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Research Article

Investigation of Laser, Wire-cut and Plasma Cutting Methods on the Residual Stress Distribution of St37 Sheet Using the Contour Method

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ABSTRACT

Cutting is one of the most important manufacturing processes in various industries. After the cutting process, residual stresses are created in different parts. Hence, the calculation and prediction of residual stresses is important and ignoring such a matter when combined with applied stresses can cause failure in parts. In this study, the effects of laser, plasma and wire-cut processes were investigated on the residual stress of st37 sheet using the contour method. For this purpose, an experiment with 8 operational steps including 3 sets of st37 sheets with thicknesses of 4, 6 and 8 mm in the dimensions of 100×100 mm^2 were prepared and, after the stress relief operation, cut by the mentioned cutting methods. After the cutting processes were conducted and the temperatures were recorded with a laser thermometer, the test specimens were prepared for the contour method. According to the results, the highest residual stress was caused due to laser cutting in the sample with a thickness of 4 mm and its value is 142 MPa. The lowest residual stress obtained in wire-cut cutting and its value was 28 MPa. As the thickness increased, the amount of residual stress decreased in all methods. The slope of the temperature changes of the part from the moment of cutting to the ambient temperature is higher in laser cutting and the residual stress in this method is higher than the plasma and wire cut method.

1. Introduction

The laser, plasma and wire-cut processes are used for the purpose of cutting parts in all industries. The construction of each piece usually starts from cutting its components. It is so important that if it is not done accurately, it may cause problems for other components. The scope of this research encompasses a comparison of the impact cutting methods (laser, wire-cut and plasma) have on the residual stresses' distribution of st37. There are several destructive methods to measure residual stresses such as the hole drilling method [1, 2], the slitting method [3, 4], the ring-core method [5], the sachs method [6] and the contour method [7-9]. The contour method was invented by Prime in 2001. He presented a powerful new method called the contour method to measure residual stress [10]. In 2006, Prime et al. expanded the multi-slice contour method that measures

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the residual stress into two directions [11, 12]. He used the new contour method to measure the cross-sectional map of residual stresses in a welded plate, which confirmed the capability of the contour method to measure complex and two-dimensional stress maps [13]. Prime et al. [14] investigated the residual stress caused by the destruction of a tungsten-carbide spherical object on a thick plate of low-carbon steel with high strength using the contour method. In 2003, Prime et al. [15] investigated and predicted the residual stress of a forged aluminum alloy sample that was quenched and hardened in several stages, and the contour method was used to experimentally measure the residual stresses. Zhang et al. [16, 17] measured the residual stress caused by welding on stainless steel 316L by utilizing the contour method. The results of the contour method were checked with the results of the neutron diffraction method, and a good agreement was observed. In 2009, Morgan et al. [18] performed a 3D transient thermal-mechanical simulation on a T-shaped joint using the finite element method to predict the longitudinal residual stresses and used the new contour method to experimentally verify the longitudinal residual stresses obtained by the thermal-mechanical simulation. They used the experimental results to agree well with the simulated results of residual stresses. Dennis et al. examined a wide range of constraints to determine the effect on measured residual stresses. Plasticity, as a result of the cutting process, is also known to be a factor that may affect the measured residual stresses [16, 19]. Arif et al. investigated the residual stress caused by laser cutting of a thick sheet of mild steel. The temperature and stress field in the cutting sections were determined using X-ray diffraction [20]. Arif et al. [21] investigated the stress and temperature field around a hole-shaped which was cut by a laser method. It was found that the main stresses in the region near the surface of the hole are tensile and as the distance from the surface of the hole to the solid mass increases, the stress components become more compressive. Harnikarova et al. [22] investigated the residual stress caused by laser cutting on three different samples of steel, aluminum alloy, and titanium. Yelbas et al. [23] investigated the residual stress resulting from laser cutting of a type of alumina ceramic. Temperature and stress field in the cutting section were predicted by the finite element software. Salvati et al. [24] analyzed the layer affected by wire cut cutting on the aluminum alloy sample created after the initial cut, as well as after the subsequent cut. Rao et al. [25] studied the effect of wire cut cutting parameters on aluminum alloy by Taguchi's method. Kumar et al. [26] described and investigated the effect of residual stresses for the surface machined with wire cut along with ultrasonic vibration as well as the surface roughness and erosion rate to increase the surface quality and prolong the life of D2 tool steel with high chromium and carbon. Bhattacharya [27] used the finite element simulation method to predict and study the residual stress in the wire cut cutting process. Ekmekci [28] investigated the effect of dielectric liquid and electrode type in electrical discharge machining in terms of residual stresses using X-ray diffraction. Ekmekci [29] used the layer removal method to measure the residual stress in the wire cut cutting process and presented the stress profile as a function of subsurface depth.

