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Experimental Investigations & Effects of Cutting Variables on MRR and Tool Wear for AISI S2 Tool Steel

Dr.G.Harinath Gowd[a]*, S. Sharmas Vali[b], V. Ajay[c], G.Guru Mahesh[d]

[a]*professor, Department of ME, Madanapalle Institute of Technology & Science, Madanapalle, Chittor Dist, A.P., INDIA.*
[b,c,d]*Assistant professor, Department of ME, Madanapalle Institute of Technology & Science, Madanapalle, Chittor Dist, A.P., INDIA.*

Abstract

Machining is the most important of the manufacturing processes which involves the process of removing material from a work piece in the form of chips. Machining is necessary where tight tolerances on dimensions and finishes are required. Generally a machining process involves a large number of variables that affect its performance. Some of them are cutting parameters, geometry of cutting tool, coolant conditions, properties of tool material, properties of work piece, machine capabilities, etc. Among them, cutting parameters have profound effect on all kinds of performances when the same tool material and the same work piece material are used for machining. Therefore cutting parameters of speed, feed and depth of cut are considered as the process control variables and two important performance measures of CNC turning, namely, Metal Removal Rate (MRR) and Tool wear (TW) are considered for investigation. This paper presents the experimental investigations on the effects of cutting variables like Spindle speed, Feed and Depth of cut on the Material removal rate and tool wear. The experiments were conducted on AISI S2 tool steel grade on a CNC turning machine using carbide insert. The experiments were conducted as per the design of experiments. Initial trial experiments were conducted to fix the ranges for the control parameters. After conducting the experiments the MRR and Tool wear were measured and recorded. The effects were studied after plotting the graphs between the Input process parameters versus the responses using Design expert software. The results obtained in this study can by further used for optimizing the process parameters there by the optimized results help the operator to enhance the quality as well as machining rate.

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Keywords: CNC Turning, RSM, AISI D2 Tool steel.

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* Corresponding author. Tel.: +91-9441190044;
E-mail address: harinathgowdg@mits.ac.in

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1. Introduction

Machining involves the shaping of a part through removal of material. A tool, constructed of a material harder than the part being formed, is forced against the part, causing material to be cut from it. Machining, also referred to as cutting, metal cutting, or material removal, is the dominant manufacturing shaping process. It is both a primary as well as a secondary shaping process. The device that does the cutting or material removal is known as the machine tool. Nearly all castings and products formed by deformation processing [bulk or sheet metal] require some machining to obtain the desired final shape or surface characteristics. The material is generally removed in the form of chips. The primary reasons for selecting machining over the other two primary shaping processes are that machining are:

- Improve dimensional tolerances
- Improve surface finish
- Produce complex geometries.
- Produce low quantities economically because of more flexibility in tooling and fixturing.
- Low operating costs.
- Lower setup times [time to prepare tooling for production]

In many cases, machining is a secondary operation for casting and forming processes, to obtain the required dimensional tolerances, surface finish, or complex geometry of the part. Machining is the only primary forming process that is also used for secondary operations. This unique characteristic has led to the dominance of this process. There are several different classifications of machining processes. One classification is by the type of cutting tools; a second is by the type of surface generated. The classification by the type of surface generated is more important, because the surface of the product is one of the major criteria considered in the selection of the manufacturing process. The classification based on the type of cutting tool considers the number of cutting edges of the tool. They are 1. *Single-point cutting:* processes such as turning, planning, shaping and boring & *2. Multiple-point cutting* (Two edges: drilling, *n* edges: milling, sawing, reaming, broaching, etc, Infinite number of edges: grinding, polishing).

1.1. Machining Variables and Relationships

There is a wide variety of machining processes, which leads to numerous variables and relationships. The key variables related to most of the machining processes are cutting speed or velocity [V], ft/min or in/sec, feed *[f],* in/rev or mm/rev and depth of cut *[d],* in. or mm. These three variables have a major effect upon the material [or metal] removal rate [MRR], which has a major role in determining the power requirements. In addition, these parameters also have a major effect upon the economics of the processes.

