Chapter 1

CHAPTER-1

INTRODUCTION

The term machining is used to define a process in which a thin layer of material is removed from a larger body by a wedge shaped tool called cutting tool. Metal machining process was considered to be an art a few decades back, but soon was developed as a science with the aid of the study of the properties of materials, theory of elasticity and plasticity and some other tools of mathematics.

A knowledge of metal machining mechanics in a machining operation is of considerable value to the engineer engaged in the design of machine tools, to the production engineer responsible for the selection of a cutting tool, to the metallurgist who must provide cutting tool materials with the appropriate strength and hardness and to the production planner who must select suitable jigs and fixtures. Before the middle of 18th century, the main material used for machining was wood with a few exceptions like boring of canon, production of metal screws and small instrument parts. The major developments in metal-machining took place after the invention of steam-engines. After the second world war an enormous effort was directed for measurements of the different machining parameters with investigations into the physical fundamentals of the cutting process.

Research into chip-formation had already been carried out by the French scientist H. Tresca[1] as far as back 1873, although fundamental theories have been developed only during the last five or six decades. The compression of the chip was

recognised correctly by Tresca by measuring the length of the chip. He concluded that the chip-length is only one third to one half of the distance traveled by the tool. Many scientists were interested in the problem of shearing of metals during machining, notable contribution being due to Thime[2], Haussner[37], Reauleax[3], Kurrein[37], Eckhard[37] and Pissipanen[9]. Coker's[5] research on plastic models proved that a shear plane exists, extending from the tip of tool to the surface of the work-piece. In the presence of a single shear plane, the gradient of stress and velocity become infinite. Hence, Rosenberg[18] proposed that a shear zone must separate the chip from the workpiece within which the material is progressively deformed. According to Hill[10], for an ideal rigid-perfectly plastic material a single shear plane involving a narrow zone of intense shear is theoretically viable, the phenomenon being similar to that of the flow of gases through a nozzle where, shock planes exist across which the pressure and velocity undergo finite change. For strain-hardening materials, however, the shear plane "opens up" giving rise to a shear zone[58].

Summarising previous research, Shaw[28] has made the following observations on the phenomenon of chip formation process:

(a) Chips are produced by shear process

(b) There is a strong interaction between shear deformation occurring in the shear zone and that occurring on the tool face.

(c) Most materials strain harden.

(d) A built-up edge is usually present at low cutting speeds.

(e) At high cutting speeds, a secondary shear zone is present in the chip along the tool rake face.

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(f) Chips frequently curl and this in turn could change the tool-chip contact length.

(g) The chip-tool contact length may be controlled by tool design.

(h) Dull tools or tools cutting with a large BUE will have a rounded cutting edge.

(i) Forces exist on the relief face of a tool especially when an appreciable wear land is present.

The ultimate aim of an analysis of the mechanics of metal cutting is to understand the basic phenomena, to predict how the chip deforms and what forces and power are required for a given material under given cutting conditions. The basic purpose of the research is to relate cutting forces, stress-distribution and other machining parameters with cutting variables and tool-geometry. The machining is a small scale operation. It is what happens in a very small volume of metal around the cutting edge that determines the performance of tools, the machiniability of metals and alloys and qualities of the machined surface. There are three important zones in the machining operation viz the shear zone, tool-chip contact zone and the flank-work contact zone. All the phenomena occurring in the above zones affect each other. The mechanism of shear in the primary shear zone has received maximum attention of researchers investigating the mechanics of chip formation process but the flank work contact zone is also equally important as it affects generation of temperature, wear of the tool, generation of vibrations and the surface finish produced.

The tool-chip contact zone is as important as the primary shear zone. In this zone the forces generated due to chip removal give rise to a force normal to the rake face and a shear force. The distributions of these frictional and normal stresses at the chip-tool interface have a profound effect on the chip-formation process, cutting

forces, chip-curling and rise in temperature etc. A number of experimental techniques have been developed by various investigators to determine the distributions of normal and shear stress on the tool rake face during machining. These include the photo-elastic method, the split-tool method and the visio-plasticity method based on the analysis of experimental flow field.

In the photo-elastic technique the tool is made of a photo-elastic material such as epoxy resin. Only soft and low melting point metals could be machined using such a tool because of the low strength of the tool.

