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# Experimental Analysis and Optimization of Process Parameters of CNC Plasma Cutting using Taguchi Method for Better Surface and Mechanical Property

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***Abstract***

In today's highly competitive industrial landscape, precision machining plays a crucial role in manufacturing efficiency. CNC plasma arc cutting, a key non-conventional machining process, has gained prominence in smart manufacturing due to its ability to handle complex geometries with high accuracy. A great deal of research has been conducted on CNC Plasma metal cutting, but only few experiments have been carried out to investigate the quality and mechanical properties of ST52 mild steel. This research investigates the influence of key process parameters; cutting current, standoff distance, and cutting speed; on surface quality and mechanical properties of a 6mm thick ST52-3 mild steel using the Taguchi method. Taguchi method using the design of experiments approach can be used to optimize a process. Different input parameters investigated experimentally before the model is built once again and experimentation carried out. MINITAB software used to generate the models and analyze the findings. This contributes to the PAC process operating more effectively and efficiently. The goal is to optimize these parameters to achieve an ideal balance between cut quality and process efficiency. The study employs an experimental approach, utilizing TR100 roughness testing and ANOVA for statistical validation. Results indicate that the optimal parameters for minimum surface roughness (0.028 μm) are 128 A cutting current, 3600 mm/min cutting speed, and 3.5 mm arc gap. Additionally, the best hardness value (821.1 HRB) is obtained at 125 A,

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3700 mm/min, and 3.5 mm arc gap. These findings provide valuable insights into CNC plasma cutting optimization.

***Keywords:*** *advanced machining, ANOVA, CNC plasma cutting, smart manufacturing, Taguchi method, surface roughness.*

## 1. Introduction

Manufacturing has contributed significantly to the advancement of human civilization. By transforming raw materials into usable products, manufacturing processes raise the value of raw materials. Surface finishing, joining, machining, casting, and forming are some examples of different manufacturing processes. Adopting innovative production processes and modern manufacturing technologies is necessary to tackle the challenges faced by the manufacturing industry [1].

In the late 1950s, plasma cutting was invented as a way to cut aluminum and high-alloy steel. Because of its extraordinarily fast cutting speeds, especially with thin materials and tiny heat-affected zones, it was intended to be used on all metals that, due to their chemical makeup, could not be exposed to oxy-fuel cutting. These days, low-alloy and non-alloy steels may also be cut using this method. Normal structural steel up to a thickness of 40 mm may be cut using plasma arc cutting, which produces relatively minimal distortion especially for thin workpieces. High cutting speeds are crucial, particularly during the initial fabrication stage. Cutting rates that are five to six times faster than oxy-fuel cutting can be attained by plasma arc cutting [2].

A plasma is created when the kinetic energy of a gas is enhanced, releasing some of the electrons from the atom's outer shell. An atom transforms into an ion when it releases electrons. A gas is considered to be ionized when enough energy is applied so that the number of atoms releasing electrons and those spontaneously recombining with free electrons are balanced. It is a plasma, this ionized gas. There are constantly free and distinct ions and electrons in a plasma because there is a significant percentage of ionized atoms present at any given moment. In order to prevent the gas from cooling down to the point where the electrons mate again with the ionized atoms, the energy input into the gas must be continuous. At that point, the plasma transforms back into a gas [3].

Optimizing the performance of CNC plasma cutting machines is crucial for ensuring high quality cuts and improving overall manufacturing efficiency. Several input parameters such as cutting speed, arc current, and standoff distance significantly influence the quality of the cut,


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especially in terms of surface roughness. Surface roughness affects the aesthetics and functionality of the final product.

This study aims to develop an efficient and systematic approach for optimizing and experimental analyzing of process parameters in a CNC plasma cutting machine for ST52-3 mild steel using the Taguchi method. It also presents an experimental investigation into the effects of key input parameters cutting speed, arc current, and gas pressure on the performance of a CNC plasma cutting machine. Using the Taguchi method, the work aims to identify optimal parameter settings that minimize surface roughness and kerf width. The study contributes valuable insights into precision machining and provides practical guidance for enhancing the quality of plasma cut components.

