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Original Article

Precision plasma arc cutting of pure copper : A parameter optimization study

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Abstract

Plasma Arc Cutting (PAC) is one of the most promising manufacturing technologies. In metalwork industry, it is a primary operation to prepare sheets and strips for later welding and/or machining operations. The cutting accuracy and surface quality have great effects on the time and cost of the preceding operations. Although PAC has many advantages for cutting different metals, it is used a little bit in cutting pure copper sheets. However, it has been observed that some factories are utilizing this operation in daily production without a sound scientific base. This is because the research in this area is rarely considered and consequently the effects of the operation variables on its parameters are not deeply investigated. In this research, the use of PAC for cutting pure copper is investigated experimentally. The aim of this investigation is to study the effect of the cutting variables on the cutting parameters. The studied cutting variables are current intensity, cutting linear speed, torch height, and plasma gas pressure. The interested cutting parameters are material removal rate (MRR), surface roughness (Ra), geometric error (Conicity) and the length of the heat affected zone (HAZ). The results are plotted and some explanations are given based on the previous work survey in this field. The results give guidelines to industry for better practice in the field of cutting pure copper using PAC.

1. INTRODUCTION

Plasma was first discovered by Langmuir in 1928 as a non-conventional manufacturing process capable of slitting a variety of electrically conductive materials.

Plasma cutting can cut more complex shapes as it has high levels of accuracy. Plasma cutting results in minimal dross as the process itself gets rid of excess material, meaning very little finishing is required. Plasma cutting does not lead to warping as the fast speed significantly reduces the heat transfer.

V. A. Nemchinsky[1] mentioned that the technology of PAC was first introduced in 1955 by Robert M. Gage who invented the byproduct to improve directional stability of the open arc used for TIG welding.

Plasma cutting was adopted in the early 1950s as an alternative method for oxy-acetylene gas flame cutting of metals especially for stainless steel, aluminum and other nonferrous metals. During that time many of the process limitations were cleared; such as low cutting speed, poor machining quality and the unreliable equipment.

Recently; plasma cutting has become much more attractive especially for both metallic and nonconductive materials.

S. Chamarthi *et al.*[2] defined plasma arc cutting (PAC) as a thermal cutting process that makes use plasma gas to melt and separate (cut) metal.

K. Salonits[3] is also defines the PAC process as a thermal cutting operation performed by a narrow high-speed jet of extremely high dissociated temperature under the existence of an ionized inert gas. Under these conditions, plasma (When substantial heat is added to a gas, it will change from gas to plasma, the 4th state of matter) can be formed. Then an electrical arc is generated between a hot tungsten cathode and the water-cooled copper anode, so the metal being machined is very rapidly melted and vaporized.

Industrial applications of the plasma arc cutting.

Foundries and automotive manufacturers degate and trim castings more effectively with plasma than with other labor-intensive and less efficient methods. Trim castings safer and quicker with proven handheld and automated plasma cutting solutions.

Plasma cutting can be instrumental in salvaging various thicknesses of scrap metal from old appliances, industrial equipment, cars, and other items as an important part of the lifecycle of raw materials. It minimizes waste, maximizes the value of manufactured goods, and significantly reduces environmental impact.

Many fabrication processes require cutting holes to bolt two or more pieces or parts together, so hole production is an important part of most cutting operations. Multiple holes can be cut into a large plate, pipe, or drum with plasma.

So, the previously discussed applications are among of many applications of this research.

2. LITERATURE SURVEY

The plasma cutting process variables are classified into cutting speed, current intensity, shielding gas type and pressure, torch height (standoff distance), material (type and thickness) to be cut.

Recently, many researches were conducted to investigate the effect of process variables on process output parameters which are material removal rate, roughness, squareness, unevenness tolerance, and burr and spatter formation. Also, temperature distribution over the cutting area and heat affected zones were investigated.

Unevenness (angularity tolerance or conicity) is defined as the distance between two parallel straight lines (tangents) between which the cut surface profile is inscribed "Fig. 1" according to ISO9013 Standard[4].

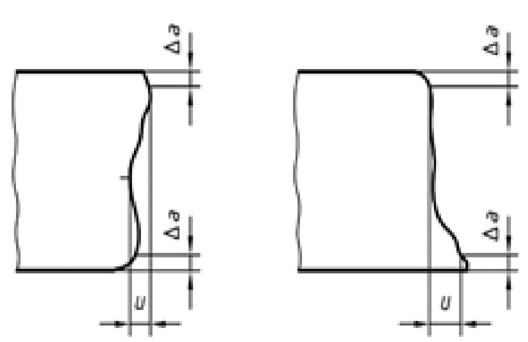

Fig. 1: Perpendicularity tolerance, ISO9013 Standard[4]

S. Chamarthi *et al.*[2] investigated the effect of the plasma cutting variables on Hardox-400 material unevenness surface. The analysis showed that Hardox-400 plates can have different profiles, depending on the specific side considered. Results showed that because cutting speed is inversely proportional to the thickness of the plate, so the reduction of the cutting speed results in an excessive amount of molten metal which is reasonably accepted.

D. N. Kumar[5] also described for Hardox-400, the material removal rate, surface roughness chamfer and kerf are considered as the output responses during the plasma cutting process and the process parameters for the operation are varied cutting current, supply gas pressure, cutting speed and Standoff distance. It was concluded that the cutting current was most influential process parameter and it contributes 37%, followed by gas pressure, cutting speed and stand-off distance.

K. Salonits[3] assessed the quality of the PAC process by measuring the kerf taper angle (conicity). The conicity was calculated as a percentage based on the kerf measurement. Results showed that conicity percentage is mostly affected by cutting height and about 14% contribution for the cutting speed.

J. Kechagias *et al.*[6] proposed an ANN (Artificial Neural Network) model to predict the bevel angle of St37 samples. Cutting speed, arc ampere, material thickness, and standoff distance were selected as the inputs for the ANN model. It was found that right handed bevel angle of the samples decreases with the decrease of torch height, an increase of arc ampere and increase of cutting speed. It was also found that the higher thickness plates have lower bevel angles.

R. Bini *et al.*[7] utilized (HTPAC) high tolerance plasma arc cutting system to cut 15 mm thickness mild steel plates and predicted the features of the kerf generated. Results showed that cutting voltage is the main affecting parameter, where decreasing the voltage means dramatic decrease in unevenness values till reaching the low voltage half region. The voltage can be also used to control and minimize the difference of unevenness values between workpiece sides. It was declared from this investigation that there is an optimum region of voltage values before which unevenness is inversely proportional to cutting speed, and after this point, unevenness becomes directly proportional to cutting speed, leading to negative bevel cuts. Also J. Deli[8] concluded that the closed loop control of the conventional constant current yields to worst of finish and deeper of the uneven ripples and the cutting precision cannot improve.

K. Salonits[3] examined the heat affected zone (HAZ) visually using a Nital etchant and determined the modifications that happened in the microstructure of S235 steel material (15 mm thickness plates) during the process. It was cleared that cutting current affects mostly the HAZ, cutting speed and cutting height are inversely proportional to the HAZ length among the specimen. Also it was cleared that the gas pressure is directly proportional to the HAZ size due to the higher plasma gas temperature associated with the pressure increase.

P. Patel *et al.*[9] worked on SS321stainless steel material to investigate the HAZ. It was found that the cutting current has a maximum effect on HAZ with 99.74 % contribution and that the cutting speed does not affect the HAZ. Also observed that, when the cutting height or gas pressure increases, HAZ increases but with slight effect.

C. Hrvoje *et al.*[10] determined the kerf value and axis accuracy of a CNC plasma cutter for the cutting of 2, 4 and 6 mm thick plates of construction steel, aluminum and stainless steel. Optimal cutting depths were determined for the thicknesses being cut, and equations were derived to predict deviations if cutting thicknesses outside the experimental range is required.