Andreev[20] and Kattwinkel[19] were among the first to investigate the stress-distributions on the tool rake face using this method taking lead as the workpiece material. They observed that shear stress increased from a low value near the point of chip separation and reached a constant value as the cutting edge was approached. However the normal stress was found to increase exponentially towards the cutting edge. The above distribution of stresses followed a pattern similar to that conjectured by Zorev[29]. However, the stress distribution obtained by Kattwinkel[19] indicated that the shear stress after reaching a maximum value in the middle part of the contact length had a tendency to fall towards the cutting edge. Usui and Takeyama[25] used the photoelastic technique to determine the stress-distribution at the chip-tool interface and obtained a similar trend as observed by Kattwinkel. Rice et al.[38] machined lead in a planer using this technique and determined the distribution of normal stress which remained constant for a short distance near the tip and decreased in a non-linear manner to zero at the chip separation point. Chandrasekaran and Kapoor[33] machined lead with photo-elastic tools having rake angles of -10^0, 0^0, 10^0 and 20^0. The distribution of shear stress for

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all positive rake angles followed the same pattern as that conjectured by Zorev[29], where as for a tool with a negative rake angle, it was identical to that of Kattwinkel[19]. It is interesting to note that in all of the above studies the maximum value of the shear stress was found to approach the yield strength in shear of the chip-material, whereas the normal stress remained constant for a short distance near the cutting edge and then decreased in a non-linear manner to zero at the chip-releasing point, the peak value of the normal stress increasing with decrease in the rake angle. Amini [42] carried out further studies on machining of lead at low cutting speeds using photo-elastic tools having rake angles equal to 10^0. In his studies both the shear and the normal stresses increased in a non-linear manner from the point of chip separation towards the cutting edge.

In the photoelasticity methods used in the above investigations the rake face stress distributions were determined by analysing the isocromatics and the isoclinics produced in the tool during machining. Okushima et al.[46] used a photoelasto-plasticity method where stresses were determined by analysing the isocromatics and the isoclinics produced in the chip.

The photo-elastic technique played a very successful role in determining the stress-distribution at the chip-tool interface. However, the major draw back of this method was that the cutting conditions were not representative of the actual cutting conditions. Bagchi and Wright[70] used single crystal sapphire cutting tools in order to simulate actual cutting conditions in metal-machining for a tool with a negative rake angle. Interestingly the distribution of shear stress followed a pattern similar to that of Kattwinkel[19]: the shear stress decreasing towards the cutting edge after reaching a maximum value at the middle of contact length, while the

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normal stress increased monotonically towards the cutting edge from a minimum value at the chip releasing point.

Most of the above experimental investigations indicate that the maximum normal stress is much higher than that of the maximum shear stress with the ratio between these two quantities being of the order of 1.9 - 3.6. One disadvantage of the photoelastic method is that it is not possible to determine the stresses immediately adjacent to the cutting edge accurately, since the contact stresses at the tool flank cause a local distortion of the isochromatic fringes in this region.

The split tool technique is an important experimental method to determine the stresses at the chip / tool interface under conventional cutting conditions. This method is based on the use of a composite tool divided into two parts by a cut parallel to the cutting edge to measure separately the forces acting on one part or the other or both parts of the tool. The two parts of the tool are separated by a thin air gap and maintained at the same level. In this method, the length of the front part of the rake face is gradually increased from the smallest value until the total load is taken by the front part of the tool.

Kato et al.[48] used a split tool dynamometry technique with an active front part to obtain normal and frictional forces for work-piece materials such as aluminium, copper, led-tin alloy and zinc using HSS tools having rake angles of 20^0. The stress distributions for aluminum, copper and lead-tin alloy in their investigation were found to be similar to that obtained by Kapoor et al.[33] and Andrev[20] with both shear and normal stresses having nearly constant values near the cutting edge. However for zinc, the normal stress was found to increase continuously from the chip-releasing point to the cutting edge. Ushi and Shirakashi[64] used the split-tool

technique to obtain stress-distribution at the chip-tool interface while machining plain carbon steels at cutting speed of 200m/minute using a P20 grade carbide tool. The shear stress in their study was found to be constant near the cutting edge and then decreased to zero at the chip-releasing point while the normal stress was found to increase monotonically from zero at the chip releasing point to the maximum at the cutting edge. Childs et al.[76] carried out split tool tests to obtain stress distributions in machining of two low alloy steels with one having free machining property at cutting speed 100m/minute. The nature of variation of stresses in this study was almost the same as that obtained by Shirakashi et al.[64].

Barrow et al.[62] used a split tool with an active rear part to obtain the stress distributions while machining a nickel-chromium steel. They used carbide tools with 0^0 rake angle over a wide range of cutting conditions(undeformed chip-thickness 0.16, 0.254 and 0.356mm and cutting speeds 30, 45, 60, 90 and 120m/minute). They used a smoothening technique in order to take into account experimental variations in cutting forces. Their results indicated that in all cases, the general form of stress distributions were similar in that the stresses were constant near the cutting edge after which they decreased to zero, the length of the constant portion of the normal stress distribution being equal to that over which the shear stress also remained constant.