## 2. Literature review

C. A. D. [3] examined the cut in plasma arc cutting quality. The EN ISO 9013 standard is used to determine the quality of cut in the plasma arc cutting process. In this work, 17 cuts were made using samples of S235 plates that were 15 mm thick. Cutting current and speed are the important factors that are taken into account. The experimental findings are found to be in line with prior experimental findings as well as theoretical considerations. It is determined that by raising the cutting speed by 20% over the tablet speed value, the optimum cut quality may be achieved. So, this helps to my research to consider different input parameters according to the reviews and there is also a gap in conducting different responses it only analysis on the Heat affected zone (HAZ).

O. M. Koura [4] the arc gap thickness, cutting speed, and gas pressure are the characteristics that affect plasma arc cutting. The purpose of this study was to assess the impact of the cutting parameters used in plasma arc cutting technology for the cutting of hard steel plates. Experimental research is done to determine how these parameters impact the kerf width and heat affected zone of the cut. Utilizing a CNC plasma arc cutting apparatus, the trials were conducted. The 400 HBW hardness Hardox 400 steel plate, which is renowned for its longer durability, lighter constructions, and noticeably higher strength, is utilized to create the test pieces. Based on the results of the testing, the maximum cutting speed of 700 mm/min produced the best quality, with a minimum Kerf width of 4.658 mm and a minimum HAZ of 0.886 mm.

K. Kadirgama [5] The creation of a mathematical model for predicting the heat-affected zone (HAZ) and optimal settings for air plasma cutting on aluminum alloy AISI 6061 were presented in this work. The similar tendency is evident in the experimental and prediction results from


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RSM. Cutting parameters were optimized using partial swarm optimization (PSO). The improved HAZ model yielded a HAZ deviance of 2.72%. The ideal cutting parameters are pressure (620.52 kPa), stand-off gap (1 mm), and output current (100 A) for the lowest possible HAZ. This study reports on the Taguchi method's testing of a plasma arc-cutting machine. In this paper, it was examine cutting speed and arc gap. Using Minitab 17 to implement the Taguchi technique also a crucial step in this procedure. They proceeded to analyse Surface roughness, kerf vs speed, and air gap are the three components of Taguchi analysis. ANOVO determines a general linear model by utilizing this method: air gap, surface roughness vs speed. The material used in this study was mild steel E350. This demonstrates that the HAZ may be reduced by varying the arc current and stand-off gap.

P. H. Agarwal [5] represents the experimental investigation on the plasma arc cutting of structural steel (IS 2062 E250 BR). This work was significant because it presents empirical relationships that are pertinent to the analysis of the machinability of structural steel material as a function of machining factors. Material removal rate (MRR), top and bottom kerf widths, and bevel angle are the reaction characteristics taken into account; current, standoff distance (SOD), pressure, and speed are the machining factors. Response surface methodology (RSM) is used in the execution of experiments. Regression analysis is used for the mathematical modelling; all answers' linear regression equations are created, and ANOVA is used to analyse process performance data for different parameters. This aids in my consideration of the bevel angle test as well. The method used was great and the normal probability plot of the residual where more effective.

## 3. Methods and materials

The methodologies used to achieve the stated objectives of the study including data collection, materials, and procedures used to conduct the experimental test. The flow chart figure of the research methodology that is followed in the study is illustrated below. The chart clarifies to understand the basic stages of the study.