1.2. Main Variables that affect the Chip Formation

There are three main variables that affect the formation of the chips in cutting. They are the tool geometry, properties of the work and tool materials. The interaction between the tool and work material is also significant: this is often mentioned as the fourth main variable. The tool geometry is described by the various angles and nose radius of the single-point tool illustrated in figure 1. The tool wear occurs on the flank face [flank wear] or on the top face [crater wear]. The types of chips formed are generally classified into three types. They are

- *Discontinuous [segmented] chips:* from hard, brittle materials and from two-phase materials that separate easily, such as leaded steels and gray cast irons.
- *Continuous chips:* sharp, long, continuous chips, which can be sharp and hot and thus dangerous, steel and aluminum.
- *Built-up edge:* part of the chip adheres to the tool, which produces rough surfaces on the finished part.

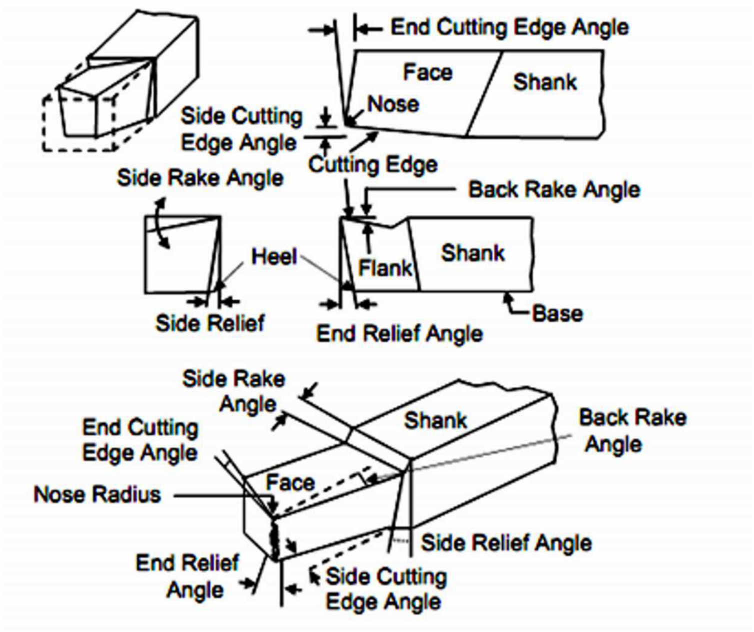

Figure 1. Tool geometry

The figure 2 is a schematic representation of the chip formation process as sketched with the help of a photograph of chip initiation [right]. In this representation, we can see a continuous plastic deformation that can be subdivided into four zones. The transition from the work piece structure [a] to the chip structure [b] is made by simple shearing [shear zone]. When cutting brittle materials, minor deformation on the shear plane can already lead to material detachment. If however the material has higher deformability, detachment first occurs in front of the cutting edge in zone [e]. The tensile load under simultaneous perpendicularly active pressure leads, together with the high temperatures prevalent here, to strong deformations on the peripheries of the rake face [c] and cut surface [d]. Sliding over the tool surfaces causes further plastic deformations to arise in the boundary layers. The “flow zone” [the non-etched white zone on the bottom of the chip], the deformation texture of which forms parallel to the rake face, gives the impression of a viscous flow process with an extremely high degree of deformation. The chip resulting from the described chip formation process is designated as a continuous chip. Other chip types include lamellar chips, segmented chips and discontinuous chips.

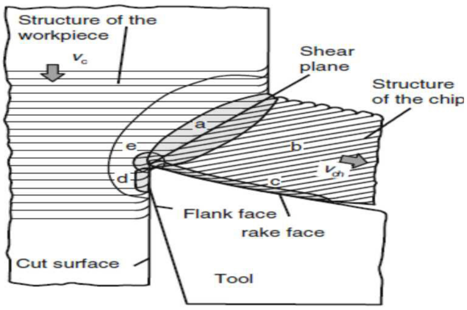

Figure 2. Chip formation

1.3. Tool Wear

During the machining process, the cutting tools are loaded with the heavy forces resulting from the deformation process in chip formation and friction between the tool and work piece. The heat generated at the deformation and friction zones overheats the tool, the chip and partially the work piece. All the contact surfaces are usually clean and chemically very active; therefore the cutting process is connected with complex physical-chemical processes. Wear on the tool, which occurs as the consequence of such processes, is reflected as progressive wearing of particles from the tool surface.

