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Influence of Rake Angle and Cutting Speed on Residual Stresses Developed in the Cutting Tool During Orthogonal Cutting

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Abstract- **In this work, the effect of tool rake angle and cutting speed on residual stresses of tool was studied, the rake angles of 0^0, 5^0, 10^0, 15^0, and 20^0 and a constant clearance (Relief angle) of 8^0 were used to turn bright mild steel on the lathe machine, A total of 15 experiments were carried out with three different cutting speeds (37.69, 59.37, 94.24 m/min) for each rake angle, keeping the feed rate and depth of cut constant. During the experimentation, the residual stresses were measured using an x-ray diffractiometer. This is all in order to explore the energy savings opportunities during regrinding of tools, useful production time and energy is being wasted due to regrinding or re-sharpening of tools when cutting tools got worn or blunt, selection of the rake angle which generate the optimum residual stresses in the tool, goes a long way in saving these time and energy.**

Keywords: **Residual Stresses, Bright Mild Steel, Rake Angles, Turning Tools.**

INTRODUCTION-

Metal cutting or simply machining, is one of the oldest processes for shaping components in the manufacturing industry. To remain in business, manufacturing company has to machine the components at required quality with minimum possible cost and hence the tool life becomes utmost important aspect for manufacturing engineers and researchers. The challenge of modern machining industries is focused mainly on the achievement of high quality, in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and increase the performance of the product with reduced environmental impact. Tool wear weakens the cutting tool, increases the forces used in cutting and causes a lack of consistency in material removal.

INFLUENCING ELEMENTS OF RESIDUAL STRESSES-

Prediction of residual stresses is complex because of the complexity of machining system. Tool stresses in cutting process is produced by the contact and relative sliding between the cutting tool and the work piece and between the cutting tool and the chip under the extreme conditions of cutting area. Following elements come from the whole machining system comprising work piece, tool, interface and machine tool.

A) Work-piece Material- It includes the work piece material and its physical properties (mechanical and thermal properties, microstructure, etc) which determine cutting force and energy for the applied cutting conditions.

B) Tool Material- The tool material, tool coatings and tool geometric design (edge preparation, rake angle, etc) need to be appropriately chosen for different operations (roughing, semi-finishing, or finishing). The optimal performance of a cutting tool requires a right combination of the above tool parameters and cutting conditions.

C) Interface Conditions- It involves the interface conditions. In 80% of the industrial cutting applications, coolants are used to decrease cutting temperatures. Increasingly new technologies, such as the minimum liquid lubrication, have been developed to reduce the cost of coolant that makes up to 16% of the total machining costs.

D) The dynamic characteristic of the machine tool, affected by the machine tool structure and all the components taking part in the cutting process, plays an important role for a successful cutting.

WORK MATERIAL, CUTTING TOOL AND METHOD-

Using the power hacksaw the steel bar of 30mm diameter work piece cut in to the shorter length 40mm to allow for easy mounting on the center lathe machine the coolant was used during cutting process to minimize heating of both the power hacksaw blade and the work piece. The cylindrical shaped work pieces were obtained. EN8 steel has been used as the work-piece material to conduct all the experiments. These types of materials are widely used in the industrial applications. For conducting experiments solid cylindrical bar with diameter of 30 mm were used. These steel are of particular importance because of unique combination of strength and toughness after heat treatment. The chemical composition and mechanical properties of the selected work-piece material are listed in Table II and Table III

Table I: Chemical composition of work material

Elements	C	Mn	P	S
Composition (%wt.)	0.17	0.55	0.015	0.010

SELECTION OF THE CUTTING TOOL MATERIAL-

In today's World - for modern industrial production, particularly on mechanical & CNC mass production, tooling is one of the key factors pertaining for the performance of shaping and forming processes. Almost all tools employed for this purpose are made from high speed steels. The use of high speed steels has also gained increasing importance for chip less shaping, e.g. for extrusion, blanking and punching tools. HSS chemical composition distinctly differentiates between W, Mo and W-Mo alloyed steel grades, which contain different amounts of carbon, vanadium and cobalt elements to strengthen its own occurrence.

PREPARATION OF THE CUTTING TOOLS-

The high speed steel cutting tools were ground on the universal grinding machine; various rake angles of 0^0, 5^0, 10^0, 15^0, 20^0 were obtained. The clearance angle of 8^0 was made for all the corresponding rake angle of each HSS turning tool. After completing the grinding the protractor is used to measure the accuracy of all the angles obtained and all were found satisfactory. For 0^0, no need of any grinding rather the most flat and smooth HSS side was adopted for that purposed. The chemical composition of the HSS cutting tool is given in Table I.