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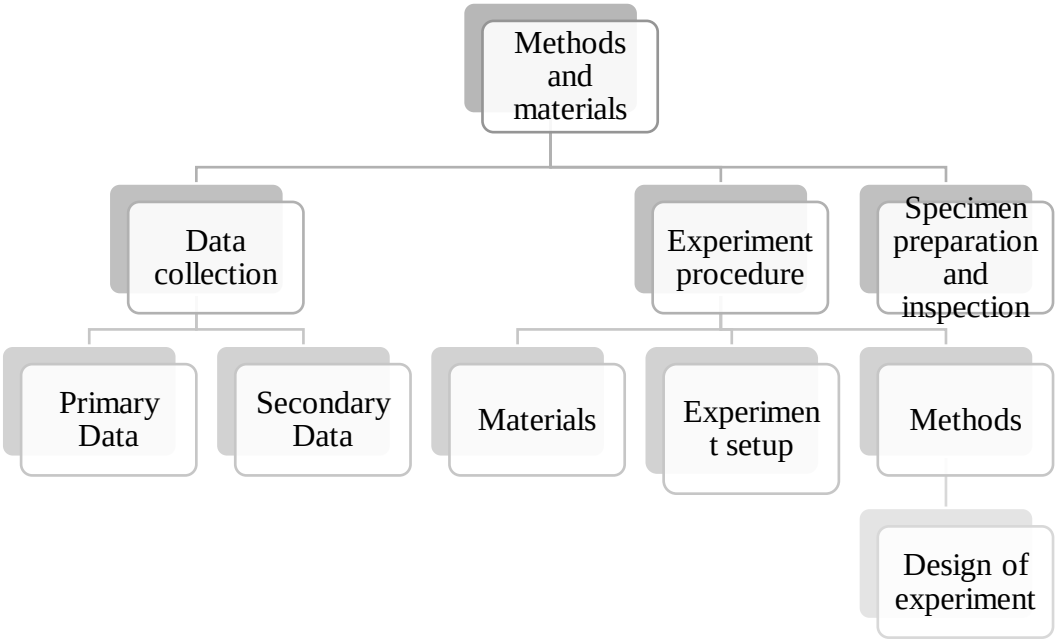


### 3.1 Materials

To perform this study and achieve the objectives of this work, suitable quantities of materials were selected from materials available at Mesfin Industrial Engineering (MIE) stock as shown in the table 3.1. The factors should be considered while selecting the material such as Mechanical strength, availability, fabric ability, design, and cost.

**Table 1:** Materials and equipment

| S/N | Type | Name |
|---|---|---|
| 1 | Measurements | Meter, caliper |
| 2 | Material | St 52-3 Mild steel, metal marker, computer, A4 paper, and safety equipment |
| 3 | Machine | CNC plasma cutting machine |

### 3.2 Experimental set up

The experiment was performed in a CNC plasma cutting machine (HyPerformance Plasma HPR260XD). The cuts were performed on 6mm thickness St 52-3 mild steel sheets, with the use of oxygen as plasma (primary) gas and air as shielding (secondary) gas. In this paper, 27 readings of material were taken. The dimension of the experiment is a rectangular block of 110x35x6mm of mild steel. All cuts were made parallel to the rolling direction. Each measurement was taken approximately in the middle of the work piece's thickness and the average value of all measurements was used and trodden as the result of a single experiment.


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### 3.3 Methods

Experimental multi-parameter optimization of the CNC PAC process according to quality indicators such as dimensional accuracy and quality of cut surface has been studied by several researchers in several materials and experimental regions.

#### 3.3.1 Design of Experiment

Design of experiments (DOE) capabilities provide a method for simultaneously investigating the effects of multiple variables on an output variable (response). These experiments consist of a series of runs, or tests, in which purposeful changes are made to input variables or factors, and data are collected at each run. Quality professionals use DOE to identify the process conditions and product components that influence quality and then determine the input variable (factor) settings that maximize results. This tool is statically has been shown to optimize the process parameters of many manufacturing sectors at the minimum number of experiments to give the best output result. This method was developed by Dr. Genichi Taguchi of Japan who maintained that variation. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied; it allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

#### 3.3.2 Taguchi Method

A scientific approach to planning the experiments is a necessity for the efficient conduct of experiments. Taguchi design and the ANOVA analysis is an engineering methodology for enhancing the quality of work at a low cost. The steps for analyzing the Taguchi methods: Select the quality characteristics, select the signal factors (control factors), selection of noise factors, orthogonal array, analysis of result, Report.