D. Singh *et al.*[11] identified the suitable combination of cutting variables that yielded to the minimum heat-affected zone during cutting the sheet of SS 304. Response Surface Methodology (RSM) was adopted to investigate the process and dependency of input variables and output parameters. Results showed that in comparing of the voltage and cutting speed it was found that they had more influence on the heat affected zone than the other input variables.

A. Suresh[12] analyzed and optimized the process variables involved in the water–acetone plasma arc cutting for Twinning Induced plasticity (TWIP) steel plates. ANOVA was used for the assessment of the process variables. The input process variables considered are voltage, current, Speed of. By adopting these input process variable values the output values obtained as material removal rate, surface roughness and time of cut. Results showed the voltage had the highest impact with 44.05% and next current has the impact with 29.69% and lastly the speed of cut has the influence of 26.25%.

P. Patel *et al.*[13] analyzed the surface roughness in plasma arc cutting of AISI D2 steel by optimizing the effect of process parameters. The cutting speed, gas pressure and torch height were considered as process variables. Gas pressure values were 4.5, 5.25, 5.75 and 6.5 bars and the torch heights were 0.5, 1, 1.5 and 2 mm. Also the cutting speed values were 1000, 2000, 3000 and 4000 m/min. The proposed TLBO Optimal provides the better result as compare to genetic algorithm.

A. Beleed[14] conducted a research about manual plasma arc cutting aiming to optimize the cutting variables for two different Aluminum 1100 alloy material thicknesses; namely 3 and 6 mm. The main conclusion using analysis of variance is that the cutting current is the most significant variable on MRR.

S. Bhowmick *et al.*[15] presented a study on AISI 304 stainless steel using the plasma arc cutting process. The input variables for the process were the gas pressure, traverse speed and thickness of material. The material removal rate and surface roughness investigated as outputs. Results showed the speed and the thickness are more significant and the MRR resulted as a function of speed and thickness of material. The gas pressure has a little effect on MRR.

P. Parthkumar *et al.*[16] investigated the effects of the plasma arc cutting process parameters of "Quard – 400" material using analysis of variance to get the contribution of process parameters on responses. Gas pressure and cutting speed were considered as process variables and the process responses were material removal rate and mean surface roughness. It was found that cutting speed had most significance.

A. Beleed[14] found that speed is mostly significant on Ra for 3 mm Aluminum 1100 plates and torch height for 6 mm plates.

M. D. Kumar *et al.*[17] presented the optimization study for PAC process parameters (gas pressure, arc current and torch height). Optimization was done based on Taguchi method coupled with grey rational analysis for the maximum material removal rate and the minimum surface roughness characteristics process parameters. Analysis of means and analysis of variance were used to estimate the effect of parameters on the material removal rate and surface roughness of EN 31 steel. Results showed that the gas pressure is the most significant influence on both material removal rate and surface roughness.

R. Kumar[18] utilized the Gray rational analysis to optimize PAC parameters where the main cutting parameters affecting PAC are the cutting speed, the arc current and gas pressure. It was found that the main cutting parameters affecting PAC are the cutting speed, the arc current and gas pressure.

A. Rajeshkannan *et al.*[19] presented a study to optimize the plasma arc cutting (PAC) process variables against both of the material removal rate and the surface roughness and used Taguchi approach and S/N ratio plots, mean of means plots and ANOVA in this study. It was considered the arc current, standoff distance and cutting speed as the process variables and the study found these variables are to be the major influencing variables in the cutting process; in each case three levels are considered.

R. Adalarasan *et al.*[20] optimized the quality characteristics of the cut (surface roughness and kerf width) with Grey Taguchi-based surface response method of 304 L stainless steel samples. The optimized values were set to the air pressure, cutting current, standoff distance and cutting speed.

S. M. Ilii *et al.* [29] presented equation (1) and referred to K. Salonits[3] to describe the relation between the cutting feed V_t and the various cutting variables which are η cutting efficiency, U_a plasma arc voltage, I_p plasma arc current intensity, b average cutting width, s thickness of workpiece, c specific heat of metal to be cut, γ workpiece atomic mass, and t_{top} melting point of the metal to be cut.

$$V_t = \frac{\eta . U_a . I_p}{b.s.c.\gamma.t_{top}} \quad \text{m/s} \qquad (1)$$

3. AIM OF THE WORK

It was observed from the literature review that many researches had been conducted to investigate and optimize PAC process parameters for different materials with no focus on cutting of copper or copper alloys. While copper material is subjected to be cut using plasma in the industry. Thus, the aim of this work is to present an investigation of PAC process variables on the produced cutting parameters for pure copper material plates.

4. EXPERIMENTAL WORK

Experiments are carried out on 30*30*5 mm copper specimens cut from continuous extrusion flat busbar strips “Fig. 5”. CNC platform equipped with Hypertherm Powermax 125 plasma cutting source is used “Fig. 2” with specifications as mentioned in Table 1. A special jig is designed “Fig. 3” and fitted on the machine bed to avoid workpiece initial piercing and machine acceleration errors (entry allowance) with speed and heat intensity supplied to the samples and to neglect preheating effects.

Measurements are carried out according to Surtronic-3 Tylor Hobson Surface texture equipment according to ISO9013 Standard[4]. It is used to measure surface roughness (Ra) values. Centerline average roughness (Ra) measurements are performed on a brushed workpiece to remove the oxide layer accumulated on the copper surface after cutting with plasma. Angularity tolerance (unevenness) is measured on visual images scanned with high precision 1200 ppi scanner. The MRR was calculated through the difference of the specimens' weight before and after the cutting. Also, the length of the heat affected zones was examined visually on an optical microscope.

Table 1: Plasma cutting machine specifications

Item		Identification
Plasma arc cutting system	Machine	Hypertherm, Powermax 125
	Cutting gas	Air
	Shielding gas	Air
	Max output current	125 A
	Max output pressure	6.1 bars
	Air flow rate	345 LPM (for 125A nozzle)
	Nozzle orifice diameter	1.5 mm (for 125A nozzle)
CNC system	Machine	Becatronics , Beca P 400
	Table Size	2000 x 4000 mm
	Torch impingement angle	90°

Fig. 2: Bechatronics CNC PAC machine with hypertherm powermax

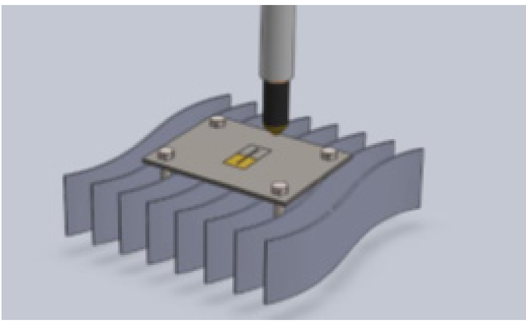

Fig. 3: Jig for fixing samples on machine bed

Experiments were done for several combinations among many process variables to investigate their effectiveness on the process parameters. The selected variables are according to the possibility of their variation on the machine. P. Patel *et al.*[9] determined most of these variables. The variables are arc intensity, cutting speed, gas pressure and cutting height (standoff distance). Table 2 shows the selected ranges of the variables for the experiments.

Table 2: Ranges of cutting variables

Variable	Range
Arc intensity	100 – 110 – 120 A
Cutting speed	1000 – 1500 – 2000 mm/min
Gas pressure	5.1 – 5.6 – 6.1 bars
Cutting height	2 – 4 – 6 mm

Specimens are made of copper with a chemical composition as mentioned in Table 3. They were weighed before and after the experiments in order to calculate the MRR. Cuts were perpendicular to extrusion direction having no impingement angle. Each experiment (factors combination) was replicated 3 times. V. A. emchinsky[1] described the burr (low speed dross) and top spatter which are generated during the Plasma Arc Cutting and need to remove them before the measurements. Similarly behaved in the samples of this research; are showed in "Fig. 4-A" and "Fig. 4-B" respectively; which they removed before any measurements specially MRR to neglect their effect on the results.