To the best of authors' knowledge, making a comparison between cutting methods as laser, plasma and wire-cut in residual stresses creation has not been reported so far. Therefore, the aim of the present research is to study the measurement of residual stress in st37 cut by the above mentioned methods using the contour method.

2. Experimental Procedure

In this research, three st37 sheets in 100 ×100 mm^2 dimensions with thicknesses of 4, 6, and 8 mm have been prepared for cutting according to the test methods. The mentioned samples were cut by laser, plasma and wire-cut methods with standard parameters and a square of 50 × 50 mm^2 dimensions was removed from the inside and middle of each. The purpose of this research is to study the residual stresses in the three mentioned cutting processes. In addition, the samples should have no residual stress before cutting. Therefore, the sheets are stress relieving by heat treatment. The desired heat treatment was performed at 600 ºC for 30 minutes [30] and then the samples were cooled in the air. Using an optical thermometer, the temperatures of the parts during cutting processes have been recorded to investigate the effect of temperature and also the slope of temperature changes on the amount of residual stress. Due to the fact that ionized water is used in wire-cut, the temperature was not recorded during wire-cut, and temperature recording was solely done in the case of laser and plasma cutting. To investigate the effect of the slope of temperature changes on the value of residual stress, the cubic equation corresponding to the temperature graph of each sample was extracted and then the slope graphs were drawn for each thickness and process using MATLAB software. To measure the residual stress after the cutting processes, the samples must be cut and prepared for the contour method. The cutting process of the parts should be done directly, with a smooth surface, at the minimum cutting width with the least amount of loading. Therefore, the electrical discharge cutting machining is reported to be the most appropriate method. The samples to be tested should be divided into two parts by using the wire-cut machine and with the quality of the surface finish so that its points can be measured with less error by the CMM machine. Wire-cut is done with brass wire with a diameter of 0.25 microns and a speed of 0.6 mm/min for a polished surface. Additionally, the measurement process must be done with accurate measurement equipment to cover most of the surface points with a suitable displacement range. The procedures of this research can be seen in Fig. 1. Once the cutting by the wire cut machine is completed and the surface is polished, the cut surfaces should be measured by CMM. The roughness of the cutting surface, which is in the form of peaks and valleys, has sizes of about 10-100 microns. Two cutting surfaces are placed on the machine for measurement. The contour-graph device must be programmed to measure the entire surface and its points with a suitable distance to cover a suitable displacement range. After performing contour-graphy, wo sets of data are extracted for each sample, which include data on two corresponding surfaces of the cut odel. In these data, nominal x and y and actual z are the data we want to analyze using MATLAB software. For this purpose, the average of the actual z should be calculated and the numbers obtained from the calculation should be used to draw a three-dimensional graph in MATLAB. After analyzing a polynomial equation in MATLAB, which is actually the deformations resulting from the release of residual stresses and includes specific coefficients, and after sorting it and applying the coefficients, it is saved and used as a displacement for the cut surface in the ABAQUS software. In the ABAQUS software, half of a cut sample is modeled, and the displacement of the points that are the result of the release of residual stresses and extracted from the MATLAB software to the cut surface is applied as displacement.

3. Results and Discussion

As mentioned, the contour method measures the residual stresses through a precise cut and dividing the sample into two parts and then measuring the deformations caused by the release of the residual stress. Due to the use of the contour method by finite element software, there is no limitation in the geometry of the parts for stress measurement and the complexity of the geometry can be solved. By measuring the contour of each surface, the normal stresses of that surface can be

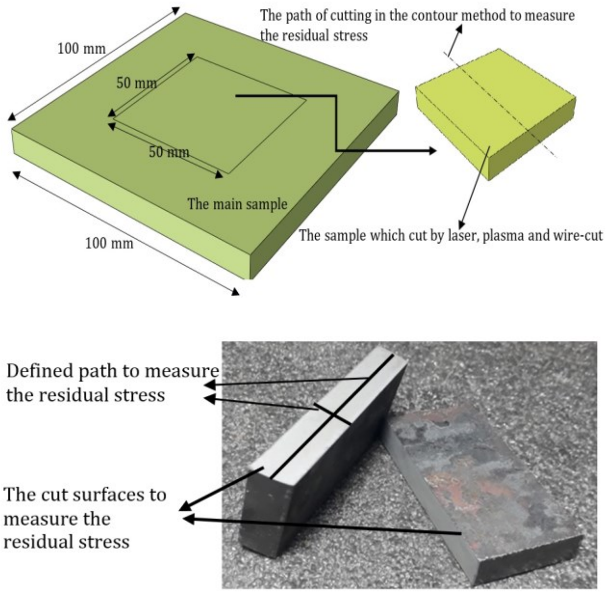

Fig. 1. Schematic of research procedure.

measured, however, as mentioned before, the effect of shear stresses is neutralized by averaging the displacement information. Figs. 2 to 10 show two-dimensional contour maps and residual stress diagrams along the length and thickness (Fig. 1) of the samples, separated by thickness and type of cutting process. It is necessary to mention that in order to verify the validity of the results, some experiments were repeated 2 times and others up to 3 times and the average results were reported.

