based on their direct impact on the physical phenomena during laser cutting operations. Cutting speed influences the interaction time between the laser beam and the material, impacting the heat affected zone and the quality of the cutting process. Laser power determines the energy input into the material, affecting the cutting temperature and, consequently, the residual stress and surface roughness of produced parts. Beam diameter affects the precision and intensity of the laser cutting process, playing a crucial role in defining the cut edge quality. To minimize residual stress and surface roughness during laser cutting operations, the Taguchi optimization method is applied. Thus, the overall performance and productivity of laser cutting operations can be enhanced using optimized machining parameters.

6- Virtual machining system to predict and minimize residual stress and surface roughness in laser cutting operations

The purpose of the developed virtual machining systems in the study is to lessen residual stress and surface integrity in products produced through laser cutting operations. The effective parameters of laser cutting in roughness of surface and residual stress of machined components including laser power, cutting speed and beam size are considered in order to be optimized. Once the thermal model is established, a stress model can be developed using the modified Jonson-Cook model to evaluate residual stresses in the material. This model is capable of accounting for both the material's physical characteristics as well as its thermal behavior throughout the procedure of cutting. It can predict the residual stresses that are left in the material after the laser cutting process is complete. The created virtual machining system can also forecast surface roughness during laser cutting process. This can be accomplished by utilizing a surface roughness equation which considers both the material's characteristics and the laser cutting settings. The laser cutting process configurations can then be optimized by employing the virtual machining technology. Next, the Taguchi optimization approach is used to calculate the optimized parameters of laser power, cutting speed and beam size during cutting operations. Thus, using the optimized parameters of lase cutting operations, residual stress and surface roughness can be minimized in the machined components. Figure 2 shows the flowchart of the virtual machining system that has been developed to minimize roughness of surface and residual stress throughout laser cutting procedures.

As a consequence, residual stress and the surface condition of machined parts produced by laser cutting can be reduced while continuing to enhance component quality by employing the optimized machining tools.

7- Simulation and validation

Utilizing the Glory Star fiber laser cutting system, expressional works are carried out to verify the methodology created in the research study. In the experimental works, a pulsed, variable-frequency CO2 laser with a nominal output power of 6000 W is utilized. The laser beam is focused by a 127 mm focal lens. The laser power and cutting speed are 6000 watts and 40 mm⁄min respectively. While laser cutting operation, the workpiece is placed on a CNC table and the laser beam is pointed at the sample plate. The sample workpice in the study is 304L Stainless Steel and sample thickness is 14 mm. The process of lase cutting during the experimental work of study is depicted in the figure 3.

A broader range of experimental conditions can be implemented to test the model's predictions against varied laser power settings, cutting speeds, and material thicknesses. In addition to the nominal output power of 6000 W, include lower power settings such as 3000 W and 4500 W, as well as higher settings like 7500 W and 9000 W. The current cutting speed is 40 mm/min. Additional speeds can also be tested, such as 20 mm/min, 60 mm/min, and 80 mm/min. The study currently uses 304L Stainless Steel with a thickness of 14 mm. To assess the model's performance with varying material profiles, it can be helpful to incorporate both thinner materials (7 mm and 10 mm) and thicker ones (18 mm and 22 mm).

The used device to measure surface imperfections of the machined sample workpiece is Mitutoyo SJ210. Also, the JIS2001 is the referenced standard for measurement process of surface roughness. 0.8, 0.5 mm/s, and x5 are cut-off value (λc), measurement speed, and number of sampling lengths (N), respectively. Surface roughness is measured using stylus tip parameters of 2 m, 60°, and 0.75 mN measuring force. The used surface roughness tester and surface roughness measurement process are shown in the figure 4.

