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“THEORETICAL INVESTIGATION OF THE EFFECT OF TOOL NOSE RADIUS AND FEED RATE FACTORS ON THE SURFACE ROUGHNESS OF A HARD STEEL MATERIAL (AISI D2).”

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Abstract

Surface roughness plays an important role as it influences the fatigue strength, wear rate, coefficient of friction and corrosion resistance of the machined components. In actual practice, there are many factors which affect the surface roughness, i.e., tool variables, work piece hardness and cutting conditions. Tool variables include tool material, nose radius, rake angle, cutting edge geometry, tool vibrations, tool point angles etc.

This paper is on theoretical investigation of the effect of tool nose radius and feed rate factors on the surface roughness of a hard material (AISI D2) during dry turning, and the optimization of this tool variable and the cutting parameter to achieve acceptable surface finishing of the material as well as avoiding chattering of the tool nose and enhancement of the productivity of the component. The method employed is the application of the mathematical model of the theoretical surface roughness (i.e. $Ra = \frac{0.0321f2}{rc}$),

Ra is calculated for a set of values of the two variables, the corresponding values of Ra is then plotted against the two variables; the intersection of the graphs gives the optimum values of the two variables.

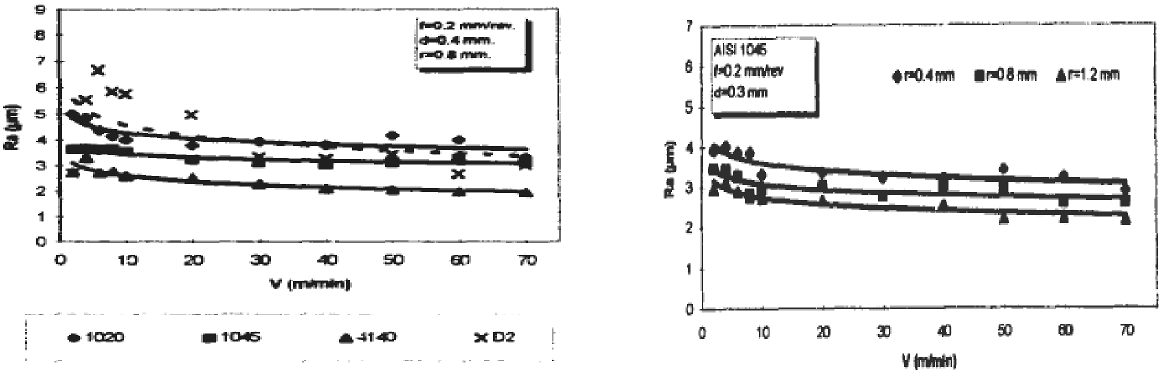
1. Introduction

Surface finish is important for manufactured components because the consumers require a consistent surface finish. The surface roughness influences the dimensional stability and operation performance of finished parts. Hence, in the production of metallic components, the surface finish achieved is normally the consequences of the manufacturing process used. Therefore, manufacturing engineers need to understand how surface finishes are obtained and how to control the process for obtaining a consistent surface finish. The surface condition of a machined component can be rated according to surface condition determined by tribological properties such as white layer formation in material surface, residual stress, surface roughness and other parameters [1].

The surface roughness values can be determined from cutting speed, feed rate and tool's nose radius [2]. Moreover, the built–up–edge [3] and tool wear [4] can affect the qualities of the surface roughness.

P. Munoz–Escalona [5] experimentally studied the behaviour of the average surface roughness (Ra) for different cutting conditions and three kinds of tool nose radius. The author's experiments were conducted on several steel bars (AISI 1020, 1045, 4140, D2 (hardness increases respectively) and variables such as roughness against cutting condition, nose radius and hardness values (these steel bars had different hardness values) were taken into account. They showed that the surface roughness is improved by increasing cutting speed, increasing the size of the tool's radius, and by lowering the feed rate. It was noticed, however, that increasing the nose radius can lead to chattering [6].