According to the Figs. 2 to 4, which are related to the residual stresses in the laser cutting process, the residual stress is compressive at the edges and tensile at the center of the samples, and the self-balanced feature of the residual stress can also be seen in them. The diagram of the residual stress along the length of the piece also shows that the residual stress is tensile in the center of the piece and compressive at the edge of the piece. In the residual stress contour, it is also possible to observe the tensile and compressive residual stress and it's self-balanced.

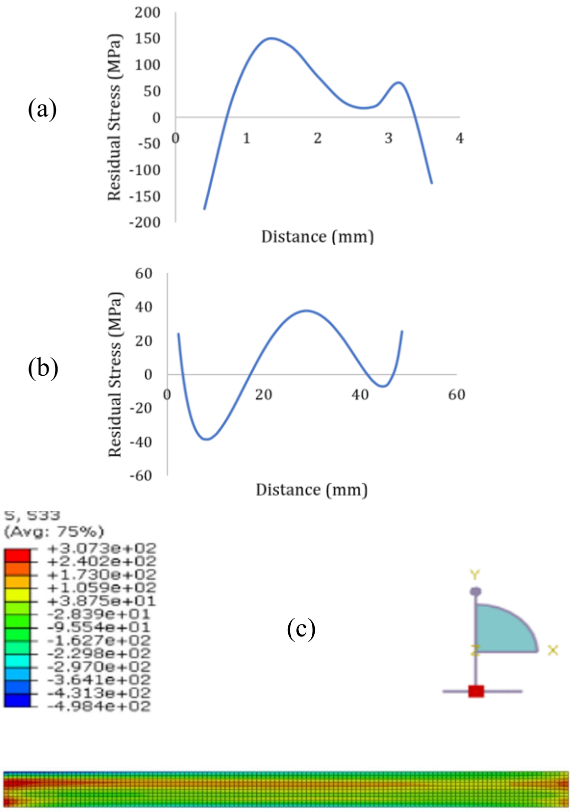

Fig. 2. Residual stress changes for thickness 4 mm in the laser cutting process (a) In line with the thickness of the piece (b) Along the length of the piece (c) Residual stress contour.

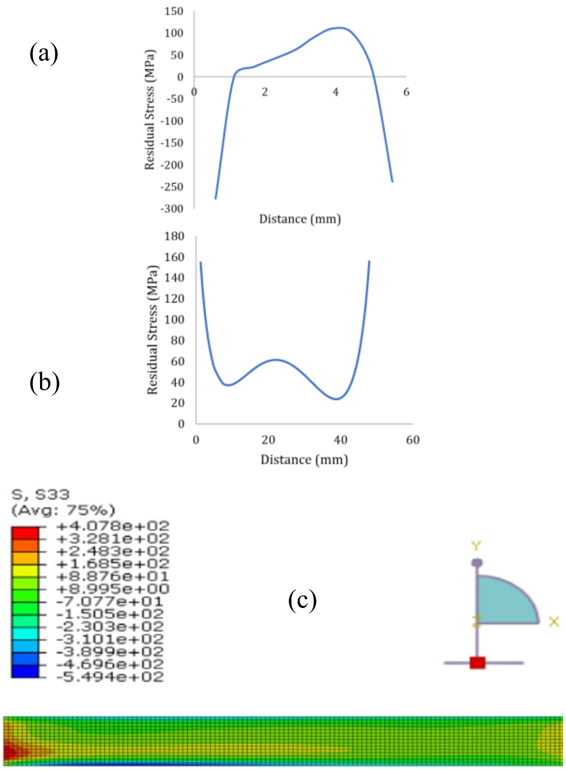

Fig. 3. Residual stress changes thickness 6 mm in the laser cutting process (a) In line of thickness (b) Along the length (c) Residual stress contour.