Table II: Chemical composition of tool material

Elements	Compositions (% wt.)
C	0.88
Si	0.41
Mn	0.22
Cr	4.11
Mo	4.74
V	1.81
W	5.85
S	0.021
Pb	0.010

Table III: Mechanical Properties of work material

Modulus of Elasticity (10^3× N/mm^2)	Density (×1000 kg/m^3)	Thermal Conductivity (W/m-K)	Poisson's Ratio
190-210	8.16	21.3	0.27-0.30

STRESS MEASUREMENT-

Residual stresses were measured by using x-ray diffractiometer. The x-ray diffractiometer consists of the x-ray tube, the collimator and the detector as shown in Fig.1.While the x-ray tube emits the radiation, the collimator enables a parallel path of the x-ray beams. When the monochromatic beams impinge the surface of the specimen, the x-rays are diffracted by near surface lattice planes. If residual stresses occur in the top layer of the target, the interplanar spacing changes. To obtain constructive interference the angle of incidence θ of the beams has to be adjusted. By using elastic constants the occurring angular offset can be converted into a stress value. The standard method for X-ray stress analysis is the $\sin^2\psi$-method. Since the penetration depth of the X-ray beams is in the range of several µm, a plane and surface parallel stress condition is assumed. The measurement of several lattice deformations in different tilting directions ψ enables the determination of the normal stress component in the x direction.

Main sources of uncertainty in this measurement are listed below:

- Elastic constants (E &v)
- Instrument alignment
- Specimen-surface height offset
- 2θ step size
- Number of ψ tilts
- Length of counting time
- Peak-fitting analysis method

• Stress analysis algorithm and software
• Specimen material
• Non-linearity due to texture, coarse grain size, stresses gradients with depth, etc.

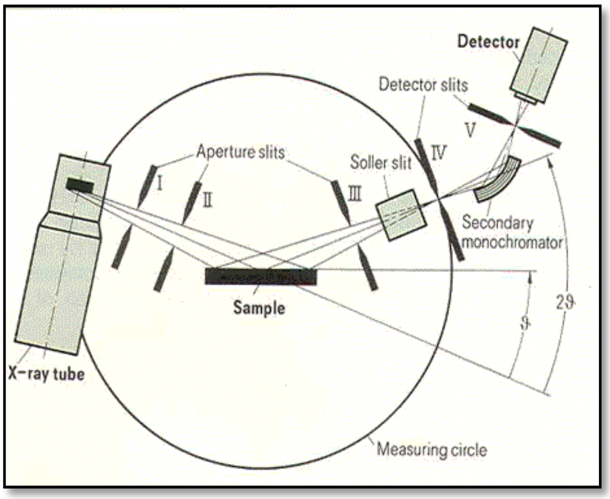

Fig.1: Construction and working of X-ray diffractometer

MACHINE TOOL AND CUTTING CONDITION-

Experiments were carried out on a Kirloskar Turn Master - 40 lathe setup using High speed steel (HSS) cutting tools for the machining of EN8 solid cylindrical work-piece, which is having diameter 30 mm. A total of 15 experiments were performed with 5 different rake angles at a 3 constant speed and depth of cut and feed constant as shown in Table IV.

Following an empirical approach, in this paper the process parameters that influence on the residual stresses of the cutting tool are identified for three different cutting speeds and five different rake angles. The effect of feed rate, nose radius, entrance angle and depth of cut on the work piece is investigated by different authors'. It is observed that the depth of cut does not influence the level of residual stresses. To find the effect of cutting speed and rake angle on the residual stresses of the cutting tool, selecting the following process parameters as shown in Table IV.

Table IV: Process Parameters and Levels

Parameters		Levels 1	2	3
	Cutting Speed (m/min.)	37.69	59.37	94.24
	Rake angle (degree.)	Rake angles		
		0	0	0
		5	5	5
		10	10	10
		15	15	15
		20	20	20

V.RESULTS AND DISCUSSION-

A set of experiments were carried out as per Table III in order to measure the effect of change in rake angle and cutting speed on residual stresses of the cutting tool. The experimental results were shown in Table IV. The residual stresses were measured by x-ray diffractiometer are plotted in graphical manner shown in Table VI.