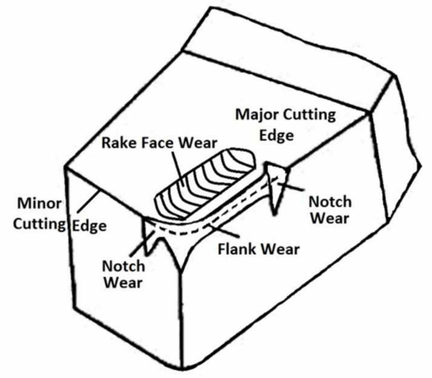

Figure 3. Tool wear phenomenon

Cutting tools are subjected to an extremely severe rubbing process. They are in metal-to metal contact between the chip and work piece, under conditions of very high stress at high temperature. The situation is further aggravated [worsened] due to the existence of extreme stress and temperature gradients near the surface of the tool. During machining, cutting tools remove material from the component to achieve the required shape, dimension and surface roughness [finish]. However, wear occurs during the cutting action, and it will ultimately result in the failure of the cutting tool. When the tool wear reaches a certain extent, the tool or active edge has to be replaced to guarantee the desired cutting action. The following are the consequences of tool wear 1. Increase the cutting force; 2. Increase the surface roughness; 3. Decrease the dimensional accuracy; 4. Increase the temperature; 5. Vibration; 6. Lower the production efficiency, component quality; 7. Increase the cost.

1.4. Cutting Tool Materials

Tool change times, and with them both manufacturing times and tool, machine and labour costs, are affected by wear. Wear is affected in turn by the properties of the cutting tool materials. Development in the cutting tool material sector is therefore far from finished, but is constantly aiming both to improve cutting tool materials that are already established as well as to discover new materials for use in the manufacture of cutting tools. Cutting tool materials should have the following properties (hardness and pressure resistance, bending strength and toughness, edge strength, inner bonding strength, high temperature strength, oxidation resistance, small propensity to diffusion and adhesion, abrasion resistance, reproducible wear behaviour) in order to do justice to the stresses placed on them. The general cutting tool materials used are Tool steels, Cemented carbides, Ceramics, Super-hard cutting tool materials made of boron nitride and diamond.

With the advent of CNC technology, the machining processes are automated through which high quality of the machined components; high material removal rates can be achieved. In general, CNC lathe machine is operated with several controllable factors such as spindle speed, feed rate, depth of cut etc. In this work, metal removal rate and tool wear are considered as the performance measures as they affect cost and quality of the finished components. The optimization of CNC turning process is often achieved by trial-and-error method based on the shop floor experiences by determining the certain parameters of the process. But this does neither guarantee the quality nor the machining economics. Therefore a general optimization plan is required to avoid cumbersome trial runs on machine and wastages. Optimization of CNC Turning has been carried out in the literature by many researchers. A few works are based on simulations [1-4] and other works are based on many experimental runs [5-6], collecting huge amount of data and processing it to achieve the result. Taguchi method is widely adopted in the literature for the improvement of quality and machining economics. Taguchi method uses the orthogonal array concept with small number of experimental runs to investigate the effects of parameters on performance measures reduces the sensitivity due to inherent variations present in the system. Moreover, Taguchi method does not consider the interactive effects of control factors. Machining is the only primary forming process that is also used for secondary operations. This unique characteristic has led to the dominance of this process. Due to the high cost of machining and problems caused by the chips produced, casting and deformation processing try to produce "near-net shape" products, which can be completed with little or no machining. So In the present work, CNC Turning process is investigated by considering the performance measures, metal removal rate (MRR) and tool wear (TW) in terms of spindle speed, feed rate and depth of cut as control factors.