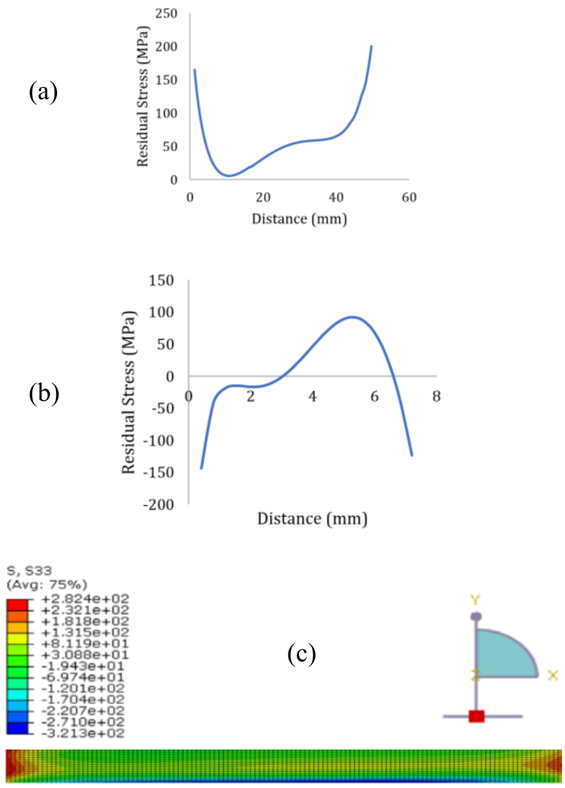

Fig. 4. Residual stress changes thickness 8 mm in the laser cutting process (a) In line of thickness (b) Along the length (c) Residual stress contour.

In the residual stress diagrams of the laser cutting process in thicknesses of 4, 6 and 8 mm, two peaks along the thickness line and two valleys along the length line are observed.

According to the diagrams in Figs. 5 to 7, which are related to the residual stress in the plasma cutting process, the residual stress is compressive at the edges and tensile positive at the center of the part. The diagram of the residual stress along the length of the piece also shows that the residual stress is tensile in the center of the piece and compressive at the edge of the piece. In the residual stress diagrams of the laser cutting process in thicknesses of 4 and 6 mm, two peaks in the thickness direction and two valleys in the length direction are observed, but in the thickness of 8 mm and in the direction of the thickness, only one peak point can be seen (Fig. 7 (b)) and in terms of residual stress changes in the thickness direction is different with the thicknesses of 4 and 6 mm.

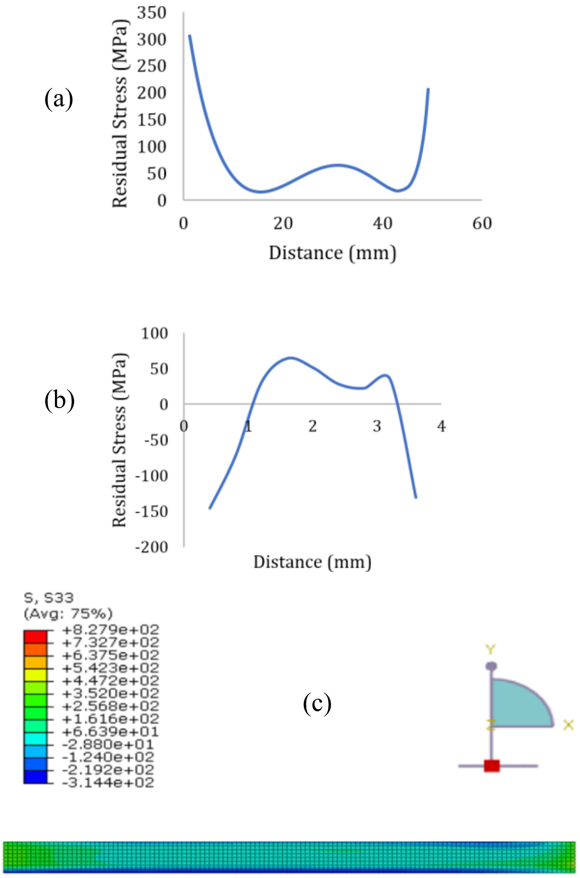

Fig. 5. Residual stress changes of the sample with a thickness of 4 mm in the plasma cutting process (a) In line with the thickness of the piece (b) Along the length of the piece (c) Residual stress contour.

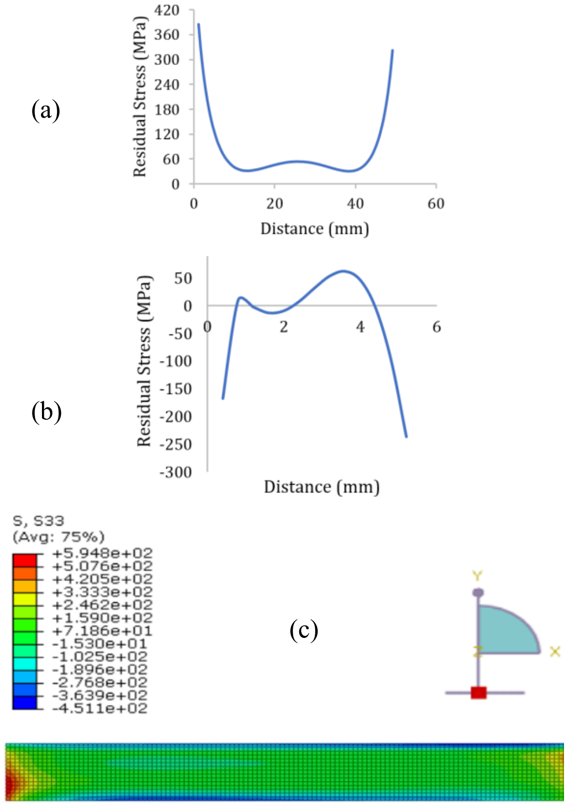

Fig. 6. Residual stress changes thickness 6 mm in the plasma cutting process (a) In line of thickness (b) Along the length (c) Residual stress contour.