Fig. 4-A: Adhering low speed dross to the bottom of the plate

Fig. 4-B: Top spatter on the upper surface of the plate

Fig. 5: 30*30*5 Samples before cutting

Table 3: Chemical composition of copper samples

Element	Zn	Pb	Sn	P	Mn	Fe	Cu
Conc.[%]	0.11656	0.00663	0.00480	0.00112	0.00018	0.04663	99.7791

V. A. Nemchinsky[1] demonstrated that the measurement process it should be identified that the right and the left sides of the samples describe how the air swirl was (clock wise). Plasma cutting torch is shown in "Fig. 6". The right side is the selected one for measuring surface roughness as described in "Fig. 7". In addition to MRR, conicity error and HAZ, the arithmetic mean deviation Ra, was selected as the surface quality indicator to be considered as the process parameter. Five readings were taken according to ISO9013 Standard[4] in the measurement process on each sample as shown in Figure 8 with cut-off distance equals to 0.8 mm and the average of all readings was calculated after rejection of outliers. M. P. Maples *et al.*[21] described how the rejection of outliers can be made according to Chauvenet's criterion.

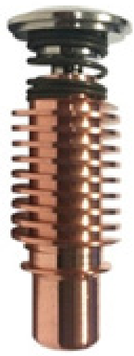

Fig. 6: Hypertherm powermax 125 electrode

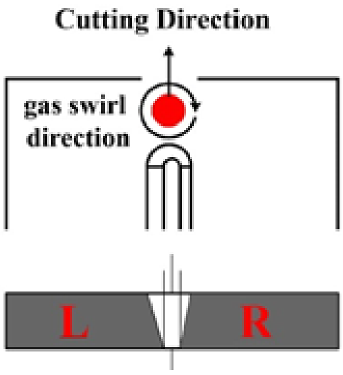

Fig. 7: Right and left (scrape) workpiece sides

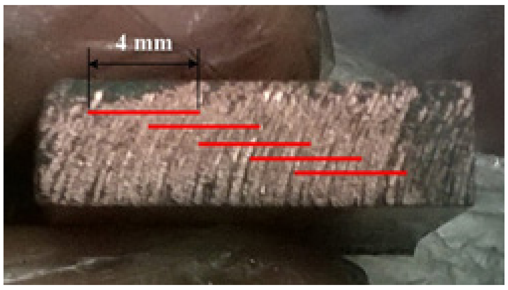

Fig. 8: Roughness measuring positions

5. RESULTS AND DISCUSSION

I. Effect of variables on Ra:

Figures from "Fig. 9" to "Fig. 17" illustrate the effect of the current intensity level, speed, standoff distance and pressure on Ra. Current levels are denoted by 1, 2 and 3 which are indicated to 100, 110 and 120 A respectively. Results show that the most effective variable on Ra is the cutting speed, where; increasing of the cutting speed increases the surface roughness Ra. It may be caused by shorter time of plasma beam into specimen, the consequence of which is a rapid melting process. As well as an increase in cutting speed causes the flame to spread more across the cut surface. The more time the flame stays on the surface of cut material, the more irregularities are observed on the surface. While; increasing of the current level for different standoff and pressure has no cleared effect on the surface roughness Ra. This may be due to the very little difference between the considered current levels and pressure values are due to machine constraints.

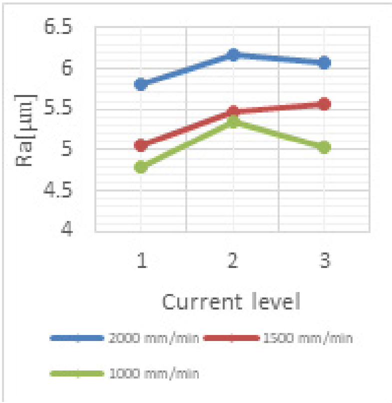

Fig. 9: Effect of the current intensity at different speeds on Ra at 2 mm torch height and pressure 6.1 bars

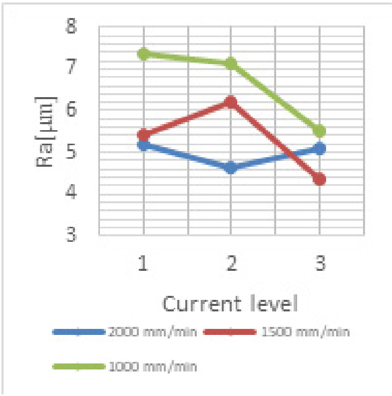

Fig. 10: Effect of the current intensity at different speeds on Ra at 4 mm torch height and pressure 6.1 bars.

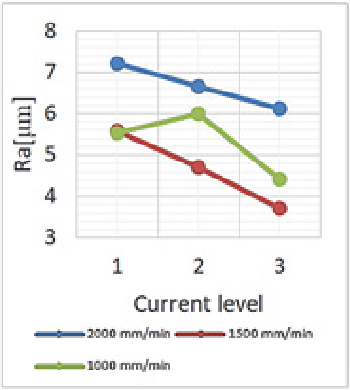

Fig. 11: Effect of the current intensity at different speeds on Ra at 6 mm torch height and pressure 6.1 bars.

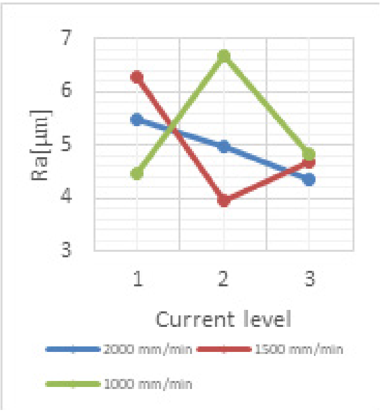

Fig. 12: Effect of the current intensity at different speeds on Ra at 2 mm torch height and pressure 5.6 bars.

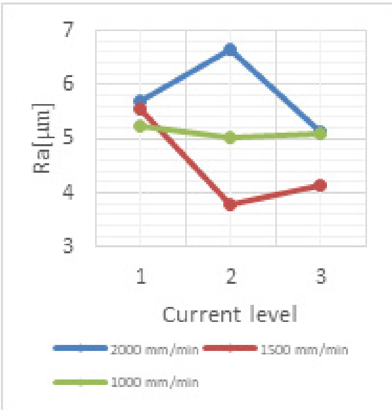

Fig. 13: Effect of the current intensity at different speeds on Ra at 4 mm torch height and pressure 5.6 bars.

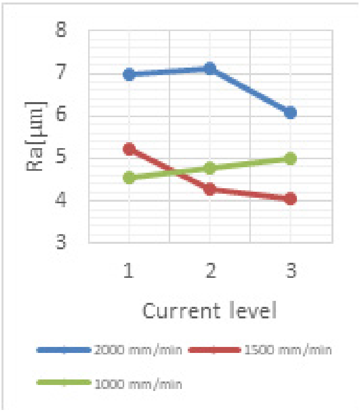

Fig. 14: Effect of the current intensity at different speeds on Ra at 6 mm torch height and pressure 5.6 bars.

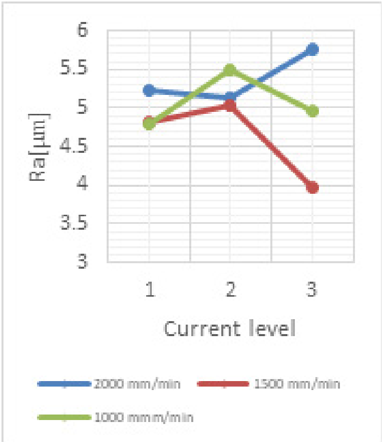

Fig. 15: Effect of the current intensity at different speeds on Ra at 2 mm torch height and pressure 5.1 bars.

