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A SEMI-ANALYTICAL METHOD FOR DETERMINING THE SUBSURFACE DAMAGE IN MACHINING

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ABSTRACT

An attempt is made to predict the subsurface damage in the machined components induced in metal cutting using a semi-analytical model based on the identation of a semi-infinite plate with a line load. A model is proposed to calculate the plastically deformed zone underneath the machined surface when cutting with sharp tools. Measured values of tool forces and the tensile yield strength of the material should be used in the analytical model.

Experimental measurements were carried out to determine the depth of the plastically deformed layer using a simplified technique. The experimentally measured values agreed well with the depth predicted from the analytical model.

INTRODUCTION

It has long been evident that the traditional machining process, although conceptually simple, is perhaps one of the most complex of the manufacturing operations employed today. In the past, the most important was the economics of the process as determined by the cost per component or the process as determined by the cost per component or the number of components produced per unit time. However, this method of assessing the economics of the process may be too restricted. An assessment of the true economics of machining must involve a consideration of the behavior of the machined components in service particularly if surface sensitive mechanical properties such as creep, fatigue and stress corrosion cracking become important. Thus, the design engineer must have complete information on the surface characteristics of a component in addition to those mechanical and physical properties generally recognized as essential.

The nature or condition of surface and subsurface must be described,

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and it is known as surface integrity. It involves study and control of surface topography, and surface and subsurface metallurgy. The study of surface metallurgy is relatively new and entails the investigation of the possible alterations in surface layers after machining. These alterations include plastic deformation, tears, laps, recrystallization, voids, grain growth, hardness variations, micro-and macro cracks, and residual stress.

Plastic deformation causes changes in surface hardness and surface dislocation density |1|. It also leads to the generation of residual stress in the surface region |2|. Many experimental techniques have been used to study surface damage through examining plastic deformation induced in the machined surface |3-5|. However, there is lack of published theoretical work or analytical models to determine the plastically deformed zone in the surface layers after metal machining.

In this work, an attempt is made to predict the depth of the plastically deformed zone induced in metal cutting. A comparison between experimental data and the predicted values is also made.

ANALYSIS

The stress distribution in a workpiece during machining is equivalent to semi-infinite plate acted upon by a line load in a direction perpendicular to the rake face of the cutting tool|6|. An element of a disc at the point of application of the oblique load (R) is shown in Fig. (1-a). For convenience, the load (R) can easily be resolved into component tangential (F) and perpendicular (P) to the edge. The results of these two cases may be added by the principles of superposition.

The stress function can be assumed in the form

$$\phi = \frac{P}{\pi} r.\Theta.\cos\Theta \qquad (1)$$

represents the solution to the problem |7| when the load (P) is perpendicular to the edge of the disc (Fig. 1-b).

In two-dimensional polar coordinates, the stresses are then given by |8|:

$$\left.\begin{aligned} \sigma_r &= \frac{1}{r}\cdot\frac{\partial\phi}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2\phi}{\partial\Theta^2} \\ \sigma_\Theta &= \frac{\partial^2\phi}{\partial r^2} \\ \tau_{r\Theta} &= \frac{1}{r^2}\cdot\frac{\partial\phi}{\partial\Theta} - \frac{1}{r}\cdot\frac{\partial^2\phi}{\partial r\,\partial\Theta} \end{aligned}\right\} \qquad (2)$$

where ϕ is the stress function as a function of r and Θ.

Differentiating Eq. (1) and substituting into Eq. (2) gives the

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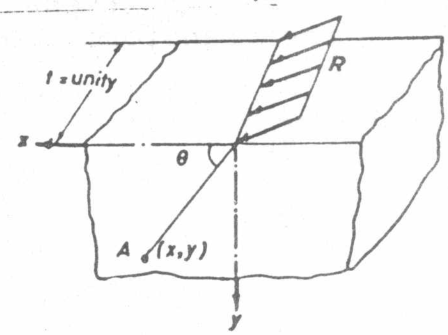
following stress components:

$$\left.\begin{aligned} \sigma_r &= -\frac{2P}{\pi r}\sin\Theta \\ \sigma_\Theta &= 0 \\ \tau_r &= 0 \end{aligned}\right\} \quad (3)$$

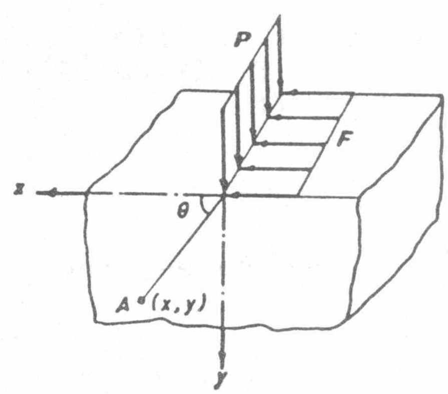
These stress components must satisfy the equilibrium equations and boundary conditions while the stress function must satisfy the compatibility equation in order that the stress components (Eq. 3) be the exact solution of the problem.