The authors [5] stated that the depth of cut exerted no influence upon the roughness values. It should also be noted that a better surface roughness can be obtained from harder materials. As shown in figure 1.0 (a), surface roughness decreases with increased hardness, but AISI D2 showed a different behaviour as the results obtained was not as expected with higher surface roughness values. In Figures 1.0 (b), the authors also observed that as nose radius is increased an improvement in the surface roughness at a constant depth of cut and feed rate is seen. From the author's experimental tests and measurements, they claimed that feed rate has the most important influence on surface roughness when conventional cutting speeds are given. The next most important influence is the tool's nose radius. The least important influence on roughness is the cutting speed.



(a) Variation of cutting speed with hardness of work piece

(b) Variation of cutting speed with tool nose radius

Figure 1.0 The Result of Surface Roughness for work material [5]

J. Rech et al [7] experimentally investigated the surface integrity for casehardened 27MnCr5 steel under the influence of feed rate, cutting speed and tool wear. The authors indicated that cutting speed has a lower influence on surface roughness than feed rate or tool wear. As shown in Figure 1.2, the surface roughness values can increase during high cutting speeds (200 ~ 250m/min). The reason might be that the tools are quickly worn after just a few seconds. As a consequence, it can be concluded that in suitable machining conditions areas, surface roughness (Ra) is not significantly influenced by the cutting speed, but is mainly influenced by the feed rate (Figure 1.2 (a))

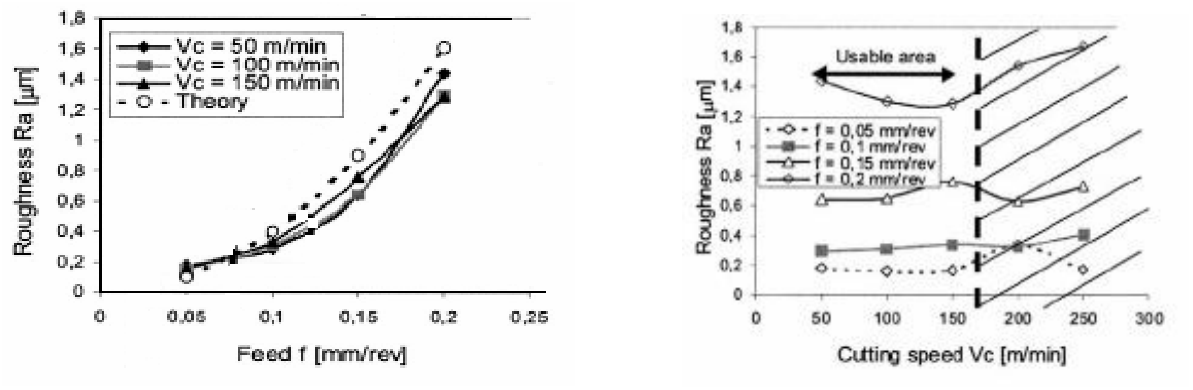


Figure 1.2 the result of surface roughness against cutting condition [7]

1.2 The residual stress and white layer for hardened steels

The tribological properties depend on the type and amount of sub–surface microstructure alterations and the state, magnitude, and through–thickness distribution of residual stress. These can be affected by material properties and machining parameters such as cutting conditions and tool geometry [8]. Therefore, it is important to correlate cutting parameters and the material properties to the work material residual stress distribution, white layer and surface roughness for hard machining.

Jeffrey et al [9] experimentally investigated the effects of tool edge geometry on work material sub–surface deformation and through–thickness residual stresses for machining of AISI 52100 bearing steel with PCBN tool. The authors said in their paper that through–thickness residual stress in large edge honed tools is deeper than in small edge honed tool. It is also stated that the large edge honed tools produce more compressive residual stresses than small edge honed or chamfered tools for hard turning of AISI 52100 steel. This can be explained by considering the stress state produced by the tool as it slides across the work material during machining. As shown in figure 1.3, the large edge honed tools (N2) result in increased frictional interaction between the tool and work piece. The interaction caused by the large edge honed tool is larger than the interaction caused by the small edge honed tool

(NI). A large edge honed tool causes an increase in the tensile stress area behind the tool (T2) relative to the small edge honed tool (TI) due to the increased interaction length. As shown in figure 1.3, the increase in the tensile field behind the tool produces larger compressive residual stresses [8].

