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Effect of Cutting Speed and Depth of Cut on Surface Roughness of Mild Steel Using a Shaping Machine

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Abstract
The surface roughness of machined components is a critical parameter influencing their performance and functionality across various engineering applications. In the context of metalworking processes, achieving desired surface quality, particularly in mild steel, holds significant importance due to its widespread use in industrial sectors. This study focused on finding optimal control parameters to get the minimum Surface roughness to enhance machining efficiency and product quality. The experimental cutting tests was conducted on a shaping machine using mild steel work piece under controlled operating conditions. Cutting speed and depth of cut parameters were systematically varied and measured to assess their impact on surface roughness. The data obtained from the experimental study was used to develop a mathematical model to predict correlating machining parameters with surface roughness. The models were validated and tested for adequacy using Coefficient of determination and their coefficient of determination values were found to be 0.9403 when varying Ram speed with constant depth of cut and 0.9271when varying depth of cut with constant Ram speed. The developed predictive models offer practical guidance for machining practitioners and engineers in selecting optimal process parameters to meet specific surface finish requirements and enhance overall machining performance.

Keywords: *Cutting speed, shaping machine, depth of cut and surface roughness.*

1.0 Introduction

Machining is the process of removing excess material from the work piece or unwanted material from the work piece using a cutting tool. Some examples of commonly used machine tools includes; Lathe machine, Shaping machine, Planer, Drilling machine, Milling machine and many more. The surface finish of a machined product significantly impacts its functional performance, and is heavily influenced by cutting parameters like cutting speed and depth of cut. Therefore, understanding the impact of these parameters on surface roughness is crucial in achieving the desired surface finish. In this experimental study, we investigated the effects of cutting speed of the reciprocating ram and depth of cut on the surface finish of a Mild steel bar using a Shaping machine.

Shaping is a widely used metal removal process in metalworking industry. A shaping machine is a traditional cutting machine used for shaping and planning flat and regular surfaces, and it is suitable for this study due to its ability to produce substantial cutting forces and highly variable cutting speed and depth. The shaper machine function through a reciprocating motion, where a hardened cutting tool moves back and forth across the workpiece. Cutting occurs only on the forward stroke, while the tool lifts on the return stroke. The workpiece is secured on an adjustable table that can be fed sideways under the tool via an automatic mechanism. The ram`s adjustable stroke length and faster return motion enhance efficiency. A vertical tool slide holds the cutting tool, allowing for precise cutting of flat surfaces. Surface roughness is a key indicator of machining quality, directly impacting the finished products performance. José et al. (2024) identified twenty-five (5) different factors influencing surface roughness creation during machining operation. The understanding of these factors is critical in determining the quality of a machined part, manufacturing sustainability, cutting process optimization and cost reduction. José et al. (2024) further demonstrated with a three case studies under which machining sustainability can be improved, and the outcome of the initial case showed a 75% reduction in CO_2 when a wiper insert was used in hard turning as compared to a conventional insert. The second case showed a 35% reduction in CO_2 emission through air cooling to a Minimum Quantity Lubrication (MQL) cooling during the milling of a punch in the tile mold industry. And the last case showed the substantial benefits achievable if grinding processes is replaced with surface roughness control in preceding milling/turning operations. In this scenario, optimizing cutting operations and employing early tool change replacement led to a 67% reduction in CO_2 equivalent emissions and eliminated the need for water consumption in flood cooling associated with conventional milling and subsequent grinding operations.