#### 3.3.3 Parameters to be considered for the study

A thorough study of the literature review was referred to; input parameters considered for CNC plasma cutting are cutting speed, standoff distance, and arc current were used based on their effect on the output. The optimized value of the design of experiment analysis results for selection factors investigate visualize values of different parameters was considered for the CNC plasma cutting process as shown in the table3.8 and 3.10 below.


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**Table 2:** Constant parameters

| S/N | Machining parameters | Fixed value |
|---|---|---|
| **1** | Material type | Mild steel (ST52-3) |
| **2** | Material thickness | 6 mm |
| **3** | Gas pressure | 8 bar |
| **4** | Kerf | 1.81 mm |

The input parameters in the present work are speed, current, and standoff distance as shown in the table 3.10. Each factor is investigated at three levels to determine the optimal settings for the CNC plasma arc-cutting process.

**Table 2:** Control factors and their levels (design variable)

| No. | Parameters | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| **1** | Cutting speed | mm/min | 3500 | 3600 | 3700 |
| **2** | Cutting Current | A | 125 | 128 | 130 |
| **3** | Standoff distance | Mm | 2.8 | 3 | 3.5 |

The experiment is based on Taguchi L27 orthogonal array design. This array can handle three-level design parameters. Each of the machining parameters is assigned to the columns of the design matrix and there are twenty seven such input parameter combinations available. Therefore, the entire parameter space can be studied by these twenty seven experiments using the L27 orthogonal array.

### 3.4 Design

For conducting the experiments, it has been decided to follow the Taguchi method of experimental design and an appropriate orthogonal array is to be selected after taking into consideration the above design variables.

Important outputs are surface roughness, bending strength and hardness have been selected as response parameters for this research work. This design give information just on the main effects and three factor interactions. The runs were randomized to prevent systematic effects on the response.

By opening a Minitab 18 on the window select the stat on the taskbar and select the DOE. So create a Taguchi design. By displaying the availability of designs select the L27 with three levels based on my research selection.


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**Table 4:** Taguchi design and design Summary

| Taguchi Array | L27(3^3) |
|---|---|
| Factors: | 3 |
| Runs: | 27 |

After performing above steps the Minitab 18.1 software display an orthogonal array or experimental layout based on a given input parameters.

### 3.5 Specimen preparation

The specimens are prepared based on the orthogonal arrays which are prepared using the Taguchi method. The specimen for surface roughness, and mechanical test (Bending and hardness) characterization was supplied with mild steel (ST-52) plate material. The entered specimen materials for the non-destructive test (surface roughness) and mechanical property characterization were prepared and the cut process was completed at MIE as shown in Figure 1 below.

**Figure 1:** Specimens of CNC plasma cut plate of ST52-3 mild steel

### 3.6 Plasma arc cutting response

Cutting current (A), Cutting Speed (mm/min) and Arc Gap (mm) are considered as input parameters. These factors are the most important to have the best value for Surface Roughness (Ra) and mechanical properties.

### 3.7 Visual inspection method

Visual inspection is a type of non-destructive test (NDT) that has three stages for testing quality cut (before cutting, while cutting, and after cutting). In this case, the external flaws of the cut area of the specimens were determined by visual inspection after cutting the specimen. Here's what to look for: Cut edge, surface finish, overall appearance. By observing these aspects during visual inspection, you can gain valuable insights into the quality of CNC plasma-cut ST52-3 mild steel and identify potential issues that might require further investigation or corrective actions.