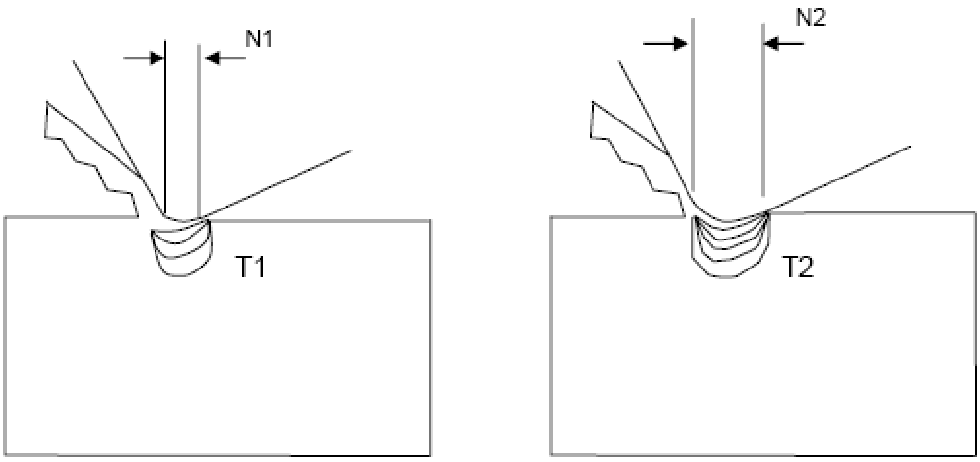


Figure 1.3 the stress distribution caused by small and large edge honed tool (Jeffrey et al [9])

Kompella et al [10] studied the mechanical properties and characteristics of surface layers in AISI 52100 steel produced when machining with CBN tools. To analyze the surface layers and mechanical properties, the authors used a nano–indentation (measuring the hardness of white layer) technique, optical microscopy and atomic force microscopy (AFM). The authors reported that the white layer in work material sub–surface has a hardness of approximately 12.85 GPa, which is higher than that of martensite structures produced commonly by heat–treatment. The burnt layer on a work material ground surface has a hardness distribution very similar to that of a white layer. The nano–hardness decreased with increasing depth of cut. However, when depth of cut is further increased, the nano–hardness is almost constant.

Ramesh [11] experimentally investigated the white layer formation using transmission electron microscopy (TEM) and through–thickness residual stress was measured by X–ray diffraction (XRD) technique. Nano–indentation is used t measure the hardness of white layer formed after machining f AISI 52100 steel (Hardness 62 HRC) with CBN tools. The authors showed that white layer can be observed at all cutting conditions as indicated by TEM. It is shown that the residual stress would become tensile with increasing depth of cut to attain equilibrium. At the high cutting speed (274 m/min), the residual stress start out being tensile near the surface and rapid become very compressive approximately 30um below the surface. The authors stated that high plastic deformation occurred at the surface of hardened steels after machining. Nano–indentation hardness test of the work material revealed a general trend of increased hardness of white layers with increase in cutting speed. The authors stated that the predominance of phase transformation effects at high temperatures (at high cutting speeds), causes all carbon to be retained in solution and thereby increase the hardness of the layer.