Table V: Process Parameters and Levels

Experiment No.	Speed (rpm)	Feed (mm)	Depth of Cut (mm)	Rake Angle(degree)
1	400	0.14	1	0
2		0.14	1	5
3		0.14	1	10
4		0.14	1	15
5		0.14	1	20
6	630	0.14	1	0
7		0.14	1	5
8		0.14	1	10
9		0.14	1	15
10		0.14	1	20
11	1000	0.14	1	0
12		0.14	1	5
13		0.14	1	10
14		0.14	1	15
15		0.14	1	20

Sample ID	CUTTING PARAMETERS			RESIDUAL STRESSES	
	Rake Angle (Degree)	Speed (rpm)	Cutting Velocity (m/min)	Normal Stresses (MPa)	Shear Stresses (MPa)
A1	0	400	638	-313 ± 113	+39 ± 15
A2	0	630	990	-302 ±55	+6 ± 4
A3	0	1000	1570	-231 ± 66	+138 ± 7
B1	5	400	638	-296 ± 36	-39 ± 31
B2	5	630	990	-578 ± 11	-22 ± 2
B3	5	1000	1570	-878 ± 23	-154 ± 4
C1	10	400	638	-317 ± 72	-35.5 ± 10.5
C2	10	630	990	-469 ± 91	-91 ± 14
C3	10	1000	1570	-157 ± 78	-113 ± 11
D1	15	400	638	-294 ± 56	-51 ± 7
D2	15	630	990	-324 ± 57	-98 ± 8
D3	15	1000	1570	-488 ± 30	-78 ± 3
E1	20	400	638	-167 ± 67	-133 ± 9
E2	20	630	990	-383 ± 78	-26 ± 17
E3	20	1000	1570	-345 ± 82	-26 ± 5

Table VI: Experimental observation

Fig.2 show the residual stress distribution of the cutting tool edge after being turned at the cutting speed of 37.69 m/min and the rake angles of 0^0 to 20^0. It is observed that the compressive normal stresses shows maximum value for lower rake angle and the compressive normal stresses shows minimum value for higher rake angle. The maximum compressive normal stresses for the rake angle of 0^0 is 313 MPa and 317 MPa for the rake angle of 10^0 at the cutting speed of 59.37 m/min. It can be seen from figure 6.1 that, as the rake angle increases the normal stress shows minimum compressive value. The compressive shear stress for the rake angle of 20^0 is 133MPa and shows minimum value for 5^0. It can be seen from Figure 6.2, that the shear stress shows the tensile nature at 0^0 and compressive nature for remaining rake angles. It is also observed that as the rake angle increase the shear stress also increases but in compressive nature.

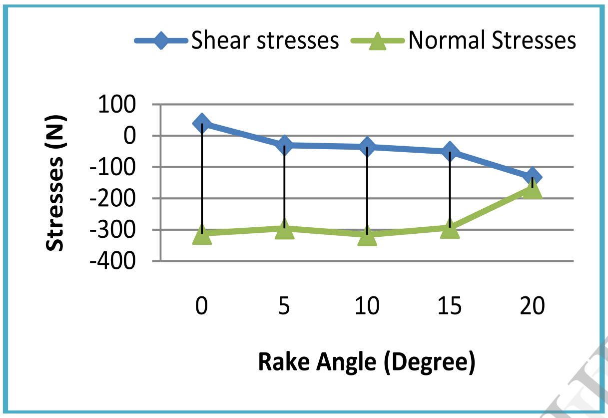

Fig. 2: Stress distribution using a cutting speed of 37.69 m/min.

Fig.3 show the residual stress distribution of the cutting tool edge after being turned at the cutting speed of 59.37 m/min and the rake angles of 0^0 to 20^0. The maximum compressive normal stresses for the rake angle of 5^0 is 578 MPa and minimum compressive normal stresses for the rake angle of 15^0 is 324 MPa. It can be seen from fig.3 that, as the rake angle increases the normal stress shows minimum compressive nature up to rake angle 15^0. The compressive shear stress shows maximum value at 15^0 and shows minimum value for 5^0. It can be seen from Fig.3, that the shear stress shows the tensile nature at 0^0 and compressive nature for remaining rake angles. It is also observed that as the rake angle increase the shear stress also increases up to rake angle of 15^0 but in compressive nature. Show the residual stress distribution of the cutting tool edge after being turned at the cutting speed of 94.24 m/min and the rake angles of 0^0 to 20^0. The maximum compressive normal stresses for the rake angle of 5^0 is 878 MPa and minimum compressive normal stresses for the rake angle of 10^0 is 157 MPa. It can be seen from Fig.4; the compressive shear stress shows maximum value at 5^0 and shows minimum value for 20^0. It is also observed that the shear stress shows the tensile nature at 0^0 and compressive nature for remaining rake angles. It is also observed that as the rake angle increase the shear stress also increases up to rake angle of 5^0 but from 10^0 it moved towards the reducing shear stresses.