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**Figure 2:** Visual inspection

### 3.7.1 Surface roughness

Roughness plays an important role in determining how a real object interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion [6].Surface roughness measurement using a TR100 surface roughness tester typically involves the following steps:

- Preparation: Clean the surface, Mount the sample, Calibrate the instrument

**Figure 3:** Bench vice and surface roughness tester

- Measurement: scan length, traverse speed, cut off value, scan the surface

**Figure 4:** Specimen and measurement

### 3.7.2 Bending test method

The bending test is an important mechanical test used to evaluate the ductility and formability of materials, particularly after undergoing manufacturing processes, understanding its bending behavior after plasma cutting is important for ensuring the structural integrity and performance


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of fabricated components [7]. The bending test for CNC plasma cut ST52-3 mild steel typically involves the following steps:

a) b) c)

**Figure 5:** a) Specimen preparation b) Test setup c) Measurement display

### 3.7.3 Rockwell Hardness Test Method

The Rockwell hardness test is a widely used method for measuring the hardness of materials. It provides valuable insights into the material's resistance to indentation and potential changes in its mechanical properties after undergoing the cutting process [8]. The Rockwell hardness test involves the following steps: Specimen preparation, indentation, depth measurement, hardness conversion.

## 4. Result

In order to improve process parameters for CNC plasma cutting of mild steel ST52-3, this study used the Taguchi technique. There were 27 experimental runs using an L27 orthogonal array. Surface roughness, bending strength, and hardness were among the response characteristics that were assessed. According to the Taguchi analysis, the best outcomes for the required response variables were obtained at the second level of cutting speed and cutting current and the third level of standoff distance. This implies that for plasma cutting ST52-3 mild steel, faster cutting speeds and longer standoff distances can result in improved surface quality, bending strength, and hardness.

### 4.1 Surface roughness analysis result

Surface roughness influences a variety of factors in different applications. Rougher surfaces create more friction, leading to increased energy loss and wear. Smoother surfaces offer better adhesion for paints, coatings, and other materials. Smooth surfaces often appear more visually appealing. Surface roughness can influence electrical conductivity, heat transfer, and other functional properties.


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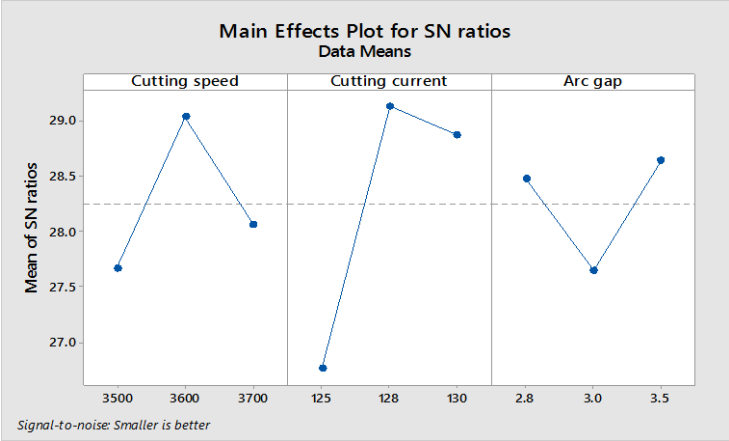


**Figure 6:** Signal to noise ratio for surface roughness

Investigating from the Main Effects Plot for S-N Ratio shown in figure 4-5 we can conclude that, the smaller S/N value corresponds to a better performance. Based on the analysis of the S/N ratio, the optimal surface roughness was obtained at 128A (level 2), Arc gap 3.5 (level 3) and 3600mm/min speed (level 2). Based on these results, we should set the factor at the calculated value. By using MINITAB software we obtain some interactions if we look at the graph we will observe that Surface roughness increases with increase in Current, Cutting Speed. Above graph represent the effect of parameters on Surface Roughness.