Buryta et al.[82] and Buryta[80] carried out a comprehensive experimental investigation using a split tool having active front and rear parts to obtain the stress distributions while machining brass, stainless steel and medium carbon steel using carbide tools with a -5^0 rake angle. They had taken the effect of ploughing force while determining the stress-distribution at the chip-tool interface. It was argued that

in calculating the tool-chip interface stresses, only those forces actually acting at the interface should be used. The values of the ploughing forces were estimated from a set of experimental forces by an extrapolation method and subtracted from the measured split tool forces before calculation of the interface stresses were made. The shear and normal stresses in this study were found to remain constant near the cutting edge after which they decreased to zero. The constant portion of the shear stress was found to be much longer than that of the normal stress.

Childs et al.[74] used a modified split-tool technique which involved two tools with split in the tools not set parallel to the cutting edge, but one at 45^0 and the other at 90^0. The method involved turning a tube with simultaneously activated axial (main) and radial (minor) feeds. The shear and normal stress distributions obtained while machining brass, aluminium alloy and mild steel were found to be constant near the cutting edge. One special feature of normal stress distribution for mild steel was that there was a sharp rise in normal stress near the tool tip.

The composite tool method was adopted by Lee et al.[84] for the determination of stress distribution on the tool face. Unlike split tool tests, there was no air gap between the front and the rear tool. These authors reported a three phase trend of stress distribution both for normal and shear stress. The stresses gradually increased from zero at the chip releasing point and remained constant for a certain portion at the chip-tool interface in the middle and finally increased to a maximum at the tool tip.

Another technique that had been used to determine the stresses involved machining with restricted contact tools(RC tools) where the tool-chip contact length was restricted by removing the rear part of the rake face. Wallace and

Boothroyd[30] used this method to investigate the relationship between the normal and shear stresses while machining an aluminium alloy with HSS tools. But the demerit of this technique is that the chip-formation process in this case is different compared to a conventional tool and as a result, the stresses would be different from that of a conventional tool.

It is evident from the reported experimental investigations that there are a lot of disagreement over the nature of the distribution of stresses at the chip/tool interface. Table .1. summarises some important experimental results. Some experimentally observed pressure distributions are also illustrated qualitatively in Fig.1. Examination of Table.1 and Fig.1 point to some typical characteristic features of the nature of pressure distribution in the natural contact length. These may be stated as follows:-

a) The nature of pressure variation is strongly influenced by the tool / work piece pair.

b) The normal pressure may vary according to any one of the following three patterns:-

    i) It may increase steadily from the chip releasing point and reach a maximum at the cutting edge.

    ii) The normal pressure after rising steadily from the chip releasing point may become uniform over a portion of the contact length adjacent to the cutting edge.

    iii) The normal pressure after rising steadily may become uniform and then may tend to rise sharply towards the cutting edge.

c) The friction stress after rising steadily may saturate to a value k (yield stress in shear of the chip material) and remains so over a significant portion of the contact length or after attaining the maximum value (= k) at approximately half the natural contact length may register a drop over the remaining portion.

d) Over a portion of the contact length adjacent to the chip releasing point where the stresses are predominantly elastic (normally refered to as elastic contact zone) the magnitude of the normal stress may be greater than that of the friction stress or may be less.

e) The coefficient of friction μ is generally found to be greater than 1.0 for machining of steel and aluminium. For free cutting steel and other low melting point metals μ value is found to be less than 1.0.

There also appears to be considerable disagreement over the friction law governing the chip formation process.

The linear friction law $\tau = mk$ has always been preferred by analysts looking into the mechanics of chip formation. Oxley and Hastings[54] have indicated that the frictional conditions along the tool rake face in machining is best represented by the above friction law.

Merchant[8], Lee and Shaffer[12], Zorev[29], Childs[60], Kudo[34] and many others have advocated that the rake friction may be adequately represented by a modified coulomb friction law which may be stated as,

$$\tau = \mu\, \sigma_n \quad \text{at low } \sigma_n \qquad\qquad (1.1(a))$$

and $\quad \tau = k \quad\quad$ at high σ_n $\qquad\qquad\qquad\qquad$ (1.1(b))

TABLE-1 Summary of some experimental data on contact stress distribution

Part-A $\mu < 1.0$

work material	tool material	Experimental method	low stress μ	reference
lead	plastic	Photoelastic	0.2 - 0.7	[42]
lead	plastic	Photoelastic	0.3 - 0.9	[33]
lead-tin	carbide	Splittool	0.6	[47]
steel	carbide	Split-tool	0.6 - 0.7	[62]
free cutting steel	carbide	Split-tool	0.75	[76]
free cutting steel	H. S. S.	Visioplasticity	0.86	[47]
brass	carbide	Split-tool	0.75	[64]
zinc	carbide	Split tool	0.7	[46]
aluminium	carbide	Split tool	0.8	[74]