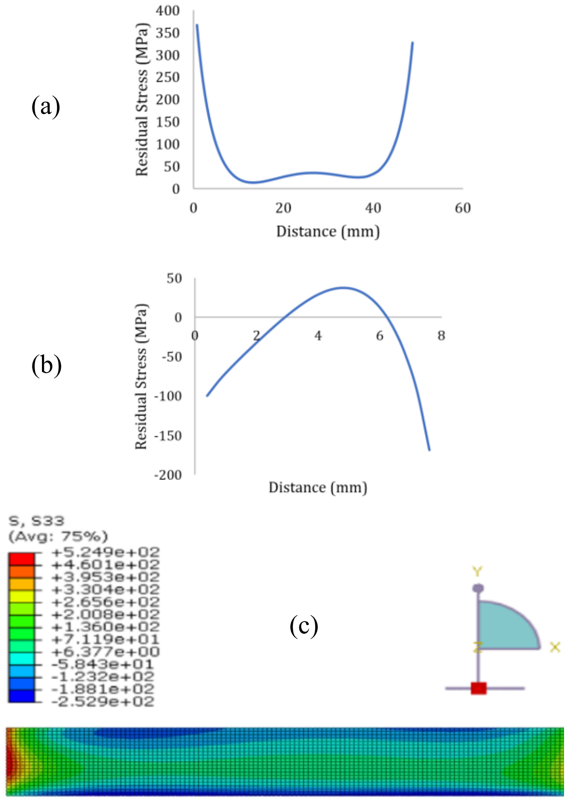

Fig.7. Residual stress changes thickness 8 mm in the plasma cutting process (a) In line of thickness (b) Along the length (c) Residual stress contour.

In the residual stress diagrams of the wire cutting process in thicknesses of 4 and 6 mm, two peaks in the thickness direction and two valleys in the length direction are observed, but in the thickness of 8 mm and in the direction of the thickness, only one peak point can be seen (Fig. 10 (b)) and in terms of residual stress changes, the thickness direction is different with the thicknesses of 4 and 6 mm.

According to Figs. 11, 12 and 13, the mechanism of residual stress changes in plasma and wire-cut processes is almost similar and different from laser. The residual stress along the length has also shown its self-equilibrium property, which can also be seen in the corresponding diagrams. The changes in the stress values resulting from the laser cutting process are more noticeable and larger in number in comparison with the two cutting processes tested. In this tensile cutting process and compression stress in both directions can be seen. If this is not the case in the other two cutting processes.

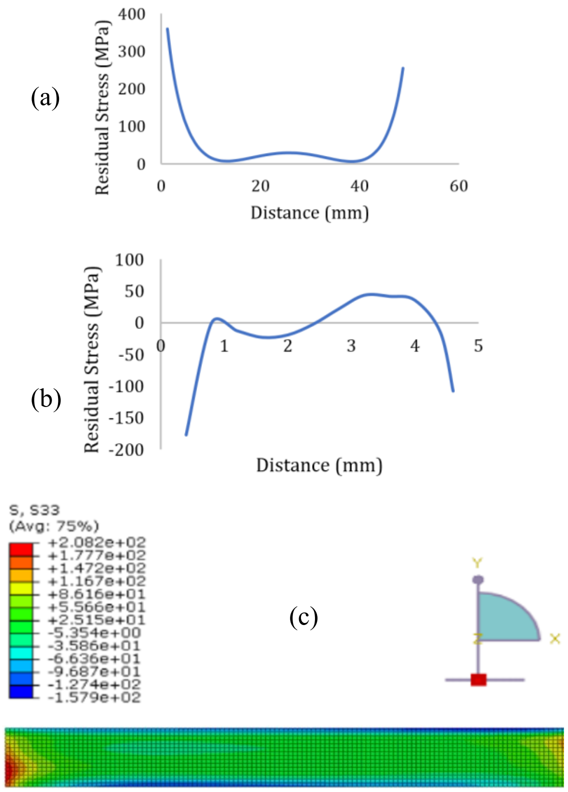

Fig. 9. Residual stress changes thickness 6 mm in the wire-cut process (a) In line of thickness (b) Along the length (c) Residual stress contour.