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Achieving optimal surface quality necessitates precise adjustment of machining parameters during operations. This ensures that the machining process is finely tuned to enhance surface finish to its fullest potential. The high friction between tool and work piece leads to high temperatures, tool wear, and poor surface quality. Mohsen and Behrooz (2023) created a virtual machining model to study the impact of cutting speed, feed rate, depth of cut, cutting temperature and rate of material removal on cutting tool life. They obtained 87.8% compatibility between the experimental and the virtual machining system which enabled them to predict accurately the heat generated in the cutter and the cutter tool life. They observed that, by increasing the speed of cutting during milling operations, less time for the generated heat in the cutting tool is provided in order to be conducted to the machined work pieces. As a consequence, heat energy is forced to stay in the milling cutter, raising its cutting temperature while lowering contact friction of machined surfaces. While increasing the depth of cut, feed rate and rate of material removal during milling operations, the cutting temperature of cutter is increased. The cross section of chips in the cutting zone is increased by increasing the feed rate and depth of cut during milling operations, and this can lead to enhance friction and a rise in the cutting tool's maximum temperature. Jean et al. (2023) investigated the wearing of cutting tools using two complementary approaches of experimental measurement and Rayleigh-ham method which were analyzed based on the speed of cut, feed and depth of cut. They came up with a law that integrates the cutting temperature into the calculation of tool lifespan during machining operation to addresses the challenges of tool wear, which is an improvement to the existing Taylor models. The proposed wear law was given as:

$$T = \frac{\theta \cdot \lambda}{V^4 \cdot \rho}$$

where T: Effective machining time of the cutting tool in seconds (S); V Speed of cut (m/s); θ Cutting temperature (˚C); λ Thermal conductivity (Kg ·m/(S3 ·K))

They further observed that, there is a minimum increase in temperature whenever a high rotational speed combined with a low depth of cut and a medium feed rate was used. Also, at a minimum temperature, high feed rate with an average rotational speed and depth of cut, a minimum machining time is obtained.

Omar et al. (2017) in their research examines the impact of cutting parameters, specifically cutting speed (Vc), feed rate (f), and depth of cut (d), on the surface roughness of annealed AISI 1020 steel during turning operations employing carbide insert tools. Their findings revealed that increasing the feed rate and decreasing the cutting speed led to heightened surface roughness, with depth of cut exerting only a marginal influence. Utilizing analysis of variance and multiple regression techniques, a quantitative equation was developed to predict roughness values based on the cutting parameters. The results indicated that cutting speed with 69.35% had the most significant effect on surface roughness, followed by feed rate of 30.13%, while depth of cut had a negligible impact of 0.52%. Mohamad (2009) conducted an investigation into the surface roughness of mild steel machining operations utilizing coated carbide cutting tools. Their primary objectives was to explore the influence of various cutting conditions on surface roughness, to identify the factors or variables predominantly affecting mild steel's surface roughness and to compare surface roughness values between experimental and predicted outcomes. Two analyses were undertaken, and from the ANOVA analysis, cutting speed emerged as the most influential variable compared to depth of cut, with P-value of 95%. More also, the results from the multiple regression analysis indicate a close alignment between predicted and experimental values, indicating a 95% accuracy level for the generated equation.

Kamil (2019), utilized regression analysis to investigate the impact of laser processing on the cutting of an inclined surface in mild steel. The study examined three key inputs of the cutting machine which were oxygen pressure, cutting speed, and power supply, along with the corresponding output response of surface roughness. The objective was to optimize the continuous laser cutting process to achieve an ideal product. The research emphasizes the interplay between these parameters, as the laser power is intricately linked to the cutting speed and gas pressure. By understanding and manipulating these interactions, the surface roughness is minimized and the quality of the cut is enhanced. Ibrahim et al. (2017), compared NOVIANO and conventional cutting tools for end milling mild steel to assess the impact of feed rate and depth of cut on cutting forces and surface roughness. They observed that as the depth of cut increases, the roughness profile of the cutting tool exhibited a corresponding increase. This trend suggests that higher depth of cut results in elevated roughness profile, indicating a more challenging chip formation process. Upon comparing both cutting tools, it was noted that NOVIANO demonstrated superior performance in terms of cutting force and surface roughness. Osarenwinda (2012), formulated empirical models to predict the surface roughness of diverse machined components at different cutting speeds using a Centre Lathe machine. He developed empirical models by utilizing the experimental surface roughness data collected during the machining of a work piece using a Centre lathe machine, while systematically varying the cutting parameters.