To measure residual stress of sample part, The Bruker D8 Focus X-ray diffractometers is used which is equipped with state-of-the-art detectors that can capture detailed diffraction patterns with high sensitivity and speed. Several XRD measurements are performed with relation to the various tilt angle ψ in order to measure the residual stress of the sample portion. In this experiment, the tilting angles are set at 0°, 14.9°, 19.5°, 25.2°, 33.8°, 36.4°, 38.8° and 41.3°. The inter-planar spacing or two-theta peak is then identified to produce a plot or curve for the observed data. As a result, the residual stress can be computed using the produced plot and a rudimentary understanding of the material's elastic characteristics. The procedure to assess residual stress usıng an X-ray diffractometer is shown in Figure 5.

The Abaqus R2016X FEM analysis program is utilized to conduct finite element analysis for the laser cutting process. The specific heat capacity of the 304L Stainless Steel is 495 J/kg-K, thermal conductivity 15.8 W/m-K, modulus of elasticity 201 GPa and Poisson ratio 0.27 during the FEM simulation. The cutting edge of the moving heat source is represented as a moving source, producing a temperature that is stated to be higher than the substrate melting point. The time step for thermal analysis was computed utilizing the designated laser speed and the size of the finite element mesh. The simulations take advantage of a configurable density of mesh with elements at least 1 µm in size. FEM Simulation of residual stress on the sample workpiece during laser cutting operations is shown in the figure 6.

In order decrease surface roughness and residual stress throughout laser processing, optimal cutting settings are found using the Taguchi method-based response surface analysis approach. The "lower-is-better" category has been implemented to determine the signal-to-noise ratios for roughness of the surface and residual stress throughout laser machining procedures. As a result, the optimized lase cutting process variables for power of laser, speed of cutting and beam size are obtained as 5000 watts, 30 mm⁄min and 120 mm respectively. Table 1 shows measured and anticipated residual stress without and with optimized machining settings.

The observed and anticipated residual stress without and with optimal machining parameters are shown in Figure 7.

Regression analysis of measured residual stress without optimization process is shown in the figure 8.

Measured and predicted surface roughness of machined plate using laser cutting operation for the 5 selected points are shown in the Table 2.

Regression analysis of measured surface roughness without optimization process is shown in the figure 9.

Prediction accuracy can be influenced by presumptions on heat transport methods, boundary conditions, and material behavior. Moreover, during the laser cutting operations, the interaction between the laser beam and the material involves complex phenomena such as absorption, reflection, and scattering. Uncertainties in modeling these interactions can lead to discrepancies between predicted and measured results.

8- Conclusion

Laser cutting is a widely used process in industry for cutting metals, plastics, and other materials. However, laser cutting can result in residual stresses and surface roughness, which can affect the quality and performance of the final product. So, minimizing residual stress and surface roughness in laser cutting is an important research topic in the field of part manufacturing. The optimized laser cutting process is validated by testing it on actual parts and comparing the results to the predicted values. As a result,

1- Using the optimized machining parameters, the measured and predicted residual stresses of the sample machined parts are decreased by 23.3% and 25.8%, respectively. Also, the measured and predicted sample part's surface roughness was also reduced by 22.1% and 24.4%, respectively.
2- By using the virtual machining system established during the research, it is feasible to reduce the roughness of surface and residual stress of machined items, improving the quality and reliability of the manufactured components while performing laser cutting operations.
3- Using the optimized machining parameters, the measured and predicted residual stresses of the sample machined parts are decreased by 23.3% and 25.8%, respectively. Also, the measured and predicted sample part's surface roughness was also reduced by 22.1% and 24.4%, respectively.

4- By using the virtual machining system established during the research, it is feasible to reduce the roughness of surface and residual stress of machined items, improving the quality and reliability of the manufactured components while performing laser cutting operations.

5- Variations in material properties such as thermal conductivity, specific heat, and absorption coefficient, especially under different temperatures, can affect the accuracy of virtual simulation. Also, variations in the laser cutting operations such as fluctuations in laser power, cutting speed and material in homogeneities can contribute to differences between simulation predictions and actual measurements.