2. Theoretical Surface Roughness

Basically, surface roughness is usually characterized through the use of statistical parameters [12]. The average roughness Ra and peak to valley height Rz are the most commonly used parameters [12] [13]. The surface roughness can be defined as the Arithmetic Mean Deviation, or Ra [14]. This value is calculated as shown in figure 2. The profile of a section of machined surface is sampled over a length L, and a datum line established. The datum line is positioned such that the sum of area of the peaks above the line is similar to the sum of the areas of the trough below the line. The Arithmetic Mean Deviation Ra, is the sum of the areas of the peaks and divided by the sample length L, as shown in equation 2.1 [14] [15].

$$R_a = \frac{A1 + A2 + A3 + A4 + A5 + A6 + A7 + A8}{L} \qquad 2.1$$

Where, L and A_n (n = 1, 2, 3, 4, 5, 6, 7, 8) are defined in figure 2

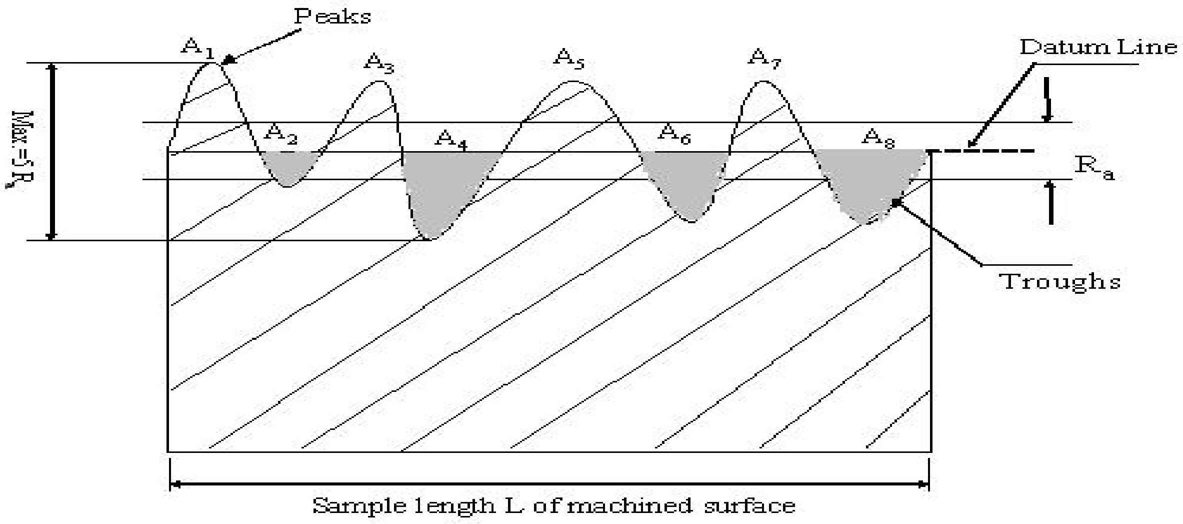


Figure 2 Method of computing the Arithmetic Mean Deviation, Ra, Surface Roughness parameter [14]

Hence, R_a, is based on mathematical concept which averages the area of surfaces above and below a centre line [13] [15].

The peak to valley height R_z, is defined as the peak to valley deviation. This is equal to:

$$R_z = R_{max} + R_v \qquad 2.2$$

Since the turning process uses a single – point tool, the geometric roughness is easily calculated from tool angles and feed rate. For a lathe with sharp–nosed tool, the peak–to–valley height roughness R_z is given by [12] [16]

$$R_z = \frac{f}{\tan C_s + \cot Ce} \qquad 2.3$$

and the average roughness R_a is equal to one–fourth the peak–to–valley height roughness [12]. C_s is the side cutting edge angle, C_e is the cutting edge angle and f is feed rate.

For a tool with a nose radius where the depth of cut is larger than the nose radius (r_c), the peak–to–valley height roughness is given by [17];

$$R_z = (I - \cos C_e) r_c + f \sin C_e \;.\; \cos C_e - \sqrt{(O\ 2fr_c \sin C_e - f^2 \sin C_e}) \qquad 2.4$$

However, for a tool with a nose radius where the depth of cut is smaller than nose radius (rc), the peak–to–valley height roughness is independent of the tool angles Cs and Ce, and can be determined by just the feed rate (f) (mm/rev) and nose radius (rc) (mm). This can be approximated by

$$R_z = \frac{f^2}{8.\, r_c} \qquad 2.5$$

In this case, the theoretical average roughness is given by

$$Ra = \frac{0.0321 \,.\, f^2}{r_c} \qquad 2.6$$

These equations (2.5) and (2.6) are based on a perfect geometrical model made of tool radius with a pitch of fmm. In this expression, all experiments have been conducted with new inserts (no flank wear).