Surface finish holds utmost significance in composite machining, which was why Nurhaniza et al. (2016), investigated the effects of machining parameters on the surface quality of CFRP-Aluminum composite material during CNC end milling operations utilizing a PCD tool. The milling parameters examined included

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spindle speed, feed rate, and depth of cut. Taguchi orthogonal arrays, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were utilized to examine the impact of these cutting parameters. Analysis of the findings reveals that the combination of high cutting speed, low feed rate, and low depth of cut yields optimal results for achieving a favorable surface finish. Continued research and development in this area are essential for addressing evolving industry demands and advancing the state-of-the-art in metalworking technologies.

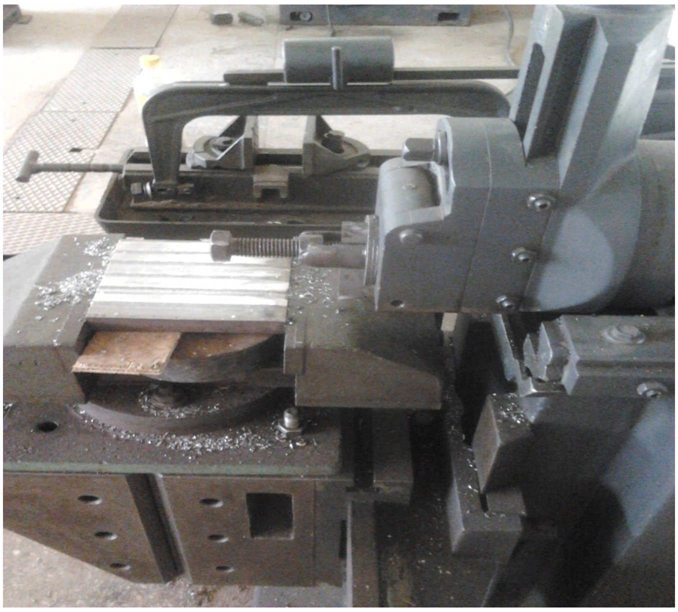

Plate.1: Machining the 12.9cm X 12.6cm X 1.9cm Mild Steel work piece

Plate.2: Digital Surface roughness tester

2.0 Materials and Methods

Machine: The experiment was carried out on a Shaping machine using the specification shown in Table1.
The Tool: High speed Steel HSS tool was used as the cutting tool
Work piece: A mild steel plate of Length 12.9 mm, breadth 12.6 mm and 1.9 mm. thickness was used.
Surface Roughness measurement: The instrument used to measure the surface roughness after machining the work piece was a portable digital surface roughness tester shown in Plate 2. Surface roughness readings were recorded at three locations on the machined work piece and the average value was used for the analysis.
Plate 1 Shows the work piece clamped by the vice being machined.

2.1 Cutting Parameters of the Shaping Machine

The speed and motion of the HSS cutting tool was specified using several parameters such as; Feed rate, Length of Ram Stroke, Length of Ram, Range of Tool Head feed.
Out of the many parameters affecting the surface roughness of a metal we limited our scope to depth of cut and the reciprocating speed of the ram based on the information obtained from literature.

- Ram speed - The reciprocating motion of the ram is measured in number of strokes per minute and the shaping machine speed used were 35, 70 and 140 strokes per minute.
- Depth of cut –This is the thickness of the material removed in one cut in mm, depth of cut which can be achieved by the tool head slide or by adjusting the table position.

3.0 EXPERIMENTAL PROCEDURE

The experimental procedure was carried out in the following eight steps:

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STEP 1: The two ends of the work piece were first smoothened by filing.
STEP 2: The tool was fixed to the tool post such that the tool movement upwards should be exactly perpendicular to the table.
STEP 3: The work piece was then set in the vice such that the HSS tool is just above the work piece.
STEP 4: The work piece position was adjusted so that the line of action of stroke is parallel to the surface of the work piece and then it is tightened firmly by the vice.
STEP 5: Depth of cut was given by adjusting the tool head, such that the HSS tool moves perpendicularly upwards or downwards as desired.
STEP 6: Finally key ways were made as we vary the cutting parameters were varied.
STEP 7: The process of shaping was been done in the following two cases
Case1. Varying speed of ram while keeping the Depth of Cut constant
Case2. Varying Depth of Cut while keeping the ram Speed constant
STEP 8: Our table is formed from the various readings gotten from the experimental process.