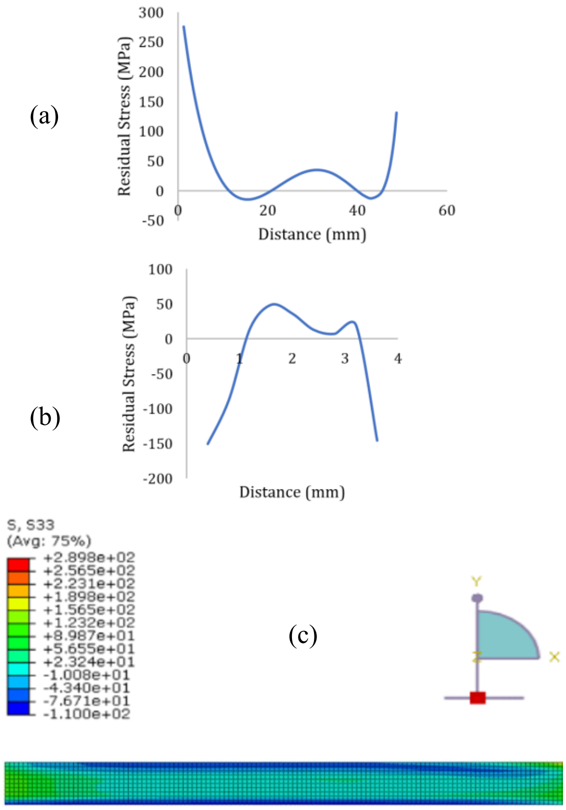

Fig. 8. Residual stress changes of the sample with a thickness of 4 mm in the wire-cut cutting process (a) in line with the thickness of the piece (b) Along the length of the piece (c) Residual stress contour.

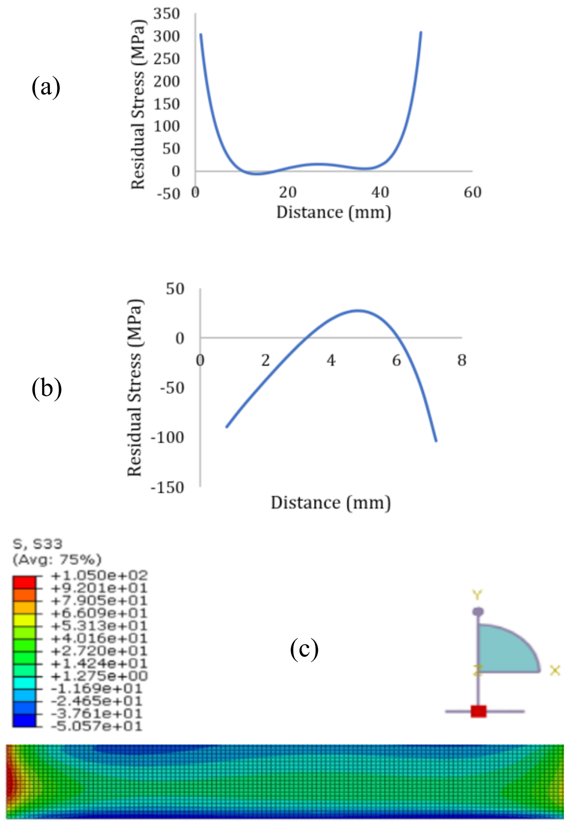

Fig. 10. Residual stress changes thickness 8 mm in the wire-cut process (a) In line of thickness (b) Along the length (c) Residual stress contour.

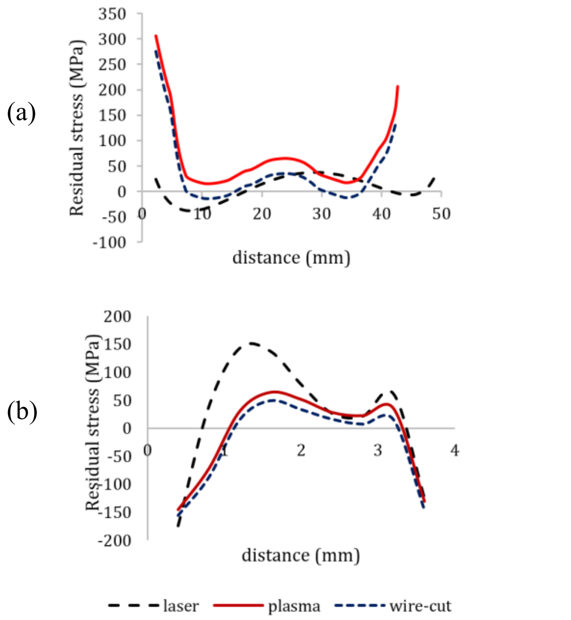

Fig. 11. Residual stress changes in the 4 mm sample along the thickness in the three tested cutting processes (a) Along the length of the piece (b) Along the thickness of the piece.