6- Discrepancies can arise due to simplifications and assumptions made in the simulation using the finite element simulation models. Assumptions regarding boundary conditions such as heat loss through convection and radiation in the simulation might differ from the real conditions, impacting the predicted thermal and mechanical responses. The reliability and accuracy of the experimental techniques used to measure residual stress using X-ray diffraction and surface roughness meter device can also cause the errors between the predictions and actual measurements.

7- Long-term performance and durability of the parts under operational conditions should be investigated to fully understand the implications of reduced residual stress and surface roughness of machined parts.

8- To enhance the sustainability of laser cutting operations, energy consumption and generated waste materials can be analyzed ad minimized. Moreover, the laser cutting operations can be combined with other techniques like waterjet or abrasive jet machining in order to decrease the residual stress and enhancing surface quality of produced parts. The ideas are concepts of future research works of the authors.

Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

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Figure:

Fig. 1. The Taguchi optimization approach.

Fig. 2. The flowchart for the virtual machining system designed to reduce roughness of surface and residual stress throughout laser cutting operations.

Fig. 3. Laser cutting operations of sample part.

Fig. 4. The used surface roughness tester and measurement process of surface roughness.

Fig. 5. The measuring process of residual stress using Bruker D8 Focus X-ray diffractometers.

Fig. 6. FEM Simulation of residual stress on the sample workpiece during laser cutting operations.

Fig. 7. Measurement and modeling of residual stress with and without optimal machining conditions.

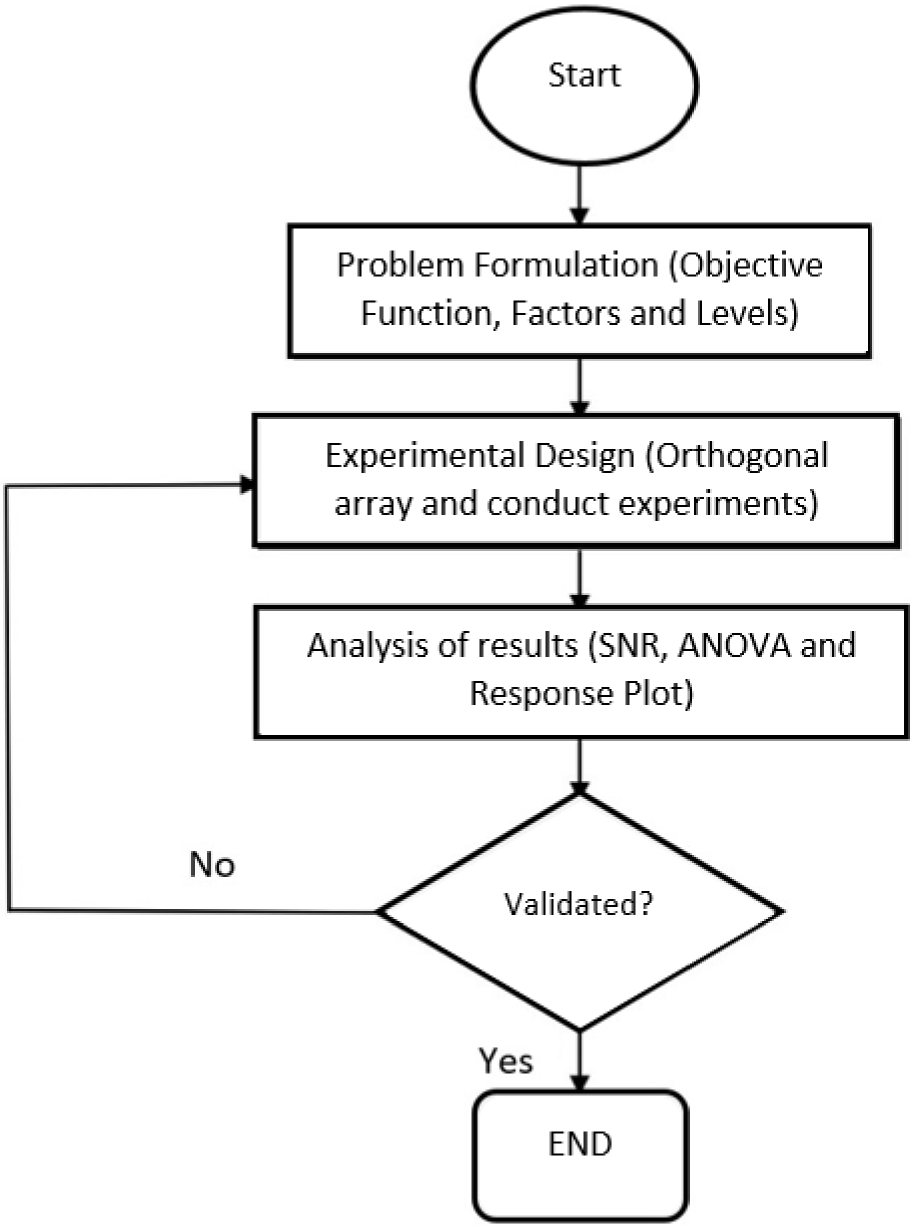
Fig. 8. Regression analysis of measured residual stress without optimization process.