The equilibrium equations in two-dimensional polar coordinates are given by the following equation |8|, assuming that the body forces are vanishingly small:

$$\left.\begin{aligned} \frac{\partial\sigma_r}{\partial r} + \frac{1}{r}\cdot\frac{\partial\tau_{r\Theta}}{\partial\Theta} + \frac{\sigma_r-\sigma_\Theta}{r} &= 0 \\ \frac{1}{r}\cdot\frac{\partial\sigma_\Theta}{\partial\Theta} + \frac{\partial\tau_{r\Theta}}{\partial r} + \frac{2\tau_{r\Theta}}{r} &= 0 \end{aligned}\right\} \quad (4)$$



a) Oblique Loading



b) Horizontal and Perpendicular to the Edge loading

Fig. (1) An Element of a Disc at the Point of Load Application.

The stress boundary conditions are given by:

$$\left.\begin{aligned} &\sigma_\theta = \tau_{r\theta} = o \text{ at } \theta = o,\pi && (a)\\ &\int_o^\pi P_{ny}\, r.d\theta = -P && (b)\\ &\int_o^\pi P_{nx} r.d\theta = o && (c)\end{aligned}\right\} r > o \qquad (5)$$

which are satisfied

The compatibility condition for the two-dimensional problem in polar coordinate is given |8| by:

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}.\frac{\partial^2}{\partial \theta^2}\right)\left(\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}.\frac{\partial \phi}{\partial r} + \frac{1}{r^2}.\frac{\partial^2 \phi}{\partial \theta^2}\right) = o \qquad (6)$$

which is satisfied by the stress function given in Eq. (1).

The stress components can be transformed from polar to cartesian coordinates using the so-called stress transformation equations. The results of the transformations are:

$$\left.\begin{aligned} \sigma_x &= -\frac{2P}{\pi} . \frac{x^2 y}{(x^2+y^2)^2}\\ \sigma_y &= -\frac{2P}{\pi} . \frac{y^2}{(x^2+y^2)^2}\\ \tau_{xy} &= -\frac{2P}{\pi} . \frac{xy^2}{(x^2+y^2)^2}\end{aligned}\right\} \qquad (7)$$

Assuming that the stress function which represents a solution to the problem when the load (F) is parallel to the edge of the disc (Fig. 1-b) of the form |7|:

$$\phi = -\frac{F}{\pi} r.\theta. \sin\theta \qquad (8)$$

In two-dimensional polar coordinates, the stress components are given by:

$$\left.\begin{aligned} \sigma_r &= -\frac{2F}{\pi r}\cos\theta\\ \sigma_\theta &= \tau_{r\theta} = o\end{aligned}\right\} \qquad (9)$$

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The boundary conditions are:

$$\left.\begin{array}{ll} \sigma_\Theta = \tau_{r\Theta} = o \quad \text{at } \Theta = o, \pi & \text{(a)} \\ \int_o^\pi P_{ny}\, r.d\Theta = o & \text{(b)} \\ \int_o^\pi P_{nx}\, r.d\Theta = -F & \text{(c)} \\ \int_o^\pi \tau_{r\Theta}\, r.rd\Theta = o & \text{(d)} \end{array}\right\} r > o \qquad (10)$$

The boundary conditions (Eq. 10-b,c,d) apply to the small semi-circular element with its center at the origin. The boundary condition (Eq.10-d) states that moment of the forces acting on the small element is zero about the origin. It can be seen that the stress components satisfy the boundary conditions(Eq. 10), and the equation of equilibrium (Eq. 4). Also, the stress function (Eq. 8) satisfy the compatibility equation (Eq. 6). Therefore, the solution (Eq. 9) is the exact solution.