From the above equations it can be seen that the feed, tool angles and tool nose radius play an important role in controlling the surface finish. The equations shown above give ideal surface finish values which can only occur when satisfactory cutting conditions are achieved [13]. The above equations can be used as estimators of determining what values should be changed to improve the surface roughness.

According to these equations, better roughness can be obtained from a smaller feed rate, larger tool nose radius and lower tool lead angle. However, it is indicated that the reduction of the feed rate can reduce the production rate [12] and increasing the nose radius can lead to chattering [12] [17].

3. Optimization of the factors affecting the Surface Roughness of the AISI D2 Steel Component

The method of optimization adopted is the graphical analysis procedure. A range of values of the tool nose radius (r_c) and the feed rate (f) (Table 1) are substituted into equation 2.6 keeping one of the factors constant while varying the other, the procedure is later reversed with the constant factor being varied and the varying one, now remains constant. Thus, a set of values of the surface roughness (R_A) are obtained as shown in the tables 2 and 3.

Table 1

Experimental Values of r_c and f

Nose Radius r_c (mm)	Feed Rate f mm/rev
0.4	0.35
0.8	0.050
1.2	0.065
1.6	0.080

Table 2

Calculated Values of R keeping r_c values constant

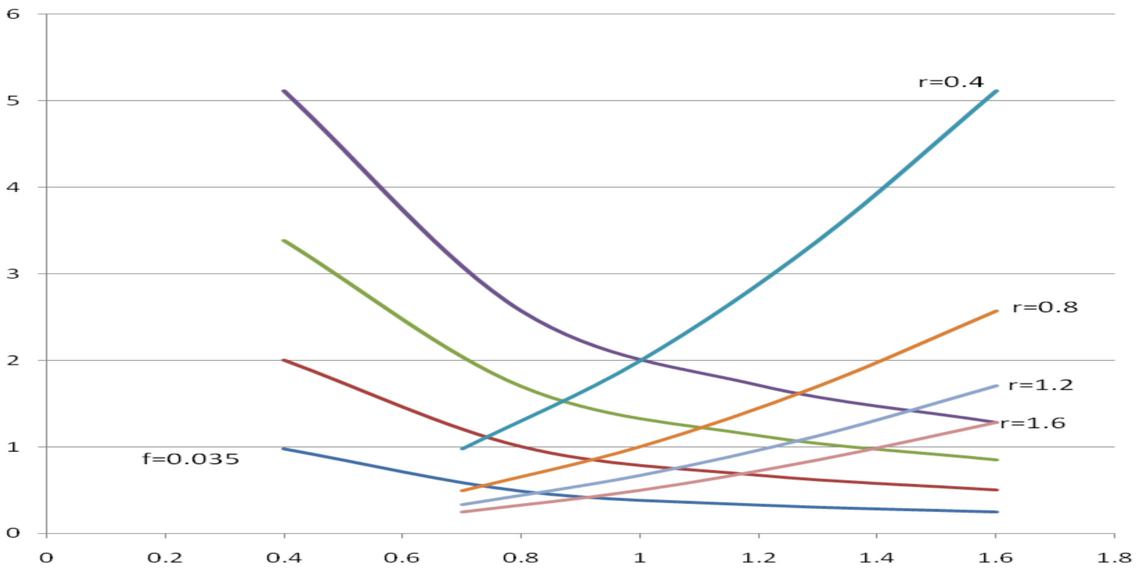
Values of Feed Rate	**Calculated Values of R_a (mm)**			
f(mm/rev)	**r_c = 0.4 mm**	**r_c = 0.8mm**	**r_c = 1.2mm**	**r_c = 1.6mm**
0.035	0.98×10^{-4}	0.49×10^{-4}	0.33×10^{-4}	0.25×10^{-4}
0.050	2.00×10^{-4}	1.00×10^{-4}	0.67×10^{-4}	0.50×10^{-4}
0.065	3.39×10^{-4}	1.70×10^{-4}	1.13×10^{-4}	0.85×10^{-4}
0.080	5.12×10^{-4}	2.57×10^{-4}	1.71×10^{-4}	1.28×10^{-4}