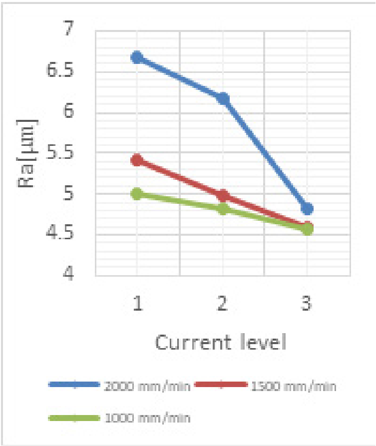

Fig. 16: Effect of the current intensity at different speeds on Ra at 4 mm torch height and pressure 5.1 bars.

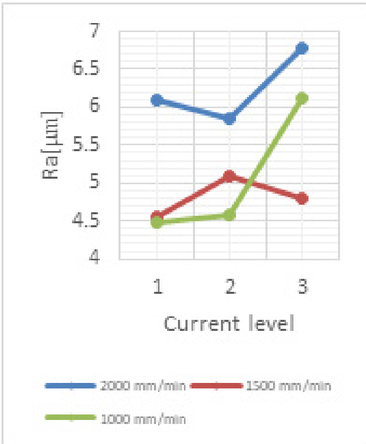

Fig. 17: Effect of the current intensity at different speeds on Ra at 6 mm torch height and pressure 5.1 bars.

II. Effect of variables on conicity error "u":

The specimens were cut using the wire cut process and visually inspected by scanning to show the cut profile along the specimen thickness, so the conicity can be determined as illustrated in "Fig. 18". Output pictures from the scanner are in with a resolution of 600 dpi giving an accuracy of ±0.05 mm. The results showing that the Δa (thickness reduction) = 0.3 mm for 5 mm thickness specimens, the reason for the reduced cut face profile is to allow for the melting of the top edge.

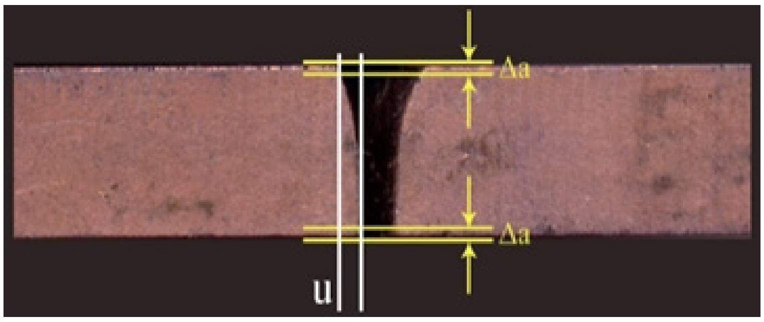

Fig. 18: Output pictures from scanner after wire cut of examined samples

Fig. 19 illustrates results of conicity in mm show that the conicity error *u* increases with the increase of cutting current and cutting feed while there are no cleared results regarding the pressure for different conditions of feed, nozzle height and current. This may be due to the higher temperature produced at higher current. Also, there is no relation with the pressure, because the used pressure levels are very close to each other according to the used machine specifications.

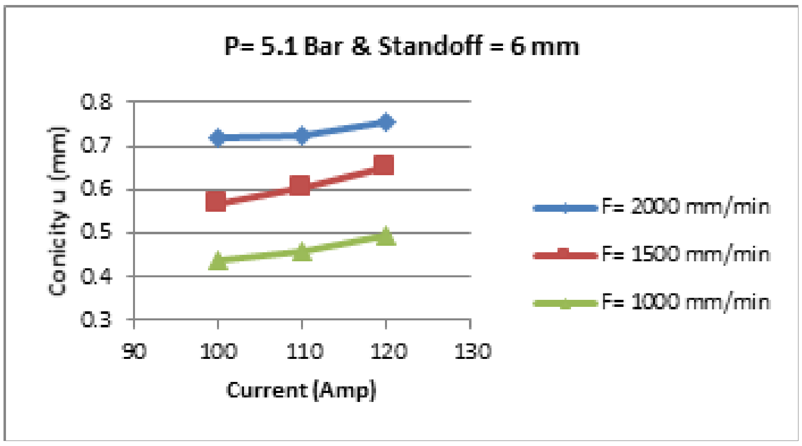

Fig. 19: Conicity error u (mm) versus current (A)

III. Effect of variables on HAZ:

S. S. Pawar[23] examined the effect of the process variables on the heat affected zones (HAZ) by etching. So each specimen is immersed in this solution (etchant) for about 30 seconds at room temperature then visually examined on an optical microscope as showed in "Fig. 20". For pure copper it is obviously seen that grain gross (coarse grains) occurs at the area next to the plasma torch "Fig. 21" like the welding operation HAZ "Fig. 22" as described by Chen *et al.*[22].

Fig. 20: Used optical microscope

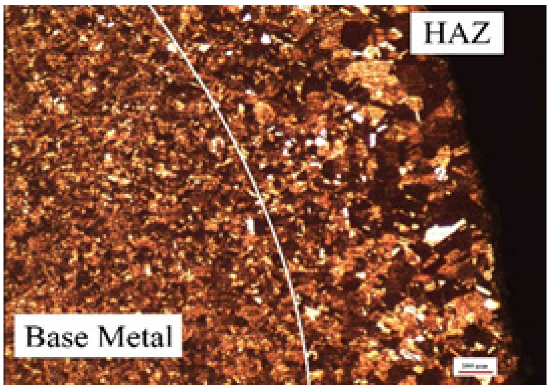

Fig. 21: Microstructures of the heat-affected zone at the copper right side for cutting variables of 100 ampere current, 6.1 bar cutting pressure, 1000 mm/min speed, and 2 mm torch height

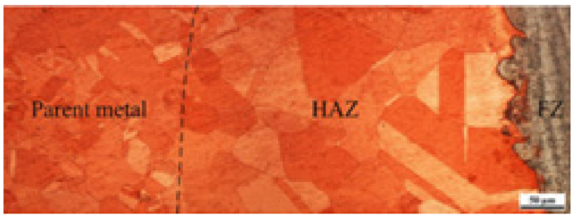

Fig. 22: Microstructures of the heat-affected zone at the copper side and at the interface between copper and the fusion zone Chen *et al.*[22].

As mentioned before and according to V. A. Nemchinsky[1], the right-hand side of the specimens was a "good" choice which gives the lowest HAZ values. Five readings were taken for HAZ in µm measurements on each side and the average of those five readings was used to plot the relations shown in "Fig. 23, 24 and 25". Figures from "Fig. 23-A" to "Fig. 23-I" (for different standoff distances and cutting speeds) show that the HAZ increases by increasing the current level because the increasing of current increases the generated heat. Also, its cleared that the decreasing of cutting speed (feed) yields increasing of the HAZ, where the slow motion does not allow the generated heat to be dissipated.