Part B $\mu \geq 1.0$

steel	carbide	Split-tool	1.6	[64]
steel	saphire	Photo elastic	1.0-2.0	[70]
steel	carbide	Split tool	1.3	[76]
aluminium	carbide	Split tool	1.0-2.0	[47]
aluminium	carbide	Split-tool	1.5-2.0	[64]
copper	carbide	Split-tool	1	[47]
steel	carbide	Splittool	1.8	[74]
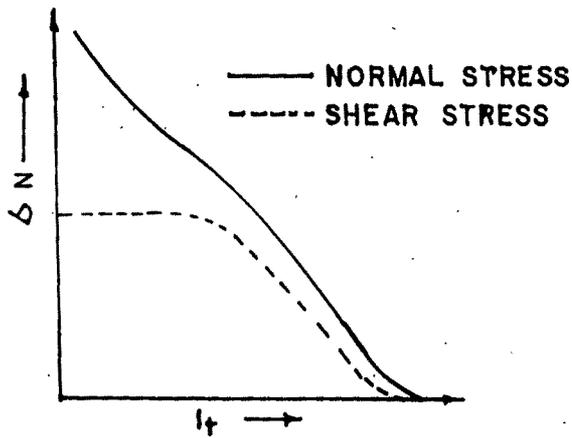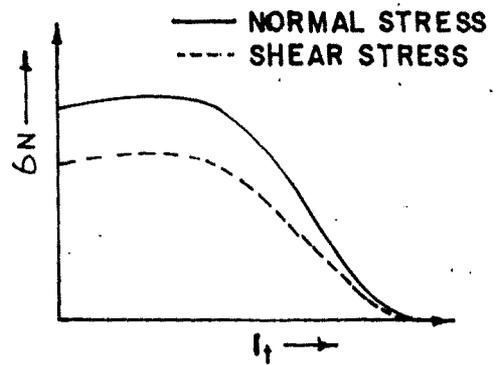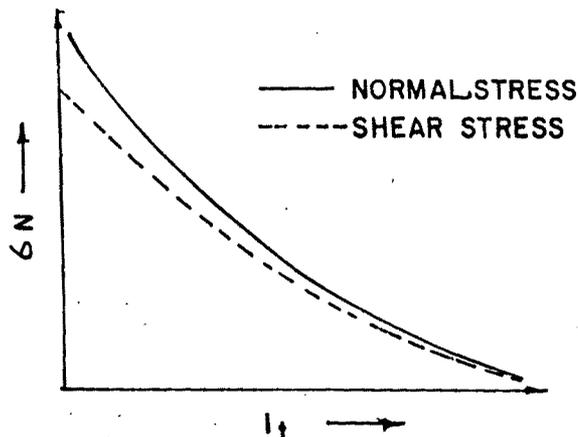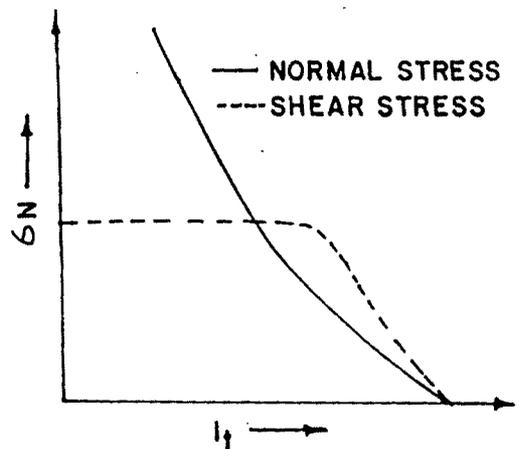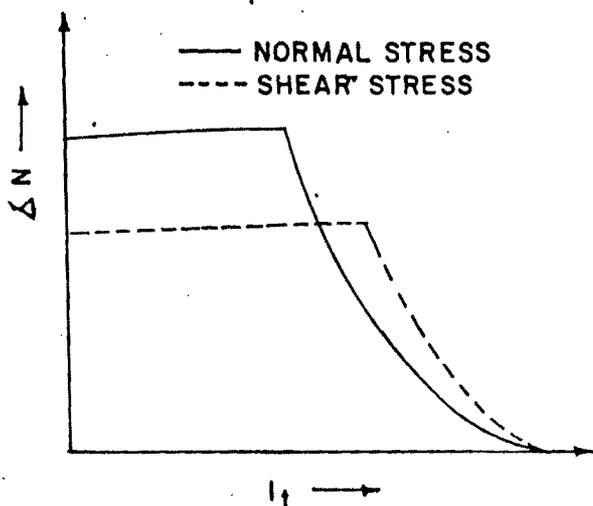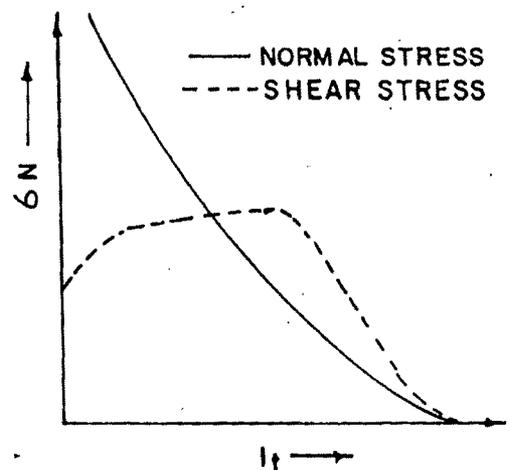
FIG.1.1 PATTERN OF VARIATION OF CONTACT STRESSES AT
CHIP/TOOL INTERFACE