Table 1: Varying Speed of ram with depth of cut constant

S/N	Ram speed strokes/min	Depth of Cut d (mm)	R_a (µm)
1.	35	0.2	14.0
2.	70	0.2	17.8
3.	140	0.2	19.4

Table 2: Experimental Data obtained Varying depth of cut with Speed of ram constant

S/N	Ram speed strokes/min	Depth of Cut d (mm)	R_a (µm)
1.	35	0.2	14.8
2.	35	0.4	17.9
3.	35	0.8	19.4

4.0 Results and Discussion

The surface roughness results observed using experimental Table 1 is depict in Figure 1 while Figure 2 depict the surface roughness results for varying depth of cut with constant ram speed.

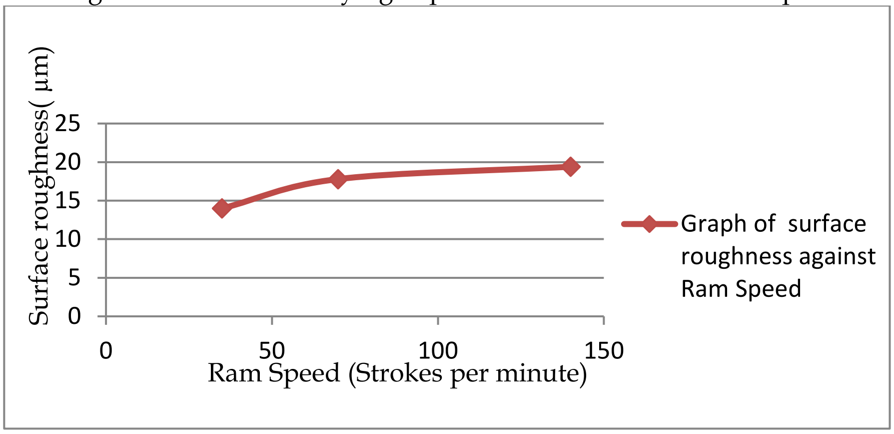

Fig.1: Graph of Surface roughness against Ram Speed

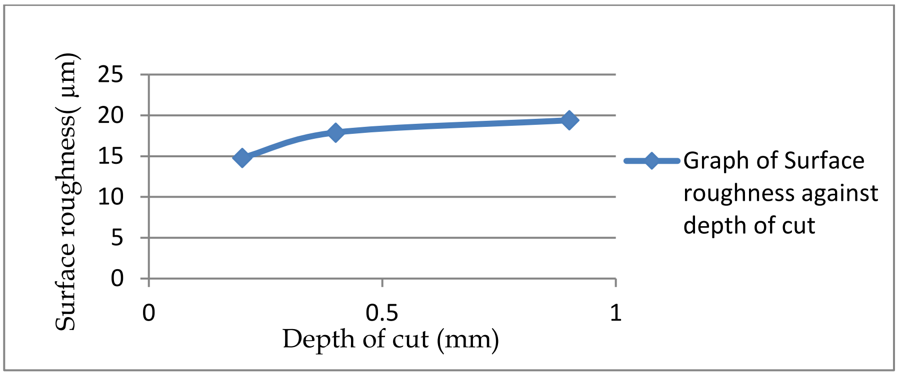

Fig.2: Graph of Surface roughness against depth of cut

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4.1 Developing the Model

Table 1 and Fig.1 shows that there is a positive correlation between the surface roughness and the speed of Ram used, however, since the graph does not portray a direct proportional increase between surface roughness and ram speed, a power function will best fit the curve.

Ra =axb ----------------------------------- --------------- (1)

Equation 1 is our proposed model, Where Ra is the dependent variable (surface roughness), “a” and “b” are regression constants and “x” is our independent variable (Ram speed).

Linearizing equation 1 by taken log of both sides we have;

Log(Ra) = Log(a) + b Log(x) ----- ------------------ --------------- (2)

Taken Log(Ra) as Y, Log(x) as X, Log(a) as A we have

Y=A+bX ---- ---------- ----------------------- --------------- (3)

Table 3 shows the values obtained in computation of our linear regression parameters for varying Ram speed.