Fig. 9. Regression analysis of measured surface roughness without optimization process.

Table:

Table 1. Residual stress measurements and predictions without and with optimized variables for machining.

Table 2. Measuring and predicting the machining plate's surface roughness at the five specified places.



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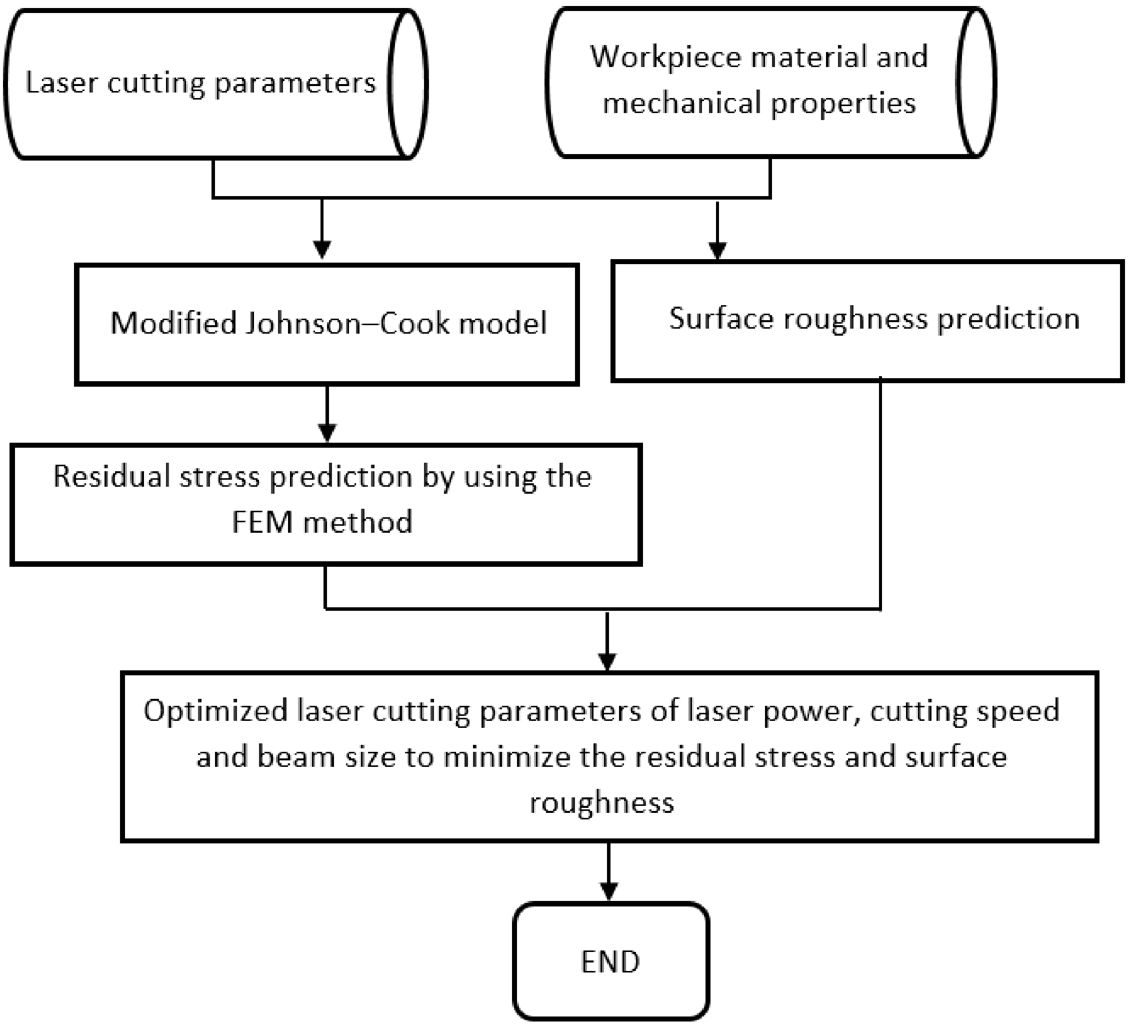

