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EXPERIMENTAL STUDIES OF SHEAR ZONES DURING CHIP FORMATION IN METAL CUTTING

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Résumé - Les études des micromécanismes de coupe rapide des métaux sont réalisées à l'aide d'une technique fondée sur le mouvement d'un pendule. Un outil tranchant fait une rayure de la forme d'un arc sur la surface de l'échantillon et la structure interne des zones de cisaillement est figée à l'aide d'un système d'arrêt rapide pendant le processus de formation du copeau. Une équation reliant des paramètres de coupe aux mécanismes de déformation dans les zones de cisaillement est proposée.

Abstract - Dynamic studies of the micromechanisms of metal cutting are performed with a pendulum technique. A tool edge cuts an arcuate groove in the specimen surface, and the internal structure of shear zones during chip formation is frozen with the aid of a quick-stop arrangement. An equation relating bulk cutting parameters to the deformation mechanisms in shear zones is suggested.

I - INTRODUCTION

Dynamic studies of chip formation mechanisms during a metal cutting represent great technical difficulties. A variety of experimental techniques have been tried on a bulk scale. One approach is to choose such a cutting geometry that an external specimen surface is normal to and intersects the bottom of the groove along the grooving direction. It is then possible to record the cutting process dynamically with high speed movie photography. If the specimen surface is chemically etched prior to cutting, the internal microstructure and microstructural changes will be revealed. Generally, however, only macro photographic methods will be applicable, and the spatial resolution will be correspondingly limited. For higher resolution, therefore, when microscope imaging is necessary, it seems impossible to achieve dynamic recording. In this case, an alternative approach is to use some quick-stop arrangement, with the aid of which the cutting process can be stopped in a presumably instantaneous manner. Because of the high inertia involved in bulk cutting, however, high enough deceleration of the tool (or the specimen) is difficult to reach, and often explosive techniques have to be used. The present report describes a new quick-stop technique, based on pendulum single pass grooving. The pendulum grooving technique was primarily developed for studies of abrasive wear /1,2/. It has, however, also been used in basic investigations of metal cutting mechanisms, irrespective of applications.

II - THE PENDULUM GROOVING TECHNIQUE

A commercial Charpy V type impact tester has been modified by attaching a cutting tool, radially protruding from the end of the hammer shaft. During a downswing of the pendulum an arcuate groove is cut in the surface of a specimen, rigidly supported by a holder at the lowest point of the swing (See Fig. 1).

The cutting tool is made of cemented carbide in the shape of a square-based pyramidal tip, with a 90° apex angle, and truncated to a 1 x 1 mm flat top. It is oriented with one facet normal to the grooving direction, which gives a 45° negative rake angle. The groove size is controlled by the adjustable specimen level. All experiments reported here were performed with a tip entrance velocity of 5.6 m/s and an entrance energy of 300 Nm.
The single pass pendulum arrangement makes it extremely simple to design a quick-stop facility: the specimen is attached to the holder with the aid of break pins, and is released and ejected from the holder when hit by, for example, a heel, positioned at the rear end of the hammerhead (see Fig. 2). The specimen ejection is practically instantaneous, and the "frozen-in" microstructure is representative of the state of deformation at the moment of ejection.

The specimen size can be kept small in order to facilitate preparations for metallographic studies. The external bulk appearance of the chip, being extruded at the front end of the groove, can be imaged in a scanning electron microscope, as demonstrated by Fig. 3a. The internal structure can be studied by classical metallographical methods in any section through chip and/or groove (Fig. 3b), and by transmission electron microscopy of thin foils. In fact, the possibility of systematic studies of the relation between cutting parameters, chip formation mechanisms and the resulting microstructure has proved to be one of the most rewarding features of the pendulum technique.
III - EXAMPLES OF RESULTS

The basic mechanism of material removal in metal cutting is the plastic shear in a zone in front of the propagating tool edge. Under appropriate conditions of rake angle, feed, cutting force, etc., a chip is formed and extruded, until it eventually gets separated from the work piece. In the absence of dynamic methods of studying the active micromechanisms of chip formation, the present technique of freezing the internal structure at selected stages of chip formation, provides an indirect method of following the process. Light optical micrographs of etched longitudinal cross sections have proved particularly instructive, making it possible to deduce the entire chip formation mechanism from series of quick-stop experiments.