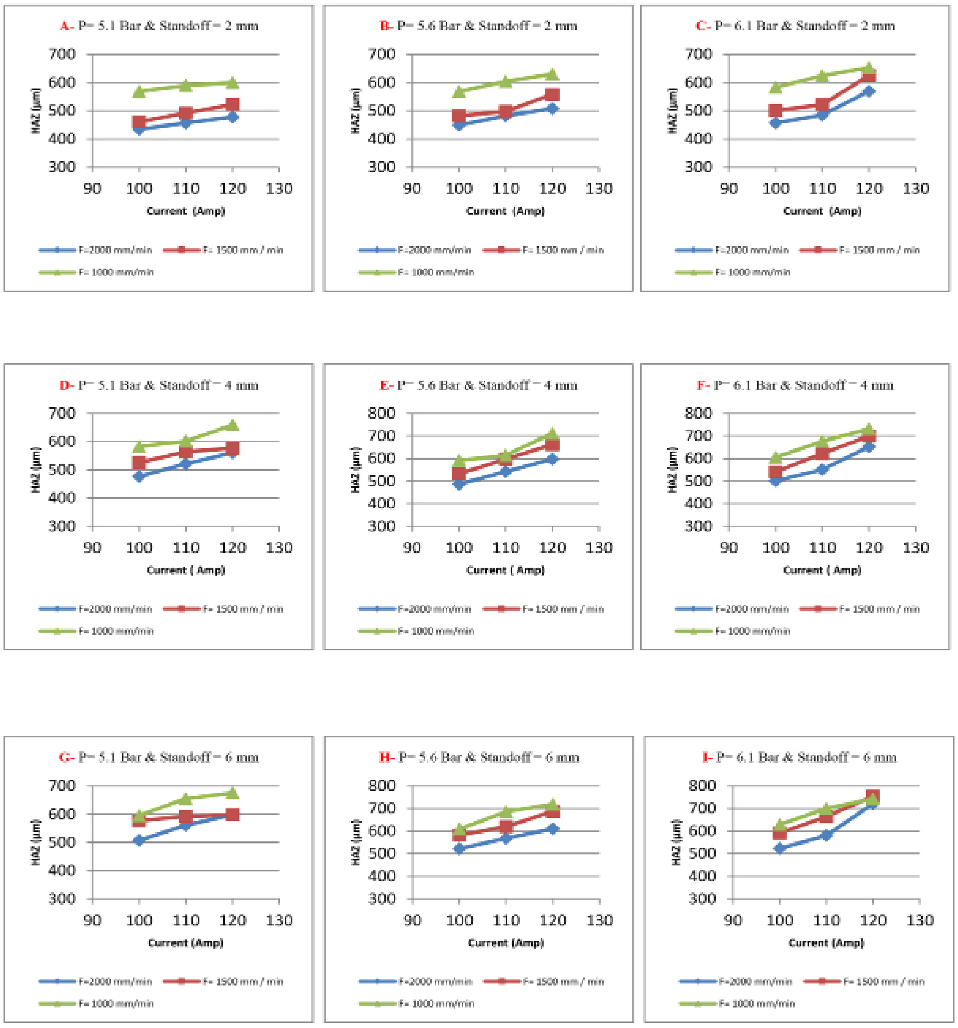

Fig. 23: A to I. Heat affected zones in µm versus the current (A) for different cutting speeds

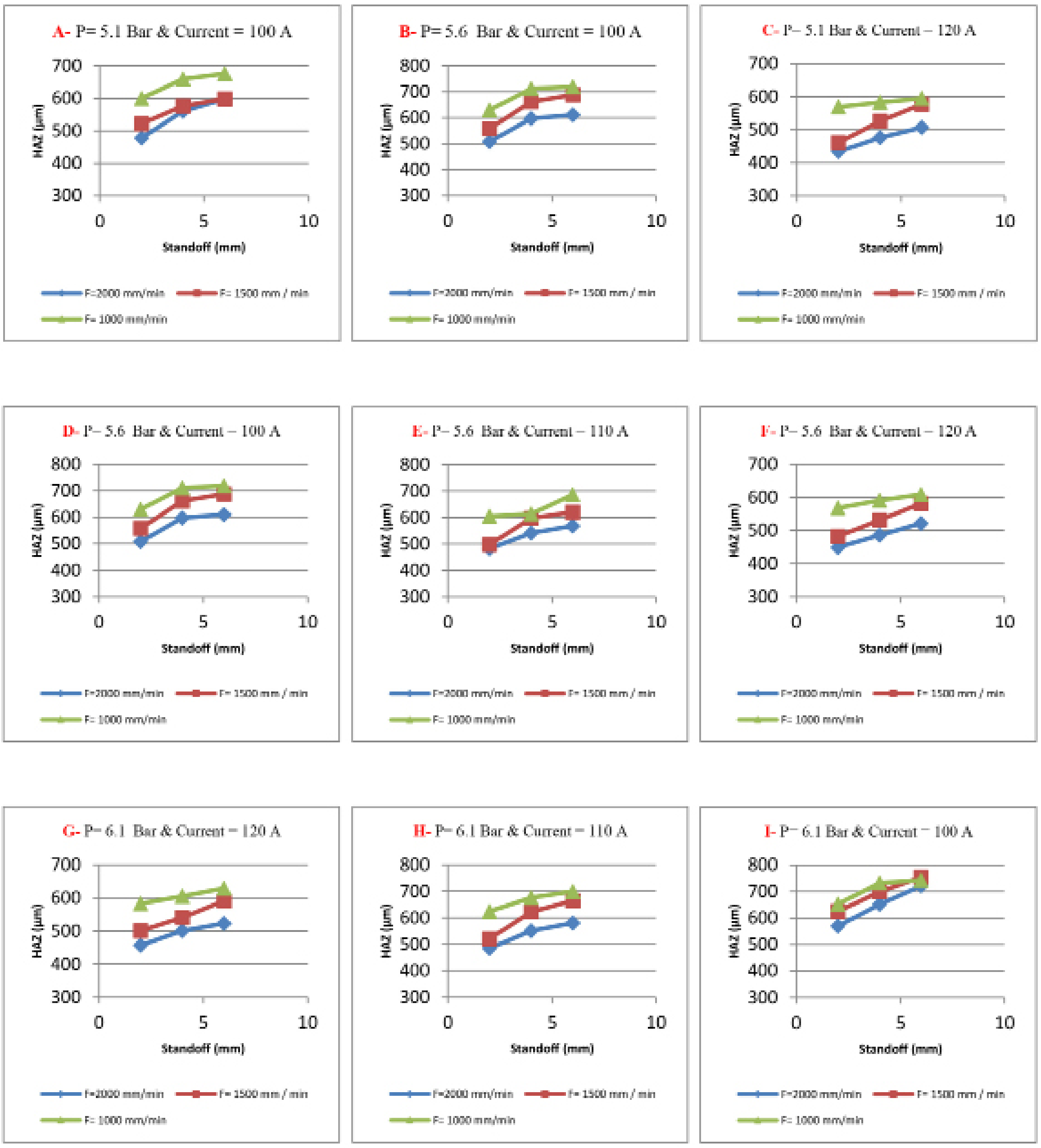

Fig. 24: A to I. –Heat affected zones in µm versus the standoff distance (mm) for different cutting speeds

Figures from "Fig. 24-A to Fig. 24-I" identify that the HAZ increases by increasing the standoff distance, because the maximum temperature of the flame is far from the nozzle tip so by increasing the distance from the nozzle tip the heat increases resulting in a wider HAZ.