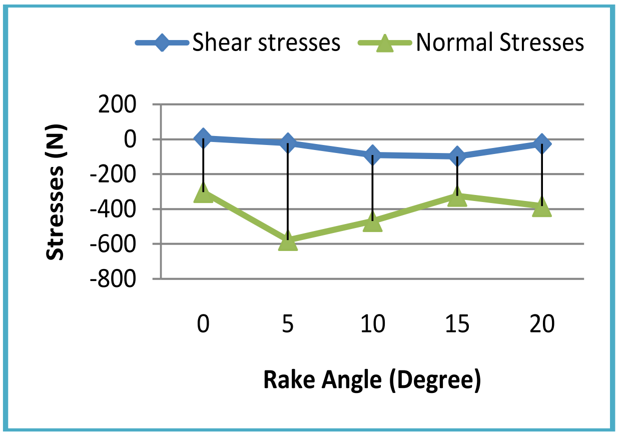

Fig.3: Stress distribution using a cutting speed of 59.37 m/min.

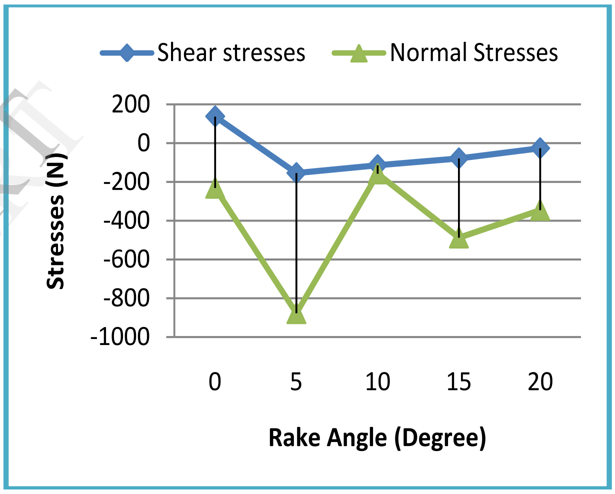

Fig.4: Stress distribution using a cutting speed of 94.24 m/min.

EFFECT OF RAKE ANGLE ON CUTTING FORCES:

It is observed from the results that, the cutting forces decreases with increase in rake angles, it is also observed from Fig.5 and Fig.6, that the cutting speed increases the cutting forces decreases. It is shown that at 37.69 m/min the cutting forces decreases up to 415 N as the rake angle increase in between 0^0 to 20^0. At cutting speed 59.37m/min, the cutting forces shows minimum value up to 317 N at rake angle 20^0 and at cutting speed 94.24 m/min the minimum value of the cutting force up to 285N for rake angle 20^0.

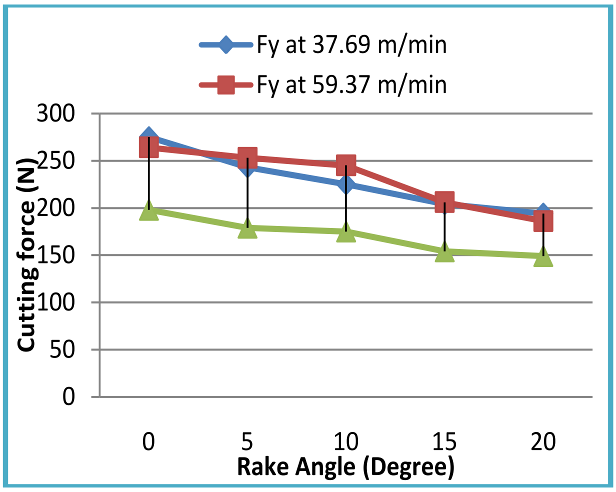

Fig.5: Variation of the cutting forces with increase in rake angle for different cutting speeds for Fy.