The stress components are again possible to be transformed from polar to cartesian coordinates. The results of the transformation are:

$$\left.\begin{array}{l} \sigma_x = - \frac{2F}{\pi} \cdot \frac{x^3}{(x^2+y^2)^2} \\ \sigma_y = - \frac{2F}{\pi} \cdot \frac{xy^2}{(x^2+y^2)^2} \\ \tau_{xy} = - \frac{2F}{\pi} \cdot \frac{x^2 y}{(x^2+y^2)^2} \end{array}\right\} \qquad (11)$$

The stresses at each point of the disc due to the application of an inclined concentrated load can be evaluated by the superposition of Eq. (7) and Eq. (11) as follows:

$$\left.\begin{array}{l} \sigma_x = - \frac{2}{\pi} \cdot \frac{x^2}{(x^2+y^2)^2} \quad (P_y + F_x) \\ \sigma_y = - \frac{2}{\pi} \cdot \frac{y^2}{(x^2+y^2)^2} \quad (P_y + F_x) \\ \tau_{xy} = - \frac{2}{\pi} \cdot \frac{xy}{(x^2+y^2)^2} \quad (P_y + F_x) \end{array}\right\} \qquad (12)$$

It should be noted that the stresses in Eq. (12) become infinite as (r) approaches zero. This kind of discontinuity is to be expected because it has been assumed that the load is acting over an infinitely small area at the origin. From these stresses the strains and displacements can be calculated and it is clear that they would become infinite, as the origin is approached.

Since large displacements are not allowed in linear elasticity theory, the solution obtained here is invalid in the immediate neighborhood of the point of application of the load. As it is well known, the yield point is the beginning of the plastic or permanent deformation. Below the elastic-plastic boundary, the deformation is elastic, and it is possible to use the above equation (12) up to and the yield point itself. In the plastic zone flow occurs.

It may be assumed that the maximum-distortion-energy theory |9|, which predicts ductile yielding under combined loading with greater accurcy than any other recognized theory, can be applied. The distortion-energy theory may be written as:

$$\sigma_e = \frac{\sqrt{2}}{2}\left[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2\right]^{\frac{1}{2}} \quad (13)$$

For plane stress, the yield criterion reduces to:

$$\sigma_e = \left[\sigma_x^2+\sigma_y^2-\sigma_x\sigma_y+3\tau_{xy}^2\right]^{\frac{1}{2}} \quad (14)$$

Substituting of Eq. (12) into Eq. (14) gives:

$$\sigma_e = \frac{2}{\pi}\left[\frac{P_y+F_x}{x^2+y^2}\right] \quad (15)$$

where the loads (P and F) and the tensile yield strength of the material (σ_e) are known values. Thus, the depth of the plastically deformed zone(y) can be calculated for any value of (x).

EXPERIMENTAL WORK

Workpieces of brass and aluminum alloy-7001 were used in this investigation. The as-recieved materials were machined into disc-shaped workpieces having a diameter of 70 mm and a thickness of 6 mm.

The side surface, of each disc was ground on successively finer grades of silicon carbide paper and then was polished to a mirror-like finish. Several vertical thin sharp lines were inscribed on the polished side of the discs. Two discs were machined together with the inscribed lines being in the mating surfaces representing workpiece middle plane. This was made to prevent the possible side flow. The workpieces were bolted to a specially-made mandrel and were machined on a lathe under dry orthogonal conditions. High speed steel tools having clearance angle of 8 degrees and rake angles of 10 and 15 degrees were used in machining brass and aluminum alloy 7001, respectively. Cutting speeds in the range from 0.12 to 1.10 mt/sec were employed. Two feed rates of 0.125 and 0.230 mm/rev were used for brass and Al-7001, respectively.

Once steady state cutting was established, the cutting and thrust components of the resultant tool force were measured using a two-component cutting force dynamometer. After machining, the deflections of the inscribed lines in the perpendicular direction of the machined surface were measured using an optical microscope. This was taken as the experimentally measured values of the plastically deformed zone underneath the machined surface.

RESULTS AND DISCUSSION

Equation (15) given above was used to calculate the depth of the plastically deformed zone using the measured values of tool forces and the tensile yield strength of the materials. Figures (2 and 3) show graphs of the depth of plastically deformed zones against cutting speed for brass and aluminum alloy-7001, respectively, where the experimental results are compared with the analytical predictions.

Figure (2) shows that the depth of the plastically deformed zone, when cutting brass, increases gradually with an increase in cutting speed. When machining Al-7001, the depth of plastically deformed layer is almost constant with increasing in cutting speed up to about 0.4 mt/sec (Fig. 3). With a further increase in cutting speed, the depth of deformed layer increases gradually.