2. Experimental work

The experiments were conducted on a high precision CNC-Turning centre. AISI S2 is taken as the work piece material for investigation. **AISI S2** is a Shock-Resisting Steel grade *Tool Steel*. It is composed of (in weight percentage) 0.40-0.55% Carbon (C), 0.30-0.50% Manganese (Mn), 0.90-1.20% Silicon (Si), 0.30% Nickel (Ni), 0.30-0.60% Molybdenum (Mo), 0.50% Vanadium (V), 0.25% Copper (Cu), 0.03% Phosphorus (P), 0.03% Sulfur (S), and the base metal Iron (Fe). It has excellent toughness and fine wear resistance and finds various applications in cutting tools for heavy plate, shear blades, cold punching and upsetting and used in various cutting tools. The specimen is prepared with the dimensions of 200mm length and 50mm diameter for turning and carbide insert is used for experimentation. The control factors considered for experiments are spindle speed, feed and depth of cut while Metal removal rate and Tool wear are considered as the output responses. The ranges of the process control variables are given in table 1.

Table 1. Control variables along with the levels.

S.No	Control Factor	Symbol	Levels			Units
			-1	0	+1	
1	Speed	A	600	800	1000	rpm
2	Feed	B	0.10	0.20	0.30	mm/min
3	Depth of cut	C	0.5	1.0	1.5	mm

After conducting the experiments as per the design of experiments, the output responses were measured and recorded. Three continuous passes are taken in order to visualize the tool wear better. Tool wear (Tw) is measured with a precision tool maker's microscope. Another response, MRR is calculated as the ratio of volume of material removed from work piece to the machining time. In order to determine the volume of material removed after machining, the weights of work piece before machining and after machining are measured. Machining time taken for each cut is automatically displayed by the machine. The output responses recorded for each set of process control variables are listed Table 2.

Table 2. Experimental observations

S.NO	**Control Factors**			**MRR[gm/min]**	**Tool wear [mm]**
	A	**B**	**C**		
1	1000	0.1	1.5	217.62	0.116
2	600	0.1	0.5	46.834	0.069
3	800	0.3	1.5	323.044	0.395
4	1000	0.2	1	221.234	0.116
5	800	0.1	1	129.75	0.108
6	1000	0.1	0.5	92.778	0.0789
7	600	0.1	1.5	125.765	0.086
8	600	0.3	1	166.78	0.109
9	600	0.2	0.5	69.125	0.0697
10	800	0.2	1	174.345	0.113
11	800	0.2	0.5	98.889	0.0798
12	600	0.1	1	96.778	0.0829
13	600	0.2	1	127.923	0.0987
14	1000	0.2	1.5	309.745	0.137
15	1000	0.3	1.5	386.498	0.167
16	1000	0.2	0.5	117.022	0.0798

17	600	0.2	1.5	183.89	0.112
18	1000	0.3	0.5	166.456	0.107
19	800	0.1	0.5	74.455	0.073
20	800	0.1	1.5	73.745	0.075
21	800	0.3	1.5	309.456	0.125
22	600	0.3	1.5	232.579	0.125
23	800	0.3	1	232.367	0.114
24	800	0.2	1.5	247.09	0.129
25	1000	0.3	1	298.09	0.131
26	600	0.3	0.5	91.56	0.0749
27	1000	0.1	1	168.05	0.1139

3. Effect of process parameters on MRR & Tool Wear

The main effects of the process variables on MRR and Tool wear are studied after plotting the graphs by using Design Expert software. The cutting variables Speed, feed and depth of cut have a major effect upon the material removal rate, which has a major role in determining the power requirements. The effect of cutting parameters on MRR is as shown in Fig. 4 to 6. As the spindle speed increases, the removal of material per unit time also increases as shown in Figure 4.