Table 3

Calculated values of R_a keeping f values constant

Values of Nose radius	**Calculated values of R_a (mm)**			
r_c (mm)	**f = 0.035 mm/rev**	**f = 0.050**	**f = 0.065**	**f = 0.080**
0.4	0.98×10^{-4}	2.00×10^{-4}	3.39×10^{-4}	5.12×10^{-4}
0.8	0.49×10^{-4}	1.00×10^{-4}	1.70×10^{-4}	2.57×10^{-4}
1.2	0.33×10^{-4}	0.67×10^{-4}	1.13×10^{-4}	1.71×10^{-4}
1.6	0.25×10^{-4}	0.50×10^{-4}	0.85×10^{-4}	1.28×10^{-4}

The set of values of RA are now plotted against the corresponding values of r_c and f to obtain the graph in Fig. 3.



Graph of Surfaces Roughness against Nose Radius & Feed Rate

As it can be seen from the graph Fig. 3 the optimum nose radius is $r_c = 0.8$, this curve intersects with the feed rate curves $f = 0.05$ and $f = 0.065$ corresponding to surfaces roughness values of 0.83×10^{-4} and 1.23×10^{-4}, the optimum values for f (feed rate) and R_A (surface roughness) can be found within these values.

Procedure

Corresponding values of R_A to the four feed rate values are obtained from the graph at the intersections of the curves of the feed rates with the $r_c = 0.8$ curve these are represented by the dotted lines traced to the R_A axis thus the table below is obtained

Table 4

Feed Rate = f (mm/rev)	0.035	0.05	0.065	0.08
Surface Roughness = R_A (mm)	0.53	0.83	1.23	1.61

Optimum Feed rate is assumed to be 0.057 which is almost midway between 0.05 and 0.065 the corresponding optimum values of surface roughness R_A is estimated using the Gauss forward interpolation formular.

The difference table is

Fe	**R_A**	**ΔR_A**	**$\Delta^2 R_A$**	**$\Delta^3 R_A$**
–1	0.53			
		0.3		
0	**0.83**		**0.1**	
		0.4		**–0 .12**
1	1.23		–0 .02	
		0.38		
2	1.61			

F = 0.057, a = 0.05, R (a) = 0.83   h = interval = 0.015

$$\text{Therefore } u = \frac{f-a}{h} = \frac{0.057-0.05}{0.015} = 0.47$$

Putting values in Gauss forward formula

$$R_f = R_0 + u_{(1)}\,\Delta R_0 + u_{(2)}\,\Delta^2 R_{-1} + (u+1)_{(3)}\,\Delta^3 R_{-1} \ldots\ldots\ldots\ldots\ldots$$

$$= 0.83 + 0.47\,(0.4) + \frac{0.47\,(-0.53) \times (0.1)}{2!} + \frac{1.47\,(0.47)\,(-0.53)}{3!} \times (-0.12) = 1.012$$

$Ra \simeq 1 \times 10^{-4}$ mm

Hence, the optimum values of R_a, r_c and f are 1×10^{-4} mm, 0.8mm, 0.057mm/rev respectively

4. Concluding Remarks

It will be observed from the graph in Figure 3 that the surface roughness reduces (i.e. improves) with increase in tool nose radius although, this has a limit, as proved by practical research work that tools chattering occurs when the nose radius is big. Also, the feed rate has a reversed effect on the surface roughness of the component as it increases with increase in the feed rate. However, researches have shown that increasing cutting speed can lead to obtaining better surface finishing. It is also noted that a better surface is achieved with harder materials; however, surface roughness can deteriorate with extreme hardness. It is also noted that the residual stress can be affected by tool edge geometry and material properties.

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