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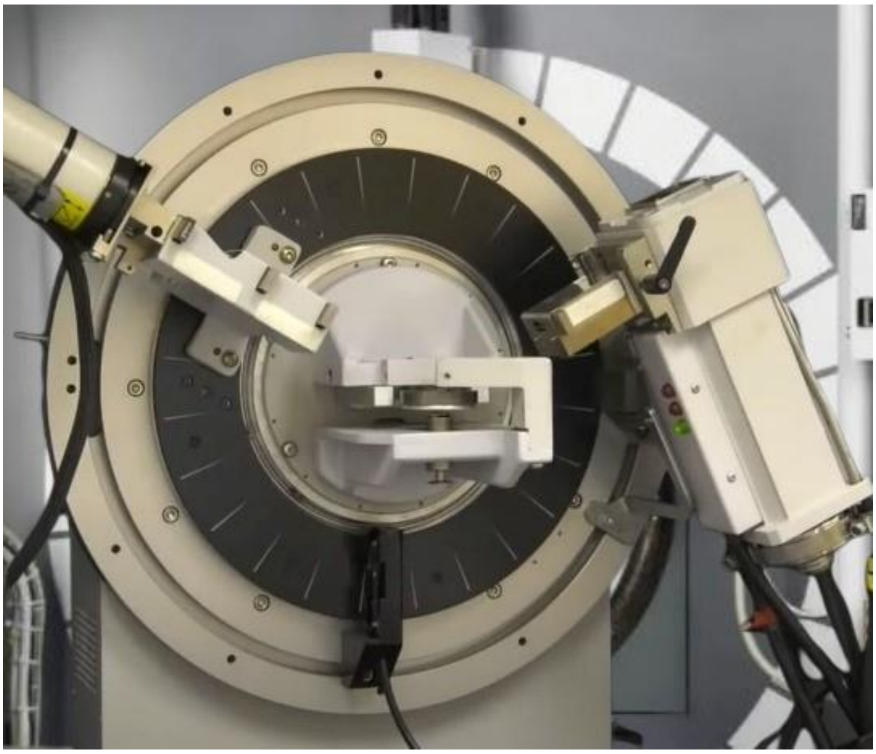