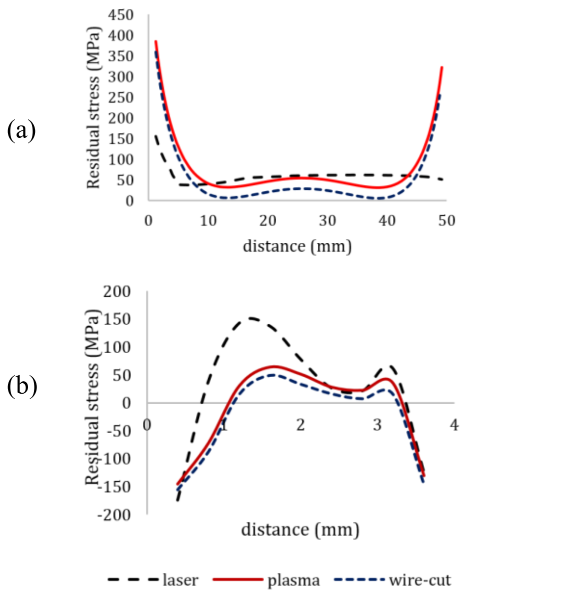

Fig. 12. Residual stress changes in the 6 mm sample along the thickness in the three tested cutting processes (a) Along the length of the piece (b) Along the thickness of the piece.

The distributions of residual stresses in the direction of length in three cutting methods follow a similar pattern, while the changes in the direction of thickness do not, and as mentioned above, the changes of residual stress in laser cutting are more than the other two laser processes (Table 1).

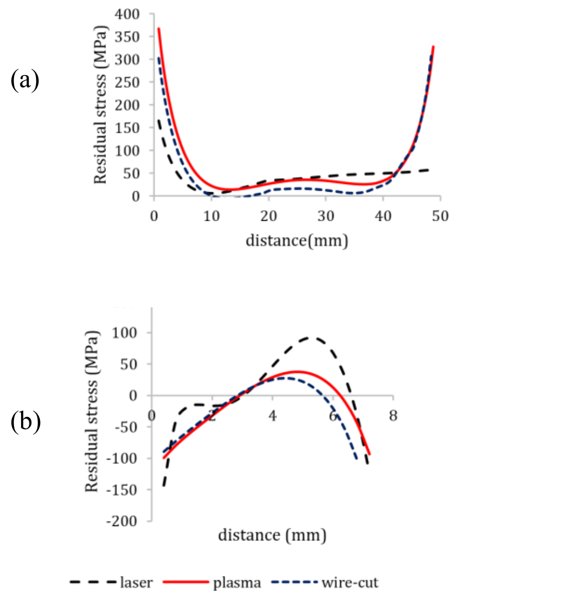

Fig. 13. Residual stress changes in the 8 mm sample along the thickness in the three tested cutting processes (a) Along the length of the piece (b) Along the thickness of the piece.

Table 1. Numbers related to the highest residual stress in the tested cutting processes

Process / Thickness	laser	plasma	Wire-cut
4 mm	142.3 (MPa)	63.8 (MPa)	48.8 (MPa)
6 mm	110.6 (MPa)	61.4 (MPa)	43.2 (MPa)
8 mm	91.4 (MPa)	37.6 (MPa)	27.6 (MPa)

According to Table 1, in all processes, by increasing the thickness, the residual stress decreases, which can be caused by increasing the surface area where the residual stress is measured. In this table, the residual stress values measured in all three cutting methods are presented, according to which the highest stress is for the laser process and the lowest is for the wire-cut process. Cutting using the wire-cut method creates less residual stress because the sample is in ionized water or in oil, and the low temperature of the part is one of the conditions of cutting in this method. But, due to the chipping through the spark and wire, to the part and the cutting surface, it applies temperature changes and causes residual stress. Investigating the effect of the temperature of the piece at the moment of cutting until it reaches the ambient temperature is one of the goals of this research. Heat can cause the release of residual stress. The temperature of the part or the thermal shock applied to it can be effective in residual stress values. As mentioned in the previous sections, in the wire-cut cutting process, due to the presence of ionized water in the cutting process, the effect of temperature is neutralized, and the part temperature is not recorded for this process. In the process of plasma and laser cutting, the temperatures of the samples are recorded from the moment of cutting to the moment of reaching the ambient temperature and are presented by the graphs drawn in Fig. 14.

According to the graphs of temperature changes given in Fig. 14, the temperature of the workpiece during cutting in the plasma process was higher than the temperature in laser cutting. But the cooling time of the workpiece to the ambient temperature in the laser cutting process is less than plasma and the workpiece reaches the ambient temperature faster**.** In order to investigate the effect of the gradient of temperature changes on the amount of residual stress, the cubic equation, according to the graph of temperature changes, was extracted and then derived and plotted by MATLAB software in Fig. 15.