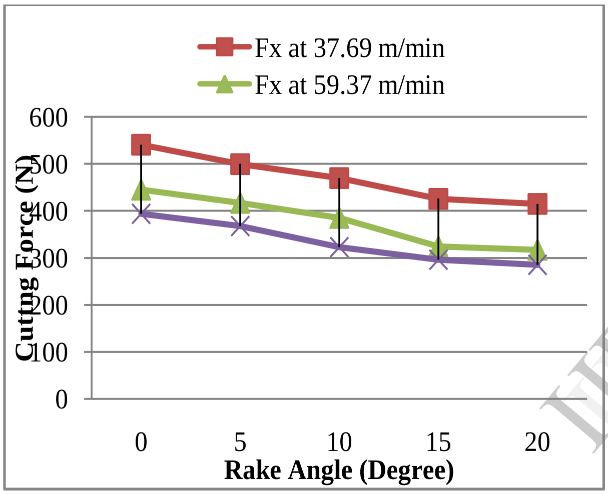

Fig.6: Variation of the cutting forces with increase in rake angle for different cutting speeds for Fy.

In this study, the significance of two parameters (cutting speed and Rake Angle) was proved that, during turning operation with various rake angle, the chip – tool interface take place and it generate the cutting forces and the nature of the cutting forces generally tensile in nature along three axes. If the surface and the subsurface of the cutting tool edge consist of tensile stresses then the resistant section is reduced and when the residual section can no longer withstand the applied load, component fatigue occurs and reduces the tool life. Hence to increase the resistant to tensile stresses which are generate during turning operation the surface and subsurface of the cutting tool edge should have compressive stresses. It is observed from the results obtained by physical and software testing , the cutting forces decreases as the tool rake angle increases, this is because the contact pressure were high for rake angles from the tool tip up to a distance along the tool surface where the contact pressures reduced to zero, this is point where the chip leave the tool surface, it is observed that the pressure acting on the tool surface is not constant and the contact pressure distribution changes as the rake angle changes. According to Naife A. Talib, the effect of cutting speed was more dominant than the effect of feed rate, which leads to the conclusion that for improved tool life slower cutting speed should generally selected in combination with suitable feed rate and rake angle. Because material removal rate is linearly related to both feed rate and cutting speed. In order to selection of the rake angle and cutting speed for turning process it is necessary to understand the impact of impact of each of these variables, but also the interactions between them. It is impossible to find all the variables (feed rate, cutting speed, depth of cut, work piece hardness, cutting edge geometry, etc) that impact tool life in turning process. In addition, it is costly and time-consuming to discern the effect of every variable on the output.

According to Maranh and Davim, Residual stresses play an important role in the performance of in the fatigue life, corrosion resistance and part distortion. Surface roughness is affected by cutting tool geometry, depth of cut, cutting speed, feed rate, work-piece microstructure and the rigidity of the machine-tool. When the cutting parameters are not selected properly, the cutting tool wears quickly or gets broken abruptly. The parameters affecting the surface roughness are, in order of importance: feed rate, insert radius and depth of cut. A good combination among these parameters should be addressed to provide better surface quality. An evident way to judge the surface quality is surface roughness. However, residual stress is not as evident as surface roughness but plays a decisive role in component performance. The fatigue crack, in general, nucleates at the surface of the part, and then propagates into the bulk. As the crack extends, the resistant section is reduced and when the residual section can no longer withstand the applied load, component fatigue occurs. Consequently, it is the state of stress at the surface, where the crack nucleates, that is of paramount importance. This state is the sum of the stress due to the applied load and of the residual stresses (or self stresses) generated during machining.

Compressive residual stresses generally improve component performance and life because they promote a service (working) tensile stresses and prevent crack nucleation. On the other hand, tensile residual stresses tend to increase service (working) stresses which lead to premature failure of components. These residual stresses may affect dramatically the performance of the machined part causing its premature failure, excessive wear and corrosion.

CONCLUSIONS-

The experimental investigation was conducted to turn mild steel as per BS: 970 grade EN: 3 using AISI: M2 high speed steel cutting tool at three level of cutting speed and five level of rake angle by employing X-Ray Diffractiometer and Finite Element Analysis. The effect of rake angle and cutting speed on the residual stresses of the cutting tool was studied under dry condition and the following conclusions are drawn:

1) Increasing the rake angle in positive section caused the decrease of the cutting forces.
2) The cutting speed has a direct influence on material removal rate. As the cutting peed increases the material removal rate.
3) For cutting speed 37.59 m/min, 59.27 m/min, 59.27 m/min, the cutting force and residual stresses shows the optimum magnitude at rake angle 20^0.

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