These figures show that the predicted depth of the plastically deformed zone is greater than that measured from experimental. It is believed that this difference arises because a portion of cutting and thrust components of the resultant tool force, that measured by dynamometer in a steady state cutting, has been used for curling the chips. The direction of this force changes during machining and must be discounted from the measured cutting and thrust components of the resultant tool force. In general, the experimentally measured values agreed well with the depth predicted from the proposed analytical model.

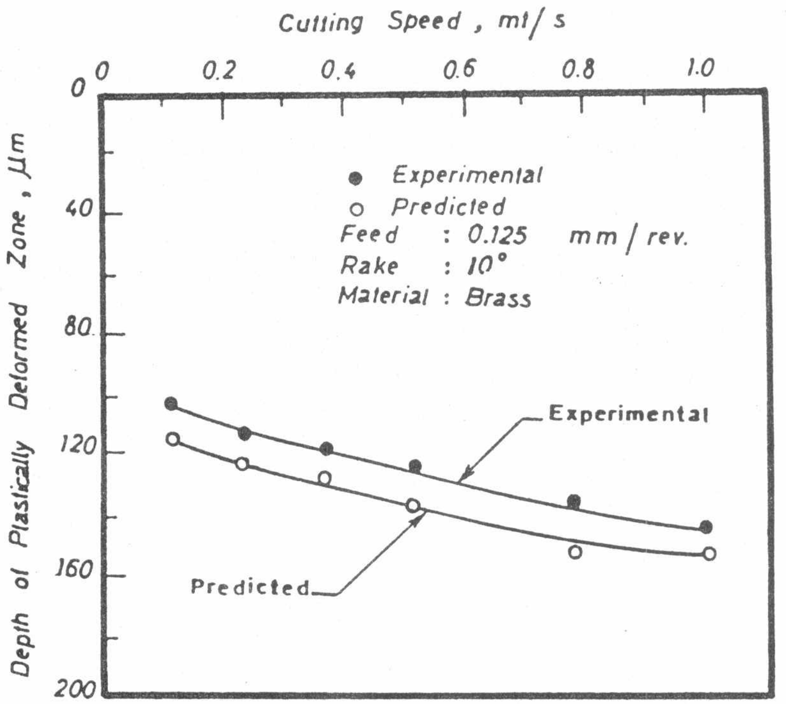

Fig.(2) Effect of Cutting Speed on the Depth of Plastically Deformed Zone For Brass.

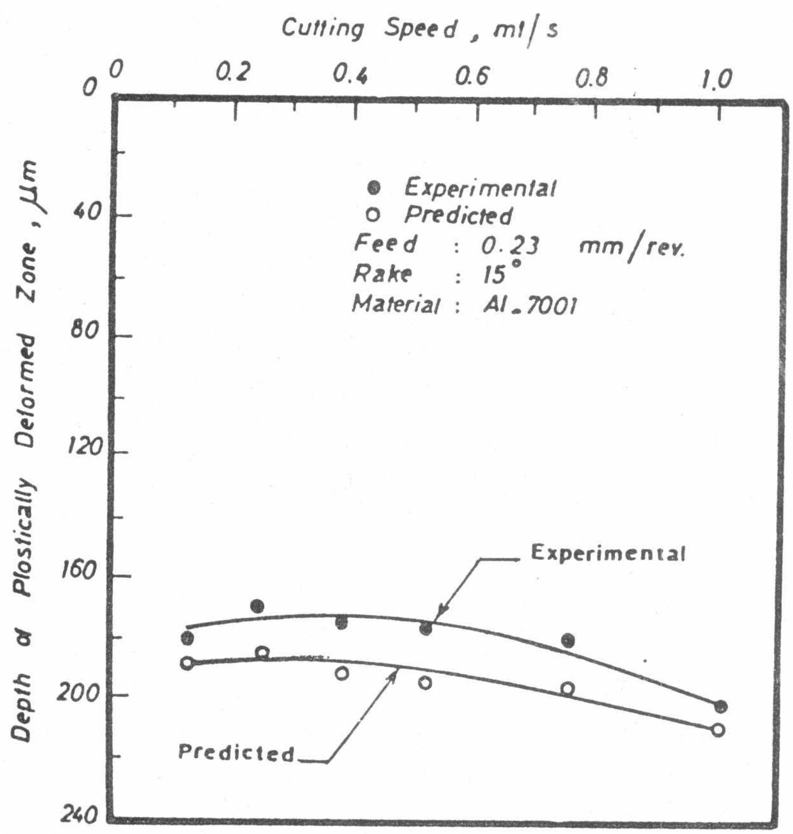

Fig.(3) Effect of Cutting Speed on the Depth of Plastically Deformed Zone For Al-7001.

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