where μ is the low stress level friction coefficient between the chip and the tool, τ is the friction stress and σ_n is the normal stress.

It may be mentioned here that in metal machining very high level of normal stresses act over a relatively small area. This may lead to contact and deformation of asperities on the chip and rake faces. Trent[79], Finnie and Shaw[17] and Shirakashi[64] have therefore postulated that the rake friction is more correctly represented by the adhesion friction law given by the equation

$$\tau = k \left(1 - \exp \left(-\mu \, \sigma_n / k \right) \right) \qquad (1.2(a))$$

It is easily verified that equation 1.2(a) reduces to equation 1.1 at high and low stresses. A modified version of the above equation has also been proposed by Maekawa, Kitagawa and Childs[87] which is written as

$$\tau = k \left(1 - \exp \left(-\left(\mu \, \sigma_n / k \right)^n \right) \right)^{1/n} \qquad (1.2(b))$$

where, n is a constant to be determined from experiments.

The friction law operating at any instant is rather difficult to predict and will depend on the nature of the tool / workpiece pair, rake angle and cutting conditions. But the linear and coulomb friction conditions generally yield a pressure distribution similar to that shown in Fig.1(a), Fig.1(b) and Fig.1(c) (refer to the results in chapter 3 - chapter 6) while the adhesion friction law results in a pressure distribution similar to that presented in Fig.1(d), Fig.1(e) and Fig.1(f).

The problem of prediction of different machining parameters has also been approached using empirical equations, machinability data banks and analytical methods. Empirical models are simple and easy to apply, but it does not provide a deep understanding of the cutting process. Apart from this an extensive new

experimentation is needed each time when the effect of a new cutting variable is to be incorporated in the empirical relation or when a new tool-work material combination is encountered. This is extremely unsatisfactory in the context of CNC shops where the variety of tools and work materials tend to be very large. A number of empirical equations have been developed by various investigators to predict different machining parameters like cutting forces, temperature and tool life. The major contributions in this regard are due to Kronenberg[37], Colding[22], Woxen[6], Rubenstin[56] and Taylor[4].

Banks of machining data have been developed over many years in particular by large industrial companies. One of the earliest data banks was established by Metcut Research Associates who carried out extensive practical conventional and non-conventional cutting tests for American space programme. More recently established data banks incorporate information from in-practice machining rather than from machining tests. The strength of data banks lies in their ability to provide information, concerning the machining of a new component based on previous experience of machining similar components.

The main flaw in the empirical approach is that it does not provide any mechanism to learn from previous machining experiences. In contrast, analytical modellers look for patterns of behavior at a higher level by invoking known relationships borrowed from Physics, Mechanics, Material Science etc.

The first analytical model is the shear plane model due to Merchant and Ernst[7] which is based on the assumption that continuos chip is formed by plastic deformation in a narrow zone that runs from the tool cutting edge to the work-piece free surface. This is shown in Fig.1.2 (a) where AB represents the shear plane.

Across this plane, the work velocity V_c (the tool is assumed stationery) is instantaneously changed to the chip velocity V_{chip}. This requires discontinuity(jump) in the tangential component of velocity across AB equal to V_S as shown in the velocity diagram(Fig.1.2(b)). Two cardinal principles were established by Merchant, which are as follows:

i) Chip Equilibrium (the chip can be considered as a rigid body in translational equilibrium under the external forces acting on it), and

ii) Force-Velocity Collinearity (the shear and friction forces at the shear plane and the tool-chip contact face are collinear and opposite to the shear and sliding velocities at the two faces respectively).