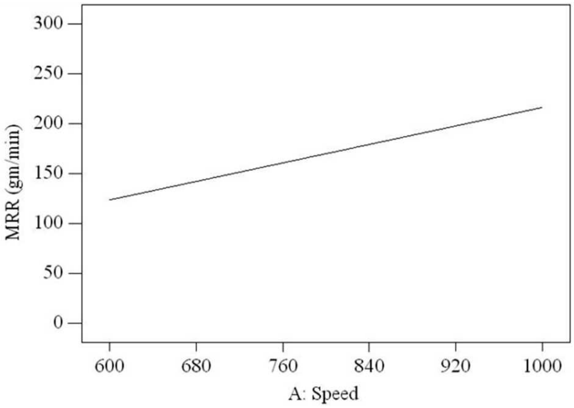

Figure 4. Effect of spindle speed on MRR

As the feed rate is increased, the material removal per unit time also becomes more as shown in Figure 5. As the tool movement per unit time increases, the greater amount of material is removed.

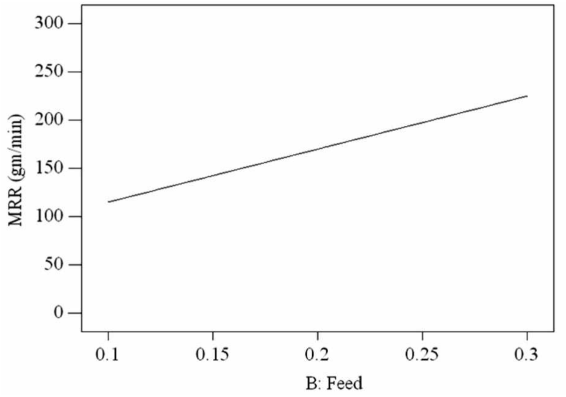

Figure 5. Effect of feed rate on MRR

The more the depth of cut, the more is the material removal rate as shown in Figure 6. The chips removed per unit time will be more and thereby quantity of material removed is also high. As the depth of cut increases, the cutting force increases thereby increase in removal of material.

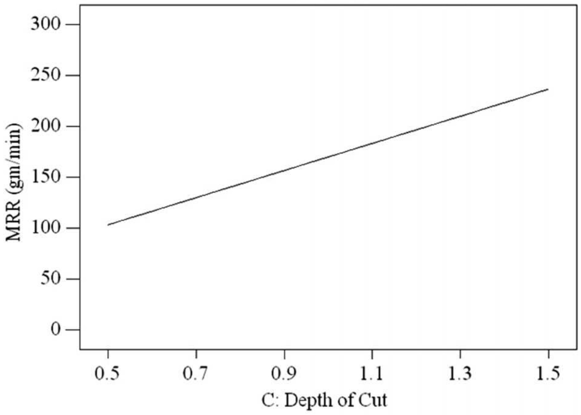

Figure 6. Effect of depth of cut on MRR

The effects of speed on the tool wear as shown in Figure 7. As the cutting speed is increased up to a certain limit, a brittle fracture occurs at the cutting edge rather than a gradual flank wear and the depth of the cracks on the cutting edge increases rapidly resulting in a catastrophic failure of the tool. When the cutting speed is comparatively low, the size and depth of the crack on the flank is very small. Crack grows rapidly at higher cutting speeds. The cutting force on the tool edge increases as the cutting speed is increased. Higher cutting speed increases tool temperature and softens material. It thereby aids abrasive, adhesive and diffusion wear. The cumulative effect is an exponential decrease in tool life as given by Taylor's life equation.

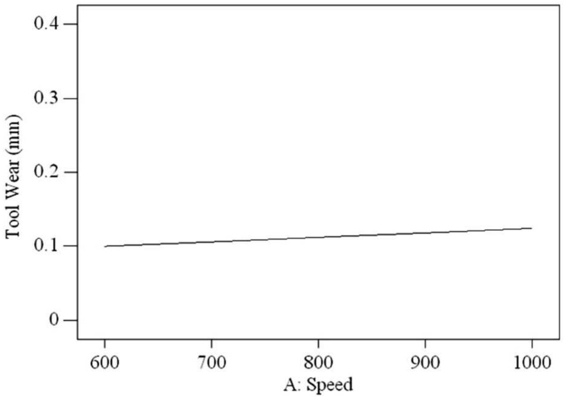

Figure 7. Effect of spindle speed on Tool wear

The effect of feed rate on tool wear is displayed in Figure 8. The larger the feed, the greater is the cutting force per unit area of chip-tool contact on the rake face and work –tool contact on the flank face. Cutting temperatures and therefore the different types of wear are increased. An increase in cutting force as a result of larger feed also increases the likelihood of chipping of the cutting edge through mechanical shock. It has, however been observed that the effect of changes in feed on tool life is relatively smaller than that of proportionate changes in cutting speed.