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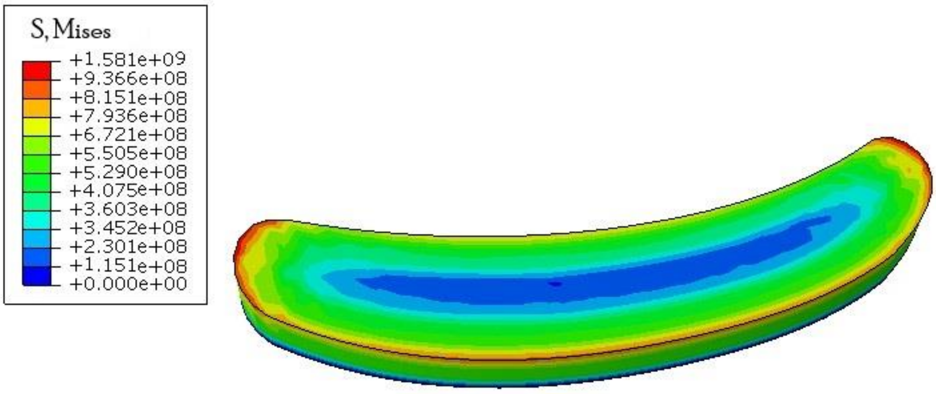

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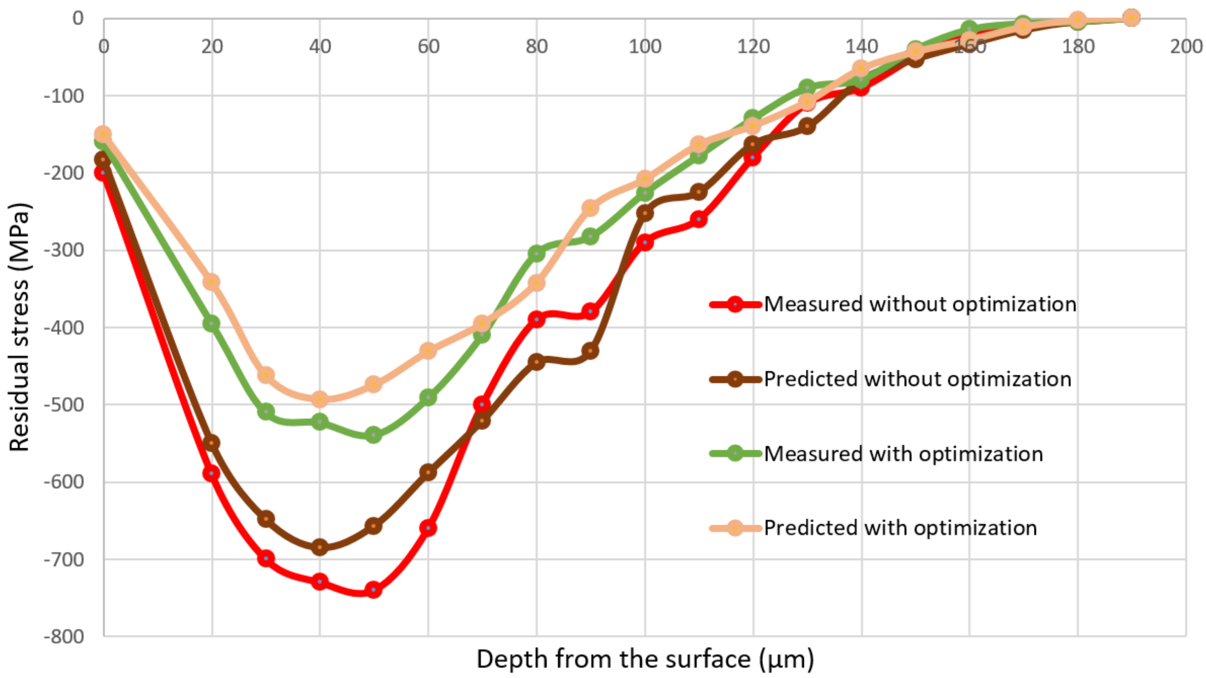