The solution proposed by Merchant is now accepted as the upper bound provided the work material can be considered to be perfectly plastic. Because of the poor agreement of this solution with some of the experimental observations, Merchant[8] introduced the effect of dependency of the shear stress on the normal stress on the shear plane. Lee and Shaffer[12] assumed a plastic zone with uniform stress distribution at the chip-tool interface and applied the slipline field theory(Fig.1.3). The boundaries AB, BC and BD in this case are straight lines. AB and BC are required to be equal for equilibrium of the chip. The hydrostatic pressure is uniform throughout the field and is equal to k, the yield stress in shear. For any given rake angle the only variable in the field angle is ξ, which is determined by the rake face friction stress ratio (τ / k), assumed to be constant over AD ($\tau / k = \cos 2\xi$). Thus for this field each of the non-dimensional machining parameters l_t/t_0, t_1 / t_0 and shear angle β is uniquely determined by τ / k and γ_0. The admissiblity of the above

solution has been examined by Hill[15]. It may be seen that under high friction condition (low value of ξ) and with a -ve rake tool, the shear angle β may be zero or -ve which is physically not tenable. Even with low +ve rake angle, the cutting forces calculated from the above field becomes extremely high. This led Lee and Shaffer to the conclusion that under such conditions a small permanent built-up zone exists. They assumed that this would be stable in character and could be likened to a cap of dead metal which was formed early in cutting and remains constant in shape and size. Kudo[34] modified Lee and Shaffer solution and suggested another field for free machining as shown in Fig.1.4. He also suggested a solution for a curled chip with slipline AB as a circular arc(Fig.1.5). The above field is kinematically satisfied but statically inadmissible for free-machining. Kudo modified the slipline field by replacing concave slipline BD by a convex slipline to satisfy static admissibility. With a convex slipline BD, however, the normal stress at the chip-tool interface decreases from the chip-releasing point to the tool tip, which is contradictory to experimental observation. Kudo finally combined the fields for straight and curled chip to develop another field for curled chip, which is also found to be only kinematically admissible but statically inadmissible.

Dewhurst[55] proposed a non-unique solution(Fig.1.6) for free-machining operation for the case of chip-curling. Initially Dewhurst proposed a unique solution assuming a small triangular plastic region with a curved free surface for a given value of tool rake angle and tool-chip interface shear stress, but with this field he could find no solutions in which the force and moment equilibrium conditions imposed by a free chip could be satisfied. He speculated that possibly in cases where
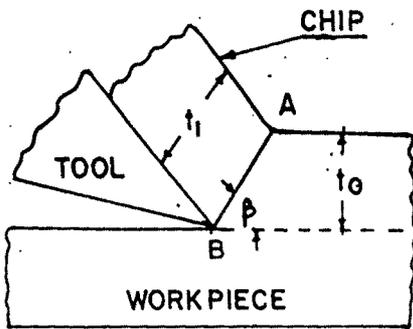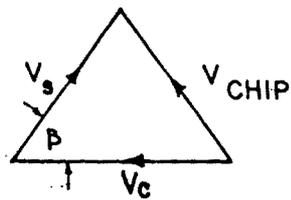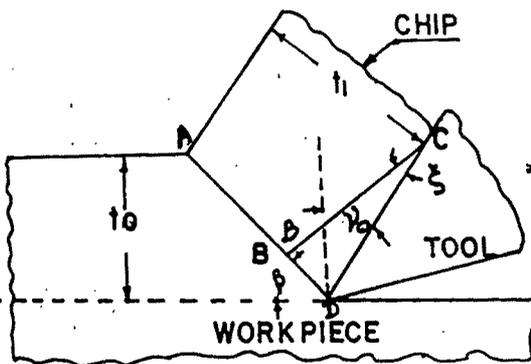
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FIG.1.2(a) SHEAR PLANE MODEL
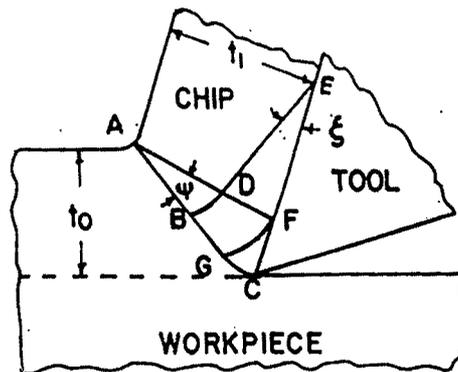