Table 3: Linear regression parameters obtained with varying Speed of ram

s/n	V	R_a	Y	Log(v) X_1	X_1^2	$X_1{*}Y$	Y^2
1.	35	14.0	1.1461	1.5441	2.3841	1.7697	1.3135
2.	70	17.8	1.2504	1.8451	3.4044	2.3071	1.5635
3.	140	19.4	1.2878	2.1461	4.6059	2.7638	1.6584
n=3			$\sum(Y)$ = 3.6843	$\sum(x_1)$ = 5.5333	$\sum(x_1^2)$ = 10.3944	$\sum(x_1{*}Y)$ = 6.8406	$\sum(Y^2)$ = 4.5354

$$b = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - (\sum X)^2} \quad \text{----- ----------------------- ---------------} \quad (4)$$

$$b = \frac{3 * 6.8406 - (5.5353 * 3.6843)}{3 * 10.3944 - (5.5353)^2}$$

$$b = \frac{20.5218 - 20.3937}{31.1832 - 30.6395}$$

$$b = \frac{0.1281}{0.5437} = 0.2356$$

$$\bar{Y} = A + b\bar{X} \quad \text{----- --------- ----------------------- ---------------} \quad (5)$$

$$A = \bar{Y} - b\bar{X}$$

$$\bar{Y} = \frac{\sum Y}{n} = \frac{3.6843}{3} = 1.2281$$

$$\bar{X} = \frac{\sum X}{n} = \frac{5.5353}{3} = 1.8451$$

$$A = 1.2281 - (0.2356 * 1.8451)$$

$$A = 1.2281 - 0.4347 = 0.7934$$

A=log(a)

$a=10^{A}=10^{0.7934}=6.2144$

From our Model $R_a = ax^b$, with a=6.2144, b=0.2356 we have that;

$R_a = 6.2144x^{0.2356}$ --------- ---- ------------------- --------------- (6)

Table 4 shows the comparison of predicted values and experimental values for varying Ram speed and constant depth of cut.

Table 4: Comparing experimental and predicted surface roughness

Ram speed strokes/min	Depth of Cut d (mm)	Experimental Surface roughness R_a (μm)	Predicted Surface roughness R_a (μm)
35	0.2	14.0	14.3609
70	0.2	17.8	16.9085
140	0.2	19.4	19.9080

Coefficient of determination $r^2 = \left[\frac{n\sum xy - \sum x \sum y}{\sqrt{(n\sum x^2 - (\sum x)^2 * n\sum y^2 - (\sum y)^2)}}\right]^2$ ---------------- --------- ---------- (7)

$$r^2 = \left[\frac{3*6.8406 - (5.5353*3.6843)}{\sqrt{((3*10.3944 - (5.5353)^2)*(3*4.5354 - (3.6843)^2)}}\right]^2 \quad \text{- ---- ---------------} \quad (8)$$

$$r^2 = \left(\frac{0.1281}{\sqrt{(0.5437 * 0.031)}}\right)^2 = \left(\frac{0.1281}{0.1321}\right)^2 = 0.9403$$