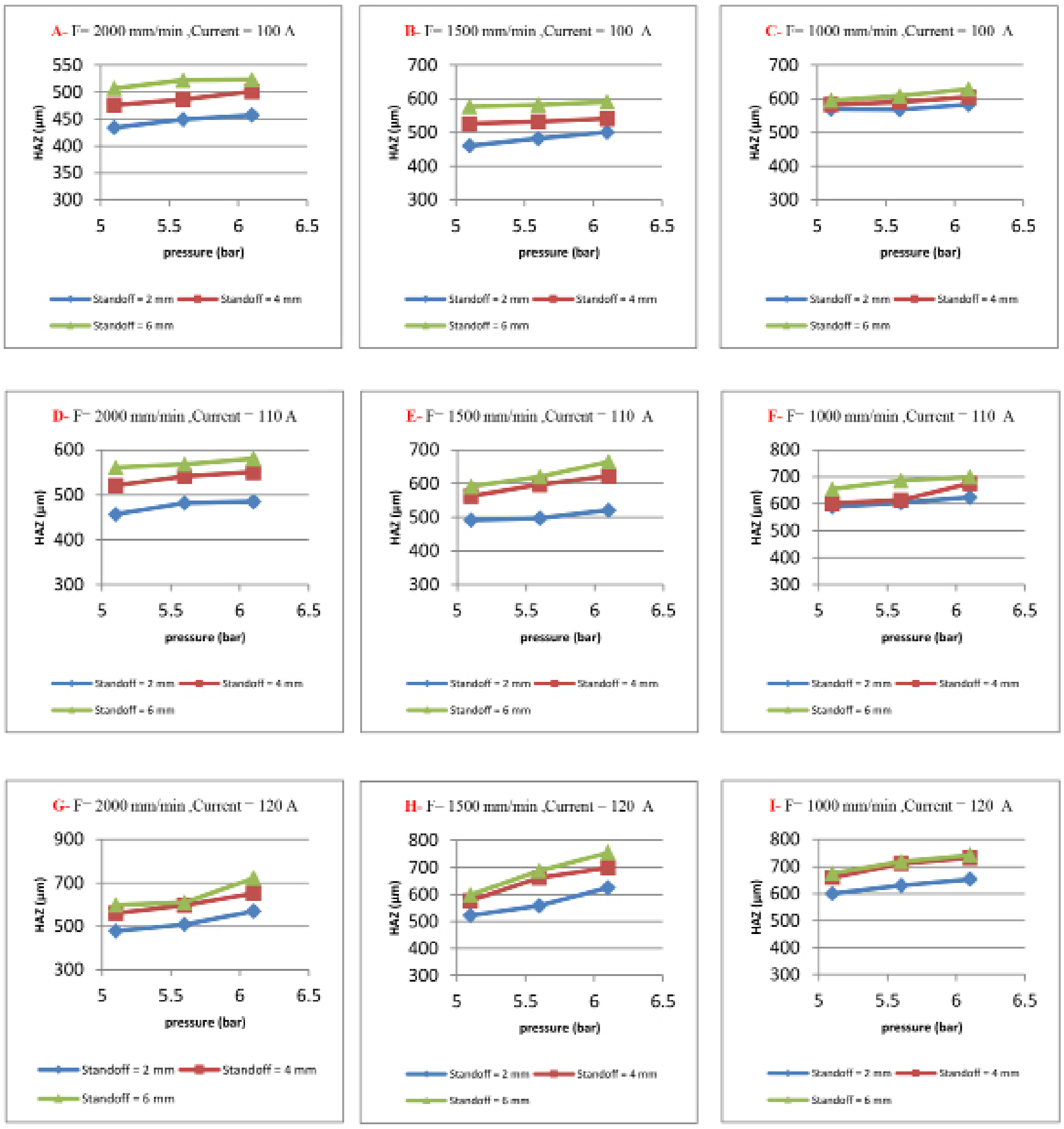

Fig. 25: A to I. Heat affected zones in μm versus the pressure (bar) for different standoff distances

Figures from "Fig. 25-A" to "Fig. 25-I" illustrate the relation between the HAZ and the plasma pressure. The figures show that a slight increase in the pressure results in a slight increase in the HAZ. This is since the pressure increases the heat diffusion in the work piece yields an increase in the HAZ. Also, by increasing the standoff distance the HAZ increases as described before.

IV. Effect of variables on MRR:

Specimens were weighed with 0.01 gm. precise scale before and after experiments, and burrs were removed and their weight was considered. Material Removal Rate MRR in gm. /min can be calculated using the following relation:

$$MRR = \frac{(Mass_{after} - Mass_{before}) * Speed}{length\ of\ cut}$$

Where specimen mass is in gram, speed is in mm/min and cutting length is in mm which is measured from the scanned picture after deburring. "Fig. 26" shows the specimen after deburring and how the length of cut was considered.

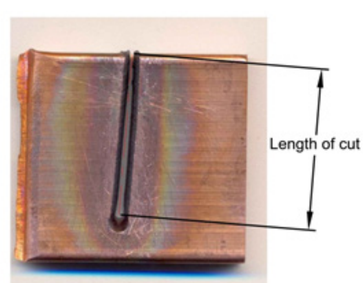

Fig. 26: Cutting length measurement in copper workpiece scanned picture

Results show that the cutting speed is the most dominant parameter on MRR, where; increasing of speed level increases MRR. This is due to the rapid removing the layers of the metal. Also, MRR is directly proportional to the cutting current level, the cutting height “Fig. 27”. This could be explained by the excess material melted at higher current levels and the large diversity of the plasma beam by increasing of the height. Also, increasing of the pressure enhances the rate of pushing away of the molten metal.

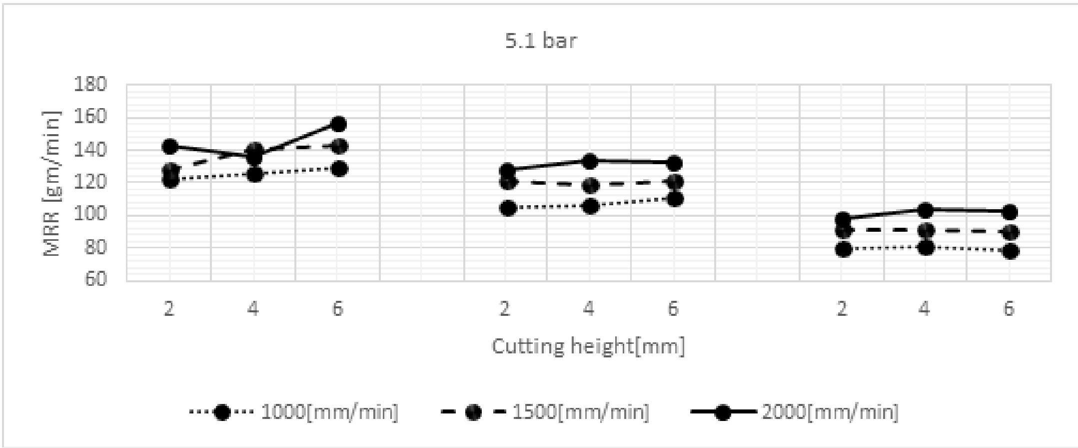

Fig. 27: MRR in gm. /min for different cutting speeds (mm/min), heights (mm) and current levels (A) at cutting pressure 5.1 (bars)

Analysis of variance (ANOVA):

General Linear regression model for surface roughness:

Data transformation (Box-Cox transformation with optimal λ) is used to normalize the resulted data and transformed set of data are subjected to ANOVA and normal probability plots are cleared in Figure 28.

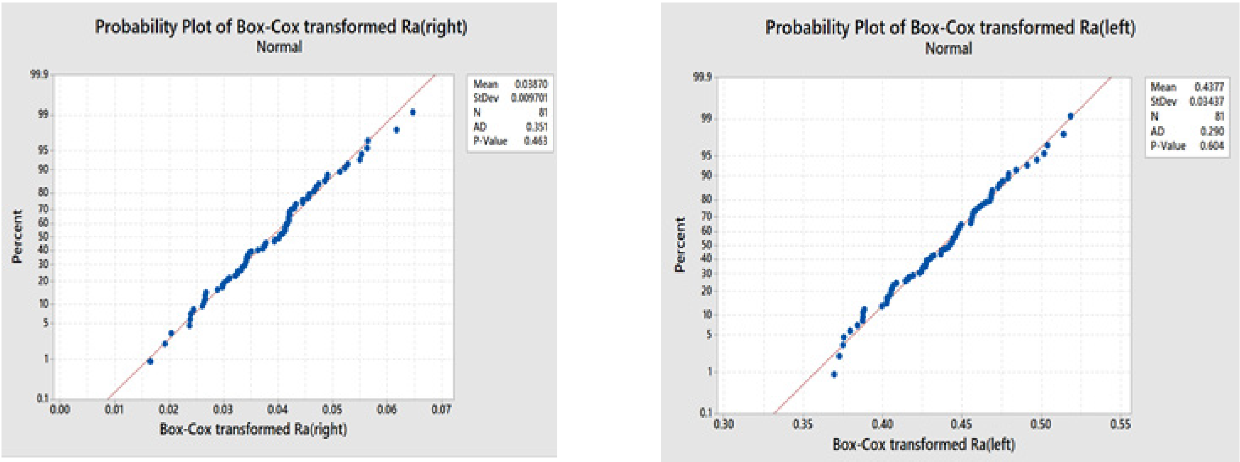

Fig. 28: Probability plots of transformed data set for Ra values to subject to normal distribution

Figure 28 shows that the data are normally distributed for both right and left sides of cut. The interaction effect between the input variables on the output Ra parameter, so ANOVA is repeated again using interaction between variables as factors for the analysis as shown in Table 4. And the interaction between variables versus Ra response is plotted in Figure 29.