FIG.1.2(b) VELOCITY FIELD

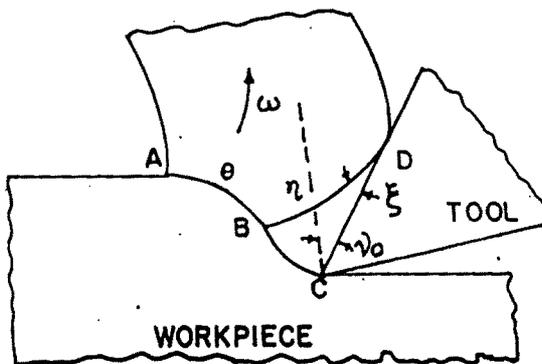FIG.1.3 LEE-SHAFFER MODEL

FIG.1.4 KUDO'S FIELD -I
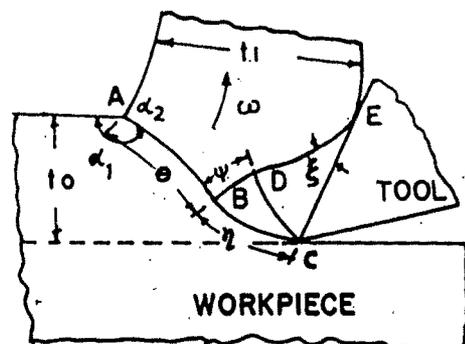

FIG.1.5 KUDO'S FIELD -II

FIG.1.6 DEWHURST'S FIELD

the chip is not free as when machining with a chip-breaker, such solutions might be found. Noting that neither the uniqueness theorem nor the limit theorems(on which the upper bound method is based) given by Hill[16] can apply to a process such as machining with its undefined boundaries, Dewhurst, following Hill, determined a permissible range of solutions which did not give overstressing in the rigid regions. Dewhurst also showed that his field degenerated into the Lee and Shaffer field(Fig.1.3) with a straight shear plane when the hydrostatic pressure at A equaled k. Dewhurst made a number of comparisons between his predicted results with experimental results of other investigators. He obtained excellent agreement between his predicted values with the experimental results reported by Ota et al[21] and Low et al[26]. He further concluded that since the machining process is not uniquely defined, it would be expected that the final steady state for particular cutting conditions will depend to some extent upon the initial conditions.

Dewhurst[59] also analysed the same field for the case of machining with a ram type chip-breaker by imposing an external force in the free chip and found the solution to be non-unique in nature. For a particular position of the chip-breaker, the solutions were found to lie between two limiting conditions, one with the largest chip-thickness, largest contact length and hence largest cutting forces and another corresponding to the field with smallest chip-thickness and contact length. This lower limit was referred as Kudo limit, as Dewhurst's field is reduced to Kudo's field having zero singularity at the tool-tip when the field angle ψ is zero. Petryk[57] developed a stress free boundary operator and introduced a predeformation region in Dewhurst's solution. Childs[60] investigated the effect of elastic contact at the chip-

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tool interface in free machining. He approximated slipline curves as circular arcs and analysed the effect of elastic contact beyond the region of plastic contact by assuming a parabolic normal stress distribution in the elastic zone. His theoretical solutions were found to be more compatible with experimental results with consideration of elastic contact. Shi et al.[78] carried out solutions for orthogonal cutting with ramp type chip-breaker assuming flank wear. They essentially extended Kudo's solution for the case of chip-curling with consideration of a predeformation region at the chip and work-piece boundary. They assumed the contact at the chip and chip-breaker to be elastic with a constant coefficient of friction. Unlike Dewhurst's solution, this solution was found to be unique in nature. Shi et al.[81] also developed a slipline field solution for machining with a tool with groove type chip-breaker and analysed the effect of different variables on the control of chip-flow and other machining parameters.

The finite element method has been applied to analyse machining process in the last two decades by various investigators. The major contribution in this regard are due to Klamecki[50], Usui et al.[64], Iwata et al.[66], Strenkowski[68], Wang et al.[72], Yang et al.[75], Shih[77], [83], Ceretti et al.[85] and others. The advantage of FEM modeling is that the realistic material properties including the effect of large strain, strain rate and temperature can be incorporated in the analysis. But it requires very high speed computational facility with large memory-space. It may be mentioned that in machining process, when the material has crossed the equivalent shear plane, the material gets hardened sufficiently. So in the deformation zone, the material behaves as rigid perfectly plastic. This is the reason why theoritical analysis based on the assumption of rigid perfectly plastic material yields solutions which

are compatible with experimental results. Further it is reported[60] that the theoretical analyses are found to be more compatible with experimental results with consideration of an elastic contact beyond the plastic contact zone.

In the present investigation some slipline field solutions are presented for metal machining when the chip/tool interface friction stress is either constant (τ = mk) or obey's coulomb's law(equation 1.1). The fields analysed are those proposed earlier by Kudo[34] and Dewhurst[55]. It was reported by Kudo that with a concave slipline DB(Fig. 1.5) it was impossible to satisfy the force and moment equilibrium in the chip. It is shown here that by assuming an elastic contact zone beyond the plastically deforming region DC with reasonable elastic stress distribution, a range of forces and moments may be imposed externally on the chip so that the above equilibrium condition is satisfied. For Dewhurst's field(Fig.1.5) solutions are also presented for free chip boundary condition and with the assumption of an elastic contact zone.