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r = 0.9697

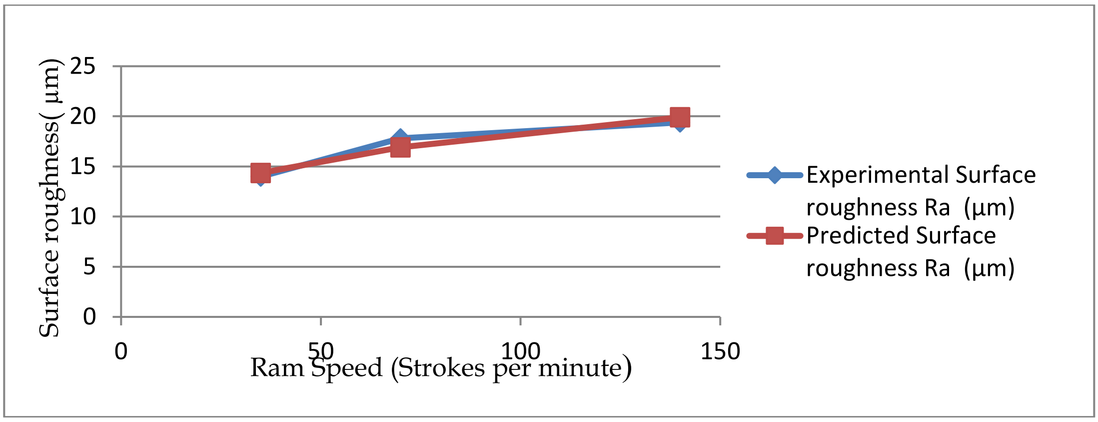

Fig.3: Combined Graph of Experimental and predicted Surface roughness against Ram speed

From Table 2 and Figure 4 shows that there is a positive correlation between the surface roughness and the depth of cut "d", again since the graph does not portray a direct proportional increase between surface roughness and the depth of cut a power function will best fit the curve.

$R_a = ax^b$ ------------------------------------- -------------- (9)

Equation 9 is our proposed model, Where R_a is the dependent variable (surface roughness), a and b are regression constants and x is our independent variable (Depth of cut).

Linearizing equation 9 by taken log of both sides we have;

$Log(R_a) = Log(a) + b\, Log(x)$ ------------------------- -------------- (10)

Taken $Log(R_a)$ as Y, Log(x) as X, Log(a) as A we have

$Y = A + bX$ ---- ---------- ------------------------ -------------- (11)

Table 5 shows the values obtained in computation of our linear regression parameters for varying depth of cut.

Table 5: Linear regression parameters obtained with varying depth of cut

s/n	D	R_a	Y	Log(d) X_1	X_1^2	$X_{1*}Y$	Y^2
1.	0.2	14.8	1.1703	-0.6990	0.4886	-0.8180	1.3696
2.	0.4	17.9	1.2529	-0.3979	0.1584	-0.4986	1.5698
3.	0.9	19.4	1.2878	-0.0458	0.0021	-0.0589	1.6584
n=3			$\sum(Y)$ = 3.7110	$\sum(x_1)$ = -1.1427	$\sum(x_1^2)$ = 0.6491	$\sum(x_{1*}Y)$ = -1.3755	$\sum(Y^2)$ = 4.5978

$$b = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - (\sum X)^2}$$
$$b = \frac{3 * -1.3755 - (-1.1427 * 3.7110)}{3 * 0.6491 - (-1.1427)^2}$$
$$b = \frac{-4.1265 + 4.2406}{1.9473 - 1.3058}$$
$$b = \frac{0.1141}{0.6415} = 0.1779$$
$$\bar{Y} = A + b\bar{X}$$
$$A = \bar{Y} - b\bar{X}$$
$$\bar{Y} = \frac{\sum Y}{n} = \frac{3.7110}{3} = 1.237$$
$$\bar{X} = \frac{\sum X}{n} = \frac{-1.1427}{3} = -0..3809$$
$$A = 1.2370 - (0.1779 * -0.3809)$$
$$A = 1.2370 + 0.0678 = 1.3048$$
A=log(a)

$a = 10^A = 10^{1.3048} = 20.1744$

From our Model $R_a = ax^b$, with a=20.1744, b=0.1779 we have that;

$R_a = 20.1744x^{0.1779}$

Table 6 shows the comparison of predicted values and Experimental values for a constant ram speed and varying depth of cut.

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Table 6: Comparing Experimental and Predicted Surface roughness

Depth of Cut d (mm)	Ram speed strokes/min	Experimental Surface roughness R_a (µm)	Predicted Surface roughness R_a (µm)
0.2	35	14.8	15.1514
0.4	35	17.9	17.1399
0.9	35	19.4	19.7998

Coefficient of determination $r^2 = \left[\frac{n\sum xy - \sum x\sum y}{\sqrt{(n\sum x^2 - (\sum x)^2 * n\sum y^2 - (\sum y)^2)}}\right]^2$

$$r^2 = \left[\frac{3 * -1.3755 - (-1.1427 * 3.7110)}{\sqrt{(3 * 0.6491 - (-1.1427)^2 * (3 * 4.5978 - (3.7110)^2)}}\right]^2$$

$$r^2 = \left(\frac{0.1141}{\sqrt{(0.6415 * 0.0219)}}\right)^2 = \left(\frac{0.1141}{0.1185}\right)^2 = 0.9271$$