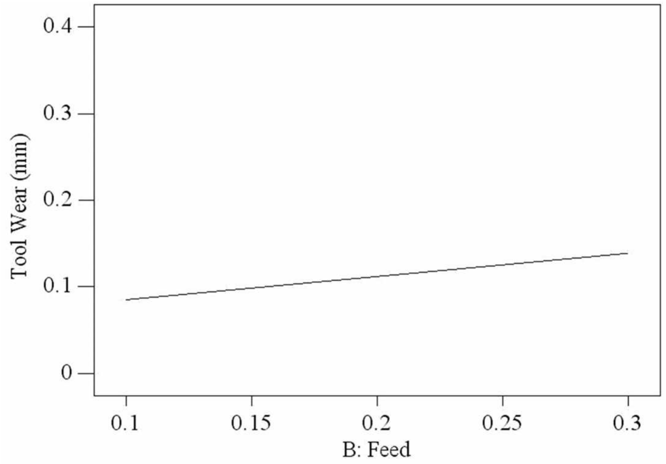

Figure 8. Effect of feed rate on Tool wear

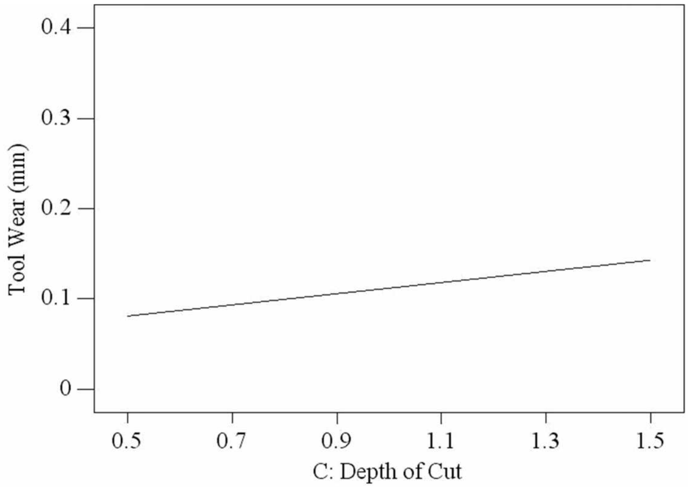

Figure 9. Effect of depth of cut on Tool wear

Figure 9 exhibits the effect of depth of cut on tool wear. If the depth of cut is increased, the area of the chip-tool contact increases roughly in equal proportion to the change in depth of cut. Consequently the rise in tool temperature is relatively small. That is not the case when feed is changed. In that case, the proportionate change in temperature is larger. This is on account of the fact that the area of chip-tool changes by a smaller proportion than the change in feed rate. Thus, an increase in depth of cut shortens tool life to some extent by accelerating the abrasive adhesive and diffusion types of tool wear.

Material removal rate in CNC turning process is an important factor because of its vital effect on the industrial economy. Figure 10 & 11 shows the interaction plots of MRR. Increasing the spindle speed, feed rate and depth of cut leads to an increase in the amount of MRR. But the most influential factors are feed rate and spindle speed. The highest value of MRR is obtained at the extreme range of the input parameters in all the interaction plots. Also the MRR increases gradually with the depth of cut.