Table 4: Interaction analysis of variance for transformed response (Ra right)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Current	2	3.4219	8.03%	3.4219	1.7109
Speed	2	2.1723	5.10%	2.1723	1.0862
pressure	2	0.9580	2.25%	0.9580	0.4790
SOD	2	0.8663	2.03%	0.8663	0.4332
Current*Pressure	4	1.5561	3.65%	1.5561	0.3890
Current*Speed	4	1.4511	3.40%	1.4511	0.3628
Current*SOD	4	1.9768	4.64%	1.9768	0.4942
Pressure*Speed	4	2.8758	6.75%	2.8758	0.7190
Pressure*SOD	4	2.4959	5.85%	2.4959	0.6240
Speed*SOD	4	3.8679	9.07%	3.8679	0.9670
Current*Pressure*Speed	8	2.3561	5.53%	2.3561	0.2945
Current*Pressure*SOD	8	1.1642	2.73%	1.1642	0.1455
Current*Speed*SOD	8	6.7176	15.76%	6.7176	0.8397
Pressure*Speed*SOD	8	6.1863	14.51%	6.1863	0.7733
Current*Pressure*Speed*SOD	16	4.5673	10.71%	4.5673	0.2855
Error	0	*	*	*	*
Total	80	42.6336	100.00%		

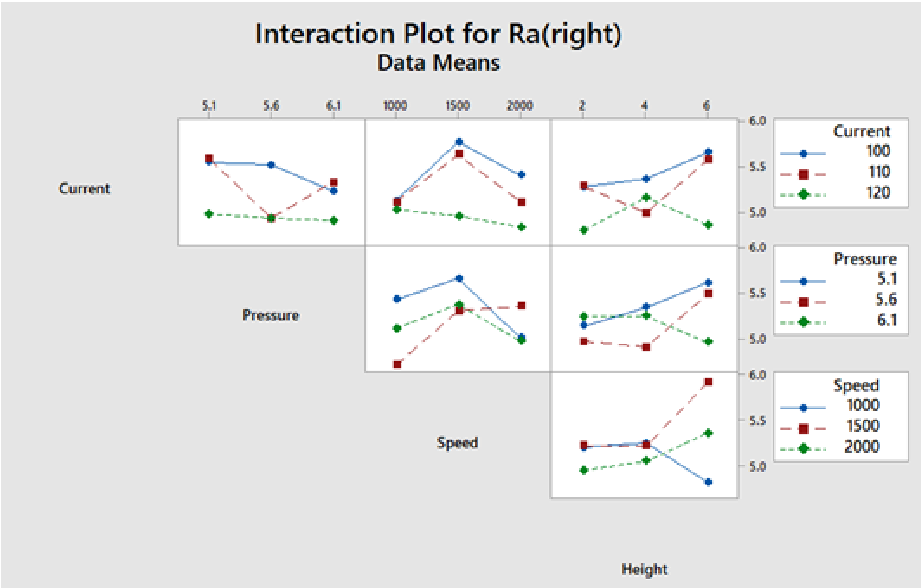

Fig. 29: Interaction effect plot of input variables versus Ra response

Results of ANOVA showed that cutting current has the most dominating effect on Ra values with 8% contribution, then cutting speed with 5% percentage contribution both SOD and pressure has less effect on Ra with approximate 2% percentage contribution.

The main effect plot of means showed that lower value of Ra could be achieved at higher values of cutting current, lower values of cutting speed and SOD, and the pressure is chosen to be 5.6 bars.

6. CONCLUSION

Plasma arc cutting is a very trustworthy and assuring thermal cutting technology which combines good cutting quality with high productivity. This cutting process is pointedly influenced by several variables. The operating conditions have to be carefully investigated through parameter adjustment in order to obtain cleared results for new cutting materials such as pure copper or copper alloys.

This paper is conducted to study the effect of different process variables for plasma cutting process on the surface of copper material. The study shows the influence on surface roughness, conicity, HAZ and MRR through of changing the cutting speed, standoff distance, current intensity and the pressure[24,25,26]. So; it's cleared in the results that the most effective variable on the surface roughness is the cutting speed as concluded by[2 , 20], while; the current level for different standoff[27,28] and pressure has no cleared effect on the surface roughness. And, the conicity error increases with the increase of cutting current and cutting feed while there are no cleared results regarding the pressure for different conditions of feed, nozzle height and current. Also, the HAZ increases by increasing the current level as concluded by[18,21] as well as the decreasing of cutting speed (feed) yields increasing of the HAZ. In addition, the cutting speed is the most dominating parameter on MRR as resulted by[16], where; increasing of speed level increases MRR and, the MRR is directly proportional to the cutting current level.

Generally; it can be concluded that the cutting speed, standoff distance, current intensity and pressure influence surface roughness, conicity, HAZ and MRR for copper which still requires further study of optimization of cutting variables to obtain the highest cut quality for copper and copper alloys. These studies may include the optimization of variables; this may be helped by a plasma machine has more facilities of changing the values of variables as well as the range of each variable set on its hardware may be more wide than used in this research.

Furthermore; the results of this research may be connected to the manufacturing industry, where all data of experiments (inputs and outputs) may be arranged into a pattern or a model by software like Matlab or any other software and treated by an intelligent technique be used to optimize the process before it may be done. So the manufacturer can expect the outputs of the process before it will be done and can change the inputs to find the preferred outputs for him.

2. REFERENCES

[1] Nemchinsky, V. A., Severance, W. S., 2006. What we know and what we do not know about plasma arc cutting. Institute of physics publishing, journal of physics d: applied physics, J. Phys. D: Appl. Phys. 39 R423–R438, DOI:10.1088/0022-3727/39/22/R01.

[2] Chamarthi, S., Sinivasa N. R., Kumar, M., E., Ramana D. V. R., 2013. Investigation Analysis of Plasma arc cutting Parameters on the Unevenness surface of Hardox-400 material. International Conference On DESIGN AND MANUFACTURING, IConDM 2013. Procedia Engineering 64 (2013) 854 – 861, India, doi: 10.1016/j.proeng.2013.09.161, http://www.sciencedirect.com

[3] Salonits, K., Vatousianos, V., (2012). Experimental Investigation of the Plasma Arc Cutting Process. Proceedings of 45th CIRP Conference on Manufacturing Systems, UK, Vol.3, pp. 287-292, DOI: 10.1016/j.procir.2012.07.050.

[4] ISO9013 Standard, 2017. Thermal Cutting: Classification of Thermal Cuts—Geometrical Product Specification and Quality Tolerances, https://www.iso.org/standard/60321.html

[5] Kumar, D. N., Maity K. P., 2018. An optimization and experimental analysis of plasma arc cutting of Hardox-400 using Taguchi based desirability analysis. Materials Today: Proceedings 5 (2018) 13157–13165. Conference: Materials Today: Proceedings DOI: 10.1016/j.matpr.2018.02.306.

[6] Kechagias, J., Pappas, M., Karagiannis, S., Petropoulos, G., Lakovakis, V., Maropoulos, S., 2010. An ANN Approach on the Optimization of the Cutting Parameters during CNC Plasma-Arc Cutting. Proceedings of the ASME 2010, 10th Biennial Conference on Engineering Systems Design and Analysis, ESDA2010-24225, Istanbul, Turkey, volume 4. DOI: 10.1115/ESDA2010-24225.