It is observed that at low values of friction coefficient μ, the deformation is associated with slipping contact only along the tool face. When μ exceeds a certain critical value(dependent on tool rake angle) both slipping and sticking zones may be present in the plastically deforming region in contact with the tool face. Solutions in the present analysis are given for both these conditions. Machining parameters such as non-dimensional cutting force, thrust force, cutting ratio, radius of chip-curl and normal and shear stress-distributions at the chip tool interface are evaluated for different rake angles and friction conditions. For higher values of μ, the sticking length and sticking ratio are also predicted.

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An analysis of machining with a tool with step-type chip-breaker has been carried out using the slipline field suggested by Dewhurst[59] assuming constant tangential traction($\tau = mk$) at the chip-tool interface. Neglecting friction at the chip-breaker the machining parameters and the force exerted by the chip-breaker is computed. The limits of overbreaking and underbreaking are determined for mild steel from slipline field analysis with reference to empirical equations of Okushima et al.[24].

It must be mentioned here that in the present study slipline field solutions are provided when the rake friction is governed either by the linear friction law $\tau = mk$ or by the non-linear friction law $\tau = \mu \sigma_n$. This is so because all slipline field analysis till date have been carried out with the assumption of the above friction laws and machining parameters have been computed as function of the friction factor m or the friction coefficient μ. But the method of analysis presented here is quite general and can be extended to include any other non-linear friction law.

In chapter II a brief account of the plane-strain slipline field theory is presented and the power series and the matrix method of analysis is explained in detail. The structure of fundamental matrix operators are discussed and equations are presented for calculation of traction and moment for any slipline curve. The coulomb boundary operator to deal with problems involving non-linear boundary condition is discussed. The method of computation and standard subroutines used are briefly described.

In chapter III a slipline field having mixed velocity and stress boundary condition is proposed for orthogonal machining process for the case of chip-curling

with sticking and slipping zones at the chip-tool interface. Coulomb friction is assumed to apply at the chip-tool interface. Length of sticking and slipping regions and the interface stress distribution are computed as a function of the coefficient of friction for different tool rake angles. Results for cutting and thrust forces, chip-curvature and cutting ratio are also presented. The computed values are compared with some experimental results available in literature.

In chapter IV, the slipline field solutions with elastic contact for two different slipline field models are carried out for the case of chip-curling. The above fields were proposed by Kudo[34]. It is shown that with the assumption of an elastic contact zone, it is possible to obtain kinematically and statically viable solutions from these fields. In this analysis, the tangential stress is assumed constant ($\tau = mk$) in the plastic contact zone, where as a power law or exponential distribution of normal stress is assumed in the elastic zone where coulomb friction condition is assumed. The cutting forces, cutting ratio and radii of curvature are computed for different rake angles and friction conditions. The variations of contact lengths with rake angles and interface friction condition is also studied. The distribution of contact stresses in the plastic and elastic zones are also predicted.

In chapter V, the above slipline fields due to Kudo[34] are analysed when coulomb friction condition obtains both in the elastic and plastic contact zones with full slipping or with slipping and sticking contact in the plastic interface. For both the situations, the machining parameters are determined as functions of rake angles and coefficient of friction. The variations of natural contact length, sticking length and sticking ratio are also calculated. The computed values are compared with experimental data available in literature.

In chapter VI, solutions are presented for Dewhurst's field with the assumption of an elastic contact length with exponential or parabolic distribution of normal stress in the elastic zone. A constant ratio of elastic to plastic length is assumed in the analysis. The solutions are carried out with sticking and slipping zones in the plastic contact region(high μ) or with full slipping (low μ) in this region. The variation of natural contact length, sticking length and sticking ratio with variation in rake angle and coefficient of friction is studied. Available experimental data are compared with theory and are found to be satisfactory.

In chapter VII, a slipline field solution for metal machining with a cutting tool having a step-type chip-breaker is carried out assuming constant friction ($\tau = mk$) at the chip-tool interface. The cutting force, thrust force, the force exerted by chip-breaker on the chip, cutting ratio, the radius of the chip curl, the natural contact length and stress-distributions at the chip-tool interface for this case are computed. The analysis predicts the position of the chip-breaker, when chip-forming action in the chip-breaker starts for a particular geometry and cutting conditions. The feeds for under-breaking and over-breaking limits are determined for mild steel with reference to empirical equations of Okushima et al.[24].

In Chapter VIII, the experimental investigation carried out for verification of the present theoretical models is described. Orthogonal cutting tests were conducted using a tool HSS(10% cobalt) tool with zero degree rake angle on round bars of mild steel and aluminium. The cutting force, thrust force, cutting ratio and

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natural contact length were measured and compared with those calculated from the

theoretical analysis.

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