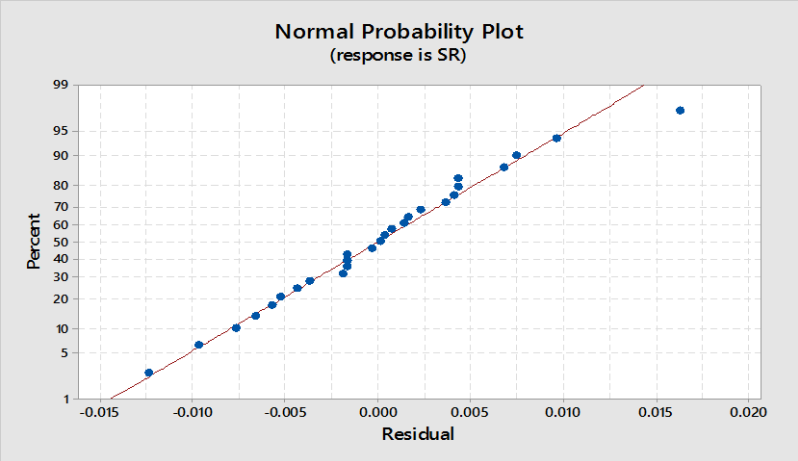


**Figure 7:** Graph of Normal probability plot for residuals of surface roughness

This graph indicates that the residual follows a straight line and there are no unusual patterns and outliers. As a result, the assumption regarding the residual were not violated and the residuals are normally distributed.

### 4.2 Bending Test Analysis Results

The results of bending strength tests conducted according to the L27 orthogonal array of Taguchi design was used with 9 experiments and 3 replications totally 27 samples were made


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to test the bending strength of the cut material. The CNC plasma cut material for Level1, Level2, Level4, Level5, Level7, Level8, Level10, Level11, Level13, Level14, Level16, Level17, Level19, Level20, Level22, Level23, Level25 and level26 to conduct bend test.

It is observed that in all specimens of bending test the bending point takes place at the base metal of mild steel (ST-52) due to the high elongation of the St-52. Bend tests for ductility provide a simple way to evaluate the quality of materials by their ability to resist cracking or other surface irregularities during one continuous bend condition. As a result, bend test of St-52 plate was successive in our experiment. Seen the above result their nothing damaged due to bend test on the specimen. So it is observed that metal to be cut by CNC plasma cutting process on ST-52 is able to resist bending up to 733.33Mpa. There is nothing was observed problematic by bend test like crack on the surface of the specimen.

### 4.3 Rockwell Hardness Analysis Results

The results of Rockwell hardness tests conducted according to the L27 orthogonal array of Taguchi design was used with 9 experiments and 3 replications totally 9 samples were made to test the Rockwell hardness of the cut material. The CNC plasma cut maintained for L3, L6, L9, L12, L15, L8, L21, L24 and L27 to conduct the Rockwell hardness test.

Analysis result of Rockwell hardness test obtained from this study show those proprieties of CNC plasma cutting of mild steel have tabulated. The values of hardness test is higher at L21, in comparison followed by L27, L9, L15, L18, L6, L24, L12 and L3 as shown in the table 4.13. The results show that, the Rockwell hardness number of the cut area are increased on increasing the cutting speed. Moreover, here we have seen that the hardness of cut zone is great at the increasing of arc gap. So, we can idealize that the grain size of cut zone is at good condition.

## 5. Conclusion

In this study attempt has been made on the experimental investigation on the cut quality of ST52-3 mild steel. In order for a good quality to be get and sustain certain external impacts, surface roughness and the mechanical property (bending, and hardness) have been examined through experimental procedures. Generally, it is concluded this study as follows:

- A CNC plasma cutting machine operating at 3600mm/min, 128amp, and 3.5mm arc gap was able to manufacture ST52 mild steel to a surface roughness of 0.028 Ra. This smoothness reduces wear and friction, thus it's appropriate. Although a rougher finish may theoretically result in a higher MRR, the existing trade-off between surface quality


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and machining speed is ideal for this application. If more demanding applications call for an even smoother surface, further research might look at different finishing methods.

- Further, the mechanical test results shows that, the highest value of mechanical properties in terms of hardness test is at level21, results at HRC1 (-4), HRC2 (-6.3) and HRC3(-3.9) with the average of 821.1 HRB at 3700 mm/min, 125amp, 3.5 mm arc gap in comparison followed by L27, L9, L15, L18, L6, L24, L12 and L3.
- The performance of bending test results shows that nothing damaged due to bend test on the specimen. So it is observed that metal to be cut by CNC plasma cutting process on ST52-3 is able to resist bending up to 733.3Mpa. There is nothing was observed problematic by bend test like crack.

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