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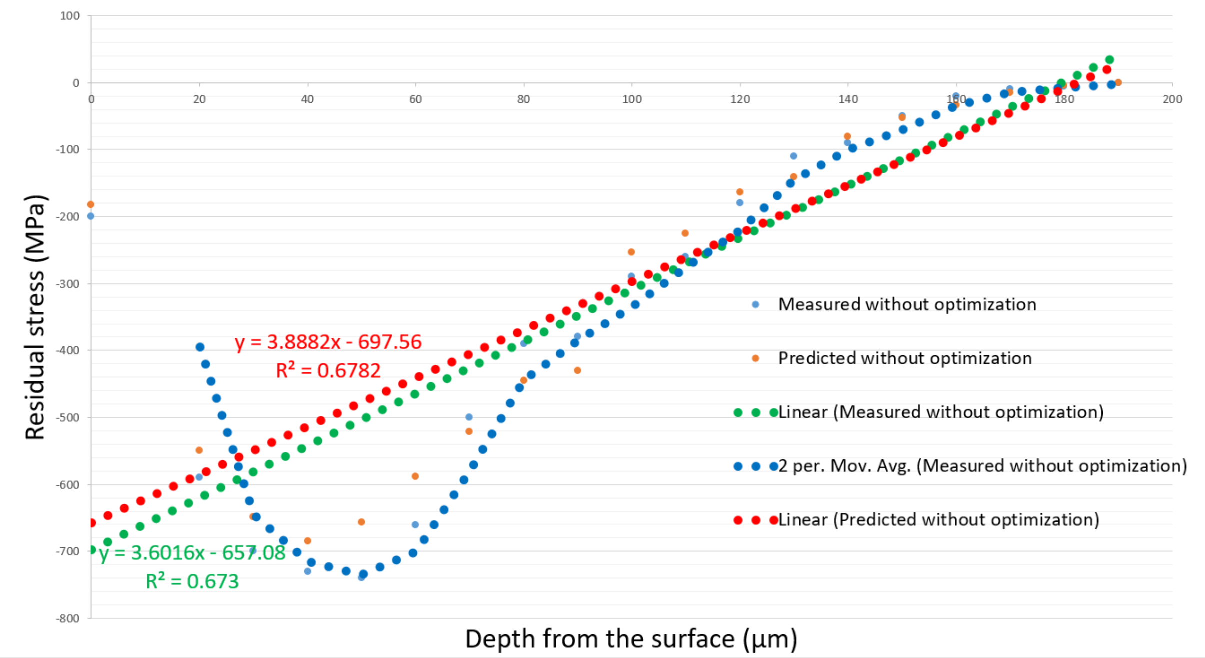

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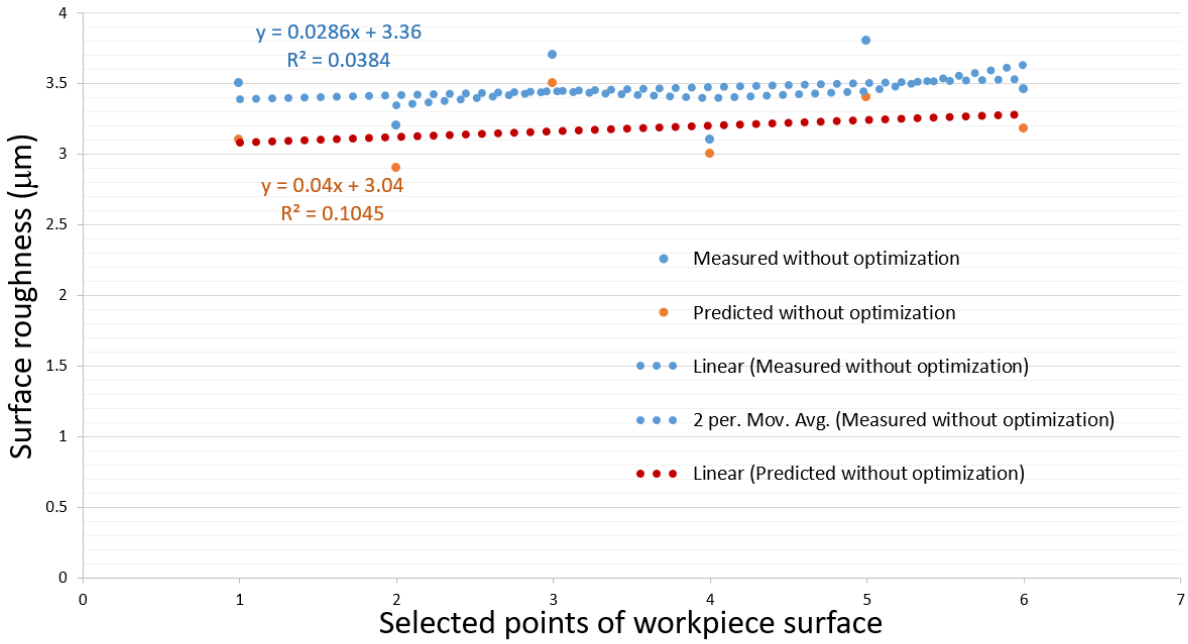