$r = 0.9629$

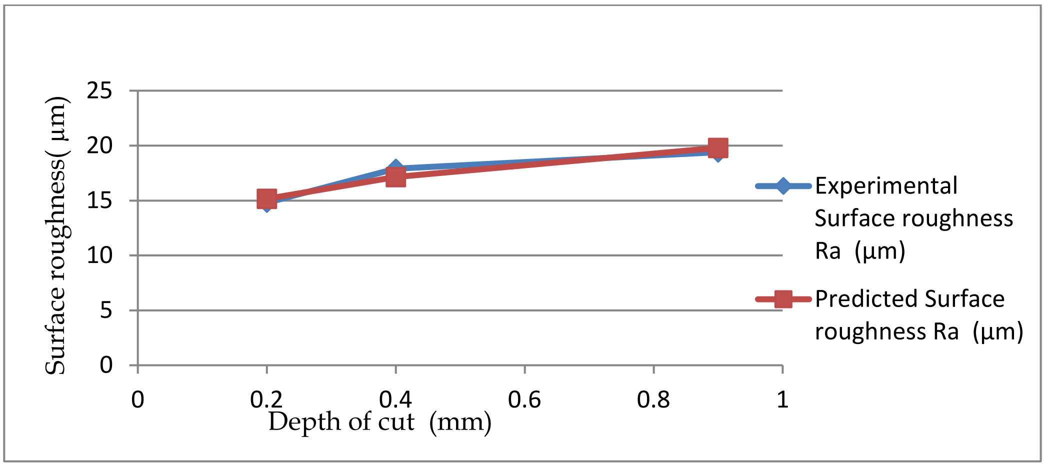

Fig.4: Combined Graph of experimental and predicted Surface roughness against depth of cut

4.2Discussion

The Surface roughness obtained from the experiment were within the range of 14µm to 20µm, Our Model developed for surface roughness using a Shaping machine and Mild Steel as our Workpiece are:

$R_a = 6.2144x^{0.2356}$ for varying Ram speed and depth of cut of 0.2mm

and

$R_a = 20.1744x^{0.1779}$ for varying depth of cut and constant Ram speed of 35strokes/min

The results obtained from our model was compared with the experimental results as shown in Table 4 and Table 6, and the graphs showing the relationship between Predicted and experimental surface roughness with speed of ram and depth of cut were also shown, From the graphs in Figure 5 and 6, It can be clearly seen that the smallest value of surface roughness (Best surface finish) was obtained when both the depth of cut and cutting speed were at its minimum values (Depth of cut 0.2mm and speed of Ram 35 strokes per minute). Hence we recommend that if aesthetics is our major priority during a shaping operation the selected cutting speed and depth of cut should be of lower values. However for machining time considerations we could increase speed and depth of cut at the expense of good surface finished material.

The generated Model was validated and tested for adequacy using coefficient of determination regression analysis technique and the model was found to be meritorious as our determination coefficient exceeded the minimum recommended value of 65% hence with our coefficient of determination values of 0.9403 and 0.9271 surface roughness predictability was highly effective while we vary the two cutting parameters.

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5.0 Conclusion

The prediction values of surface roughness in mild steel cutting using a shaping machine holds immense potential for improving manufacturing efficiency, product quality, and competitiveness in industrial settings. We have successfully demonstrated the combinations of the depth of cut and the speed of the Ram and have identified the values of the optimum cutting parameters (Depth of cut 0.2mm and speed of Ram 35 strokes per minute) to get the minimum Surface roughness. The models developed which can confidently make prediction with an accuracy of 94.03% for the empirical model with varying ram speed and 92.71% for the empirical model with varying depth of cut. This serve as a valuable tools for optimizing shaping machining parameters to achieve desired surface quality targets while minimizing production costs and cycle times.

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