[7] Bini, R., Colosimo, B. M., Kutlu, A. E., Monno M., 2008. Experimental Study Of The Features Of The Kerf Generated By A 200 A High Tolerance Plasma Arc Cutting System. Journal of Materials Processing Technology. Vol. 196, no. 1-3, pp. 345-355, DOI:10.1016/j.jmatprotec.2007.05.061.

[8] Deli, J., Bo, Y., 2011. An intelligent control strategy for plasma arc cutting technology. Journal of Manufacturing Processes. Vol. 13, Issue 1, pages 1-7, DOI:10.1016/j.jmapro.2010.08.003.

[9] Patel, P., Soni, S., Kotkunde, N., Khanna, N., 2018. Experimental investigation of cut quality characteristics on SS321using plasma arc cutting. Journal of the Brazilian Society of Mechanical Sciences and Engineering, Volume 40, Article no. 60, https://doi.org/10.1007/s40430-018-0997-8.

[10] Hrvoje Cajner*, Vid Križanić, Tihomir Opetuk, Maja Trstenjak, 2024. Optimisation of Parameters for Metal Part Cutting on a CNC Plasma Cutting Machine. TECHNICAL JOURNAL volume 18, issue 1(2024), pages 122-128, ISSN 1846-6168 (Print), ISSN 1848-5588 (Online), https://doi.org/10.31803/tg-20230508230247

[11] Singh D., Shrivastava Y., Kumar r., 2021. Identification of suitable machining zone during the plasma arc cutting of SS-304. Materials Today: Proceedings 38. Volume 38, Part 1, Pages 413-417, https://doi.org/10.1016/j.matpr.2020.07.598.

[12] Suresh, A., Diwakar, G., 2021. Optimization of process parameters in plasma arc cutting for TWIP steel plates. Elsevier Ltd, Materials Today: Proceedings 38, pages 2417–2424 https://doi.org/10.1016/j.matpr.2020.07.383

[13] Patel, P., Nakum, B., Abhishek, K., Rakesh V. K.,Kumar, A., 2018. Optimization of Surface Roughness in Plasma Arc Cutting of AISID2 Steel Using TLBO. Materials Today: Proceedings Volume 5, Issue 9, Part 3, 2018, Pages 18927–18932. https://doi.org/10.1016/j.matpr.2018.06.242

[14] Beleed, A., Rajamony, B., 2016. Plasma Arc Cutting Optimization Parameters For Aluminum Alloy With Two Thickness By Using Taguchi Method. The 2nd International Conference On Functional Materials And Metallurgy (ICFMM 2016), New York, DOI: 10.1063/1.4958776.

[15] Bhowmick, S., Basu, J., Majumdar, G., Bandyopadhyay, A., 2018. Experimental study of plasma arc cutting of AISI 304 stainless steel. Materials Today: Proceedings Volume 5, Issue 2, Part 1, 2018, Pages 4541-4550. https://doi.org/10.1016/j.matpr.2017.12.024

[16] Parthkumar, P., Shrekumar S., Nitin K., Navneet K., 2018. Study the effect of process parameters in plasma arc cutting on Quard-400 material using analysis of variance. 7th International Conference of Materials Processing and Characterization. Elsevier Ltd. Materials Today: Proceedings Volume 5, pages 6023–6029.

[17] Kumar, M.D., Kumar, K., Barman, T. Kr., Sahoo, P., 2014. Optimization of Process Parameters in Plasma Arc Cutting of EN 31 Steel Based on MRR and Multiple Roughness Characteristics Using Grey Rational Analysis. International Conference on Advances in Manufacturing and Materials Engineering, AMME 2014, Procedia Materials Science 5 (2014), Volume 5 page number 1550 – 1559, DOI: 10.1016/j.mspro.2014.07.342.

[18] Kumar, R., Stalin, T., 2015. Analysis in Plasma Arc Cutting Of 21Cr Ferritic Stainless Steel. International Journal of ChemTech Research, CODEN (USA): IJCRGG ISSN: 0974-4290, Vol.8, No.11 pages 474-483, https://doi.org/10.20902/ct

[19] Rajeshkannan, A., Ali, M., Prakash, R., Prasad, R., Jeevanantham, A.K., Jayaram, K., 2018. Optimizing the Process Parameters in Plasma Arc Cutting using Taguchi Approach for the Case Industry in Fiji. IConAMMA 2018. Materials Today: Proceedings Volume 24, Part 2, 2020, Pages 1122-1131. https://doi.org/10.1016/j.matpr.2020.04.425

[20] Adalarasan, R., Santhanakumar, M., Rajmohan, M., 2015. Application Of Grey Taguchi-Based Response Surface Methodology (GT-RSM) For Optimizing The Plasma Arc Cutting Parameters Of 304L Stainless Steel. International Journal of Advanced Manufacturing Technology. Vol. 78, pp. 1161-1170, DOI 10.1007/s00170-014-6744-0

[21] Maples, M. P., Reichart, D. E., Konz, N. C., Berger, T. A., Trotter, A. S., Martin, J. R., Dutton, D. A., Paggen, M. L., Joyner, R. E., Salemi, C. P., 2018. Robust Chauvenet Outlier Rejection. The Astrophysical Journal Supplement Series, 238:2 (49pp), https://doi.org/10.3847/1538-4365/aad23d.

[22] Chen, S., Huang, J., Xia, J., Hua, Zhag, H., Zhao, X., 2013. Microstructural Characteristics of a Stainless Steel/Copper Dissimilar Joint Made by Laser Welding. The Minerals, Metals & Materials Society and ASM International, DOI: 10.1007/s11661-013-1693-z. VOLUME 44A, pages 3690—3696.
[23] Pawar, S. S., Inamdar, K. H., 2017. Analysis of Heat Affected Zone in Plasma Arc Cutting of SS 316l Plates. International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6, Issue 5, DOI:10.15680/IJIRSET.2017.0605152.
[24] Hussain, S., Qazi, M.I. and Abas, M., 2024. Investigation and optimization of plasma arc cutting process parameters for AISI 304 by integrating principal component analysis and composite desirability method. J Braz. Soc. Mech. Sci. Eng. 46, 33 (2024). https://doi.org/10.1007/s40430-023-04614-y
[25] Wima Azis Khanafi, Yanuar Rohmat Aji Pradana, and Suprayitno, 2022. Robust Parameter Design to Optimize Kerf Width and Material Removal Rate on Plasma Cutting of Stainless Steel 316. Springer Nature Singapore Pte Ltd. 2023 I. Tolj *et al*. (eds.), Recent Advances in Mechanical Engineering, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-19-0867-5_20
[26] Andjela Lazarevic∗, Dragoljub Lazarevic, 2022. Effects of plasma arc cutting process parameters on the cutting speed optimization based on the required cut quality. Elsevier, CIRP Journal of Manufacturing Science and Technology 38 (2022) 836–843 https://doi.org/10.1016/j.cirpj.2022.07.003
[27] Khushboo Sharma, Jai Kishan Sambharia, and Alok Khatri, 2021. Optimization of Process Variables in Plasma Arc Machining of Inconel-718 Alloy Using Taguchi with Grey Relational Analysis. Nature Singapore Pte Ltd. 2021 H. K. Dave and D. Nedelcu (eds.), Advances in Manufacturing Processes, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-15-9117-4_4
[28] Milos Milovancevic, Kamen Boyanov Spasov , Abouzar Rahimi. Optimization of the Plasma Arc Cutting Process Through Technological Forecasting. Journal of Engineering Management Systems Engineering, vol. 3, no. 1, pp. 30–37, 2024. https://doi.org/10.56578/j emse030103
[29] Ilii, S. M., Apetrei L., Carp I., 2008. Considerations Concerning Plasma Arc Cutting Machining. 3rd International Conference on Manufacturing Engineering (ICMEN2008), Greece.