Fig. 9. Regression analysis of measured surface roughness without optimization process.

Tables:

		Before optimization		After optimization		Percentage of change	
No.	**Depth from surface (μm)**	**Measured residual stress (MPa)**	**Predicted residual stress (MPa)**	**Measured residual stress (MPa)**	**Predicted residual stress (MPa)**	**Measured residual stress**	**predicted residual stress**
1	0	-200	-183	-160	-150.8	20	17.59562
2	20	-590	-550.1	-395	-342.32	33.05084	37.77131
3	30	-700	-648.8	-510	-462.7	27.14285	28.6837
4	40	-730	-685.2	-523	-493.4	28.35616	27.9918
5	50	-740	-657	-539	-474.75	27.16216	27.73972
6	60	-660	-588.5	-491	-431.5	25.60606	26.6779
7	70	-500	-520.9	-410	-395.375	18	24.09771
8	80	-390	-445.5	-304.5	-342.5	21.92307	23.12008
9	90	-380	-430.9	-282.5	-246.175	25.65789	42.86957
10	100	-290	-253	-226	-208.6	22.06896	17.54940
11	110	-260	-225.4	-177.8	-163.8	31.61538	27.32919
12	120	-180	-163.2	-130	-139.4	27.77777	14.58333
13	130	-110	-140.5	-90.2	-108.2	18	22.98932
14	140	-90	-80	-79.5	-65.7	11.66666	17.875
15	150	-50	-52.9	-40.2	-43.5	19.6	17.76937
16	160	-20	-33.4	-14.7	-28.125	26.5	15.79341
17	170	-10	-15.1	-7	-11.37	30	24.70198
18	180	-5	-4.1	-4.7	-2.3	6	43.90243
Average	94.44444	-328.05555	-315.41666	-243.61666	-228.36194	23.340436	25.50228

Table 1. Residual stress measurements and predictions without and with optimized variables for machining.

	Before optimization		After optimization		Percentage of change	
No.	Measured surface roughness (μm)	Predicted surface roughness (μm)	Measured surface roughness (μm)	Predicted surface roughness (μm)	Measured surface roughness	predicted surface roughness
Point 1	3.5	3.1	2.8	2.3	20	25.80645
Point 2	3.2	2.9	2.6	2.3	18.75	20.68965
Point 3	3.7	3.5	2.7	2.6	27.02702	25.71428
Point 4	3.1	3	2.6	2.2	16.12903	26.66666
Point 5	3.8	3.4	2.7	2.6	28.94736	23.52941
Average	3.46	3.18	2.68	2.4	22.17068	24.48129

Table 2. Measuring and predicting the machining plate's surface roughness at the five specified places.

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Mohsen Soori is assistant professor of mechanıcal engıneerıng at the Final International University. He received his Ph.D. in mechanical engineering from the Eastern Mediterranean University, Cyprus. His research interests are Computer Aided Design and Manufacturing (CAD/CAM) and virtual manufacturing.

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