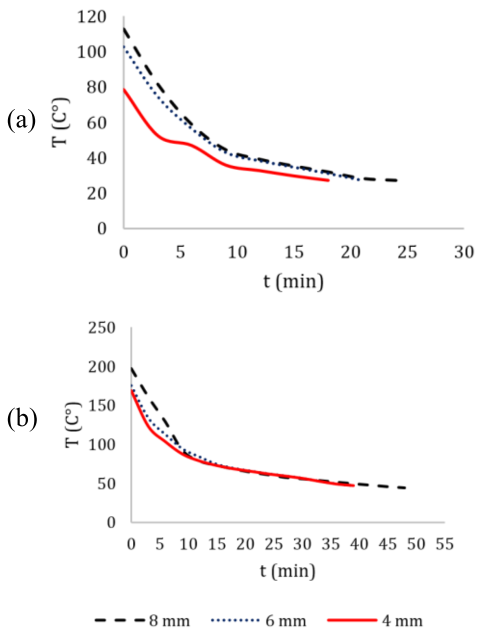

Fig. 14. Temperature change graph in the tested samples from the time of cutting to reaching the ambient temperature (a) Laser cutting (b) Plasma cutting.

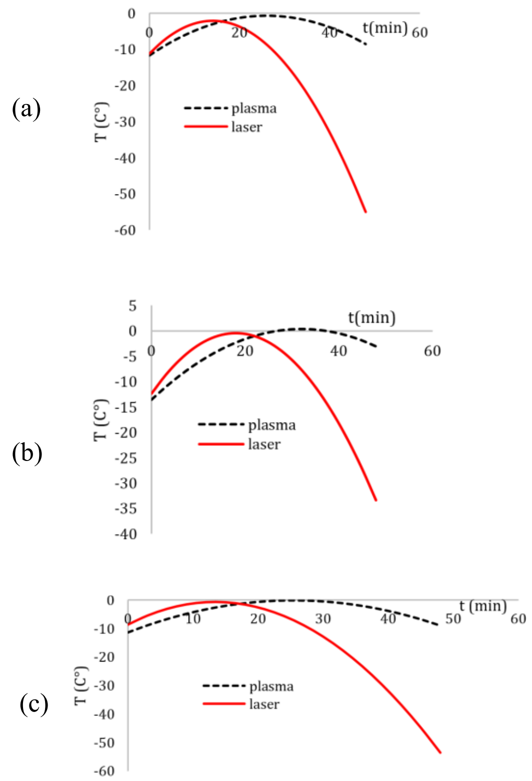

Fig. 15. Slope diagram of temperature changes of 4 mm samples in plasma and laser cutting process (a) 6 mm thick sample (b) Sample with a thickness of 4 mm (c) Sample with a thickness of 8 mm.

After plotting the slope of temperature changes in the two processes of laser and plasma cutting shown in Fig. 15, it is found that the slope of temperature changes for all three thicknesses tested in the laser process is greater than in plasma cutting, and in the case of samples tested in plasma cutting with a slope Fewer changes have reached the ambient temperature.

According to this information, it can be concluded that in plasma cutting, due to the gentler slope and longer time to reach the ambient temperature, less residual stress has been created in the sample. But in laser cutting, which has more intense temperature changes and more slope, more residual stress is also seen in the tested samples.

4. Conclusion

The purpose of this research was primarily to measure residual stress by using the contour method in three different cutting methods including laser, plasma and wire-cut on ST37 sheets. After that, the effect of temperature in the process of cutting on the residual stress was also investigated. Due to the use of three different cutting methods, a comparison was also made between these three methods, as well as the use of three different thicknesses for each cut which has been investigated in various ways.

In general, the identification and study of residual stress in different production methods has always been of interest to engineers. The contour method is an effective method for measuring residual stress, through which complex stress fields can be relatively simply measured, and the complexity of the part geometry is considered a solved limitation.

In this research, the residual stress caused by three different cutting methods was investigated experimentally, and the following results were obtained:

- The highest residual stress was found in the sample cut by the laser method and related to the sample with the lowest thickness of the test, i.e. 4 mm.
- By increasing the thickness from 4 mm to 6 and 8 mm, the residual stress decreased. This issue was observed in all three cutting methods.
- The slope of temperature changes from the moment of cutting the sample to reaching the ambient temperature in the laser cutting process that more than the plasma cutting process, and then the residual stress in the laser process is also reported and measured to be more than the plasma cutting process.
- The higher temperature of the cutting process does not necessarily cause more residual stress and the gradient of temperature changes is an effective factor.
- In wire-cut cutting, the lowest amount of residual stress was measured.
- Considering that the cutting methods used in this research are among the most widely used cutting methods in the industry, we will continue to provide suggestions for reducing or controlling the residual stresses caused by cutting. In addition, since residual stress measurement with the contour method is dependent on the cutting area and its deformation, the quality of surface and cutting in this area improves the measurement of surface displacements, and as a result, residual stress is measured more accurately.

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Conflict of Interests

The authors have no relevant financial or non-financial interests to disclose.

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