Fig. 3b is a typical light optical micrograph of a longitudinal section through a chip, demonstrating the principal image layout, used throughout this report. The cutting direction is from left to right, with a primary shear zone extending from the lower edge of the cutting tip (a fragment of which often stays in the groove), and bending upwards, toward the surface ahead of the groove. It can be seen, how the negative rake angle generates the extrusion of material between the primary shear zone and a secondary shear zone at the rake face. A tertiary shear zone is created by the friction force at the interface between the tool flank and the bottom of the groove under formation. The secondary and tertiary shear zones represent tool/workpiece interfaces, and are of less interest from the materials point of view. The primary shear zones, however, are characteristic of the plastic deformation properties of the work piece material itself under the prevailing conditions of dynamic load, and will be studied in some detail below in a series of light optical micrographs.

Fig. 4 shows an early stage of nucleation of a shear zone in a High Strength Low Alloy (HSLA) high speed steel. The propagating tool causes a compressive strain ahead of the rake face, which appears to be mainly elastic. At the lower edge, the stress field gradients initiate the thin shear zone, in which virtually all the plastic deformation, necessary for the extrusion process, will take place. The interpretation of the micrograph in terms of deformation mechanisms requires an understanding of the relations between the micrograph contrast,
created by the topography of the etched cross section surface, and the corresponding internal microstructural details. According to the results of extensive previous studies of this type of material /1-3/ the image can be interpreted as follows. Because of the appreciable amount of deformation that has to be accommodated by the thin shear zone, the strain density as well as the strain rate locally attain very high values. Nevertheless, the structural changes and corresponding image contrast are not primarily associated with dislocation movements, but rather with phase changes. The high strain density will cause heating to local temperatures in the austenite range, and most of the plastic deformation takes place in an austenitic matrix. After the tool has passed (or after the quick-stop event), the shear zone is deactivated and rapidly cooled by conduction to the surrounding material. The cooling is equivalent to a quench, and a martensitic transformation is triggered. The zone will be left with an extremely fine grained martensitic structure that may be as-quenched or annealed, depending on local cooling conditions. This kind of martensite is quite well-known in tribological applications, and often referred to as "friction martensite". It responds only weakly to etching and therefore appears bright ("white etching") in metallographic images. In Fig. 4 the nucleating primary shear zone is revealed mainly by its content of friction martensite, which is found to increase towards the tool edge, and that also the tertiary zone is characterized by its friction martensite.

Fig. 4 Nucleation of a shear zone.

Fig. 5 is an image montage, showing different stages of lamellar chip extrusion from an HSLA steel. In Fig. 5a, a primary shear zone has just reached the external surface, and the extrusion of a chip lamella is beginning. Fig. 5b represents a slightly later stage, when the lamella is being extruded between the primary and secondary shear zones. The well developed friction martensite reveals that both zones operated at high local temperatures, typical of so called adiabatic shear. In Fig. 5c, the extrusion of a lamella is nearly completed. The primary and secondary shear zones have merged into one lamella stalk of typical adiabatic shear, which is just about to be cut off by the lower edge of the propagating rake face. Simultaneously the next primary shear zone is being nucleated.

Fig. 5 Different stages of lamellar chip extrusion in a HSLA steel.
Hadfield steels are characterized by an austenitic structure, which is thermally meta stable at room temperature, and will undergo local, strain-induced martensitic transformation in regions of high stress concentrations. Fig. 6 demonstrates the propagation of a primary shear zone through the austenitic matrix of a Hadfield steel specimen. The stress field initiates martensitic transformation in small scattered regions (hardly visible in light optical micrographs) within a volume around the leading tip of the shear zone. However, no extensive martensite formation can be observed within the core of the shear zone. This may be explained by the fact that, if local plastic deformation takes place at elevated temperatures, the austenitic phase will be thermally stable, effectively preventing strain-induced martensitic transformations. After the passage of the tip, the temperature is again low, but then the local stress field has also passed, and no strain-induced transformation can be initiated.