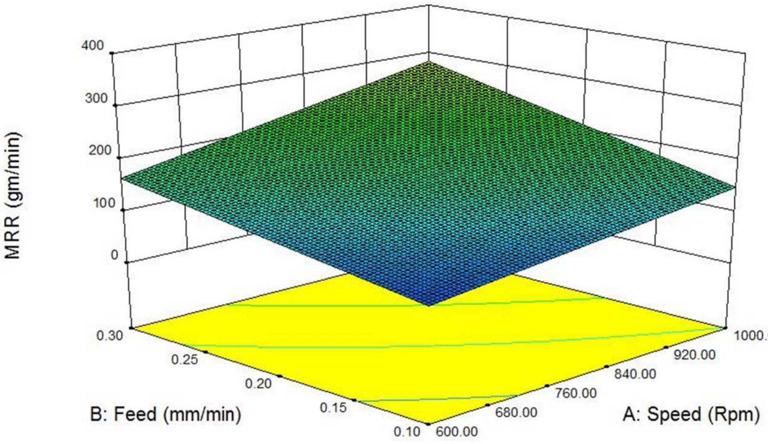

Figure 10 Interaction effect of spindle speed and feed rate on MRR

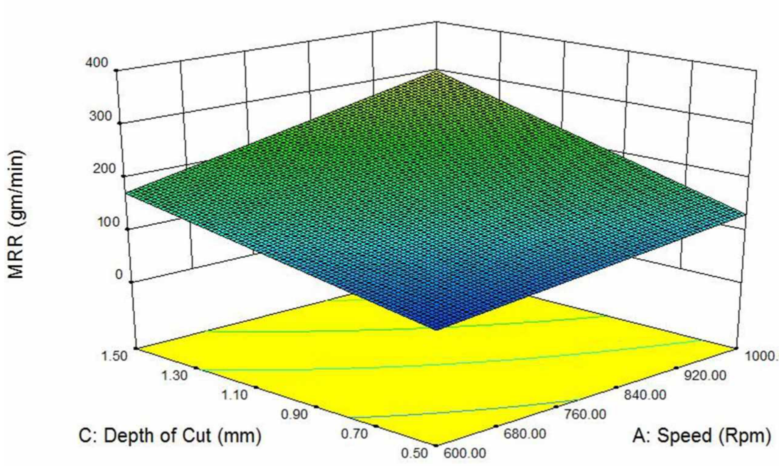

Figure 11 Interaction effect of spindle speed and depth of cut on MRR

The figure 11 illustrates the interaction effect of feed rate and spindle speed on the tool flank wear after machining of 5 passes. The drastic decrease in tool wear is mainly due to significantly increased heat involved in the cutting process, leading to rapid tool wear. Tool flank wear tends to increase with an increase in cutting speed, however a not much significant trend was observed for feed rate.

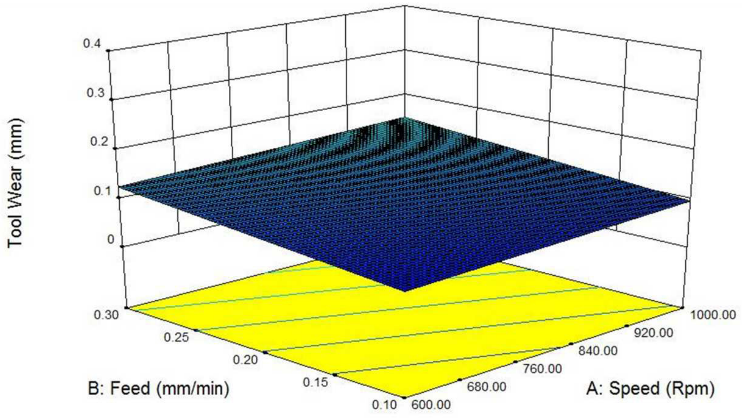

Figure 12 Interaction effect of Spindle speed and feed rate on tool wear

4. Conclusions

In this work, the important performance measures namely the metal removal rate and the tool wear of CNC Turning on AISI S2 material are analyzed. For conducting the experiments first trial experiments were conducted to fix the ranges of the process control factors and then the experiments were conducted as per the design of experiments. The results presented in the work can be used for further analysis. That is using the experimental data empirical models can be developed and then these models can be used for finding the optimal process parameters to get the best output. Then the problem can be formulated as the multi-objective optimization problem and get it solved using an efficient evolutionary approach to find out the optimal combinations of machining parameters, thereby the manufacturing engineer can choose the right combination depending upon his requirement.

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