![Fig. 6 Propagation of primary shear zone in a Hadfield steel.](image)

**IV - DEFORMATION MECHANISMS IN SHEAR ZONES**

The pendulum technique inherently offers the opportunity of defining and measuring cutting parameters, which can be related to the localized deformation mechanisms within the shear zones in terms of dislocation mechanics. Detailed descriptions can be found in e.g. references 1 and 2. A brief summary is given below with special emphasis on shear zones in metal cutting applications.

**IV.1 - Specific grooving energy**

The energy $E$ consumed in making a groove (the grooving energy) is experimentally determined from the difference between the downswing and upswing angles of the pendulum shaft, and can be read from a gauge, which is standard equipment on all impact testers. $E$ has been found to be related to the mass $W$ of the chip (the specimen weight loss) by a power function

$$E(W) = k \cdot W^q$$  \hspace{1cm} \text{(4)}

The energy $e = E/W$, consumed in removing the unit mass (the specific grooving energy) has been found to be a measure of the resistance to grooving. Logarithmic plots of measured $e$ values as a function of $W$ (i.e. for different groove sizes) for a material,

$$e(W) = k \cdot W^{q-1}$$  \hspace{1cm} \text{(2)}

yield intervals of straight line segments, from which experimental values of $k$ and $q$ can be obtained for each $W$ interval. The $k$ and $q$ values characterize the $e$-$W$ relation of a material completely. Therefore, it is of great interest to relate these originally empirical parameters to the deformation behavior of the material.
Specific grooving energy related to localized deformation in shear zones

The process of deformation by shear zones is mainly characterized by the pronounced spatial inhomogeneity of the deformation. In fact, because essentially all the deformation is concentrated to the small volume within the shear zones, it is the maximum local strain density, rather than the total strain, that determines the dislocation mechanical behavior of the material. In an experimental study of a HSLA steel, heat treated to four different hardness levels, measured $k$ values were plotted versus the corresponding $q$ values as shown in Fig. 7.

Each point corresponds to one groove, and numbers 9-12 refer to successively lower hardness values of the steel. The $q$ axis is subdivided into three intervals, I corresponding to homogeneous deformation of the chip, II to the formation of shear zones, and III to fully developed adiabatic shear zones. Experimentally, these morphological variations were achieved by increasing the groove size (maximum chip thickness). The curve shape of Fig. 7 suggests the following dislocation dynamical interpretation.

$k$ may be related to the local shear stress, acting on the dislocations in the most favorably oriented slide system in a shear zone. Similarly, $q$ may be associated with the local strain density in the zone. The $k(q)$ curve then represents a stress-strain curve, with a hardening peak in interval II, describing a balance between work hardening and dynamic softening. In interval I the strain density is low, and work hardening is a predominating low-temperature characteristic. A softer material work hardens more easily, giving the 9-12 sequence in Fig. 7. For increasing strain density ($q$), however, the local temperature increases, and softening by dynamic recovery will play an increasingly important role. At the transition to interval II softening predominates, and the $k(q)$ curves passes a maximum. Interval III, finally, corresponds to high temperature adiabatic conditions. Dynamic recrystallization has drastically reduced the effect of previous structural obstacles to dislocation movements, such as precipitates, grain boundaries, etc. The result is a catastrophic softening, that highly reduces the influence of the structural hardness differences, and the points corresponding to the four different hardness levels are closely spaced in interval III of the diagram. Still, however, the same sequence (9-12) is maintained.
V - CONCLUSIONS

The single pass pendulum technique offers unique possibilities of quasi-dynamic studies of high-strain and high-strain-rate deformation mechanisms during metal cutting. The development and operation of shear zones can be followed in detail.

It is possible to work out an equation, relating the specific grooving energy to the weight of a chip, produced by a pendulum stroke. This equation contains two measurable empirical parameters, which can be used for a dislocation mechanical description of the deformation within shear zones.

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