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FLOW OF WORKPIECE MATERIAL IN THE VICINITY OF THE CUTTING EDGE

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Abstract—Experiments designed to simulate cutting when the depth of removal is less than the cutting edge radius reveal that a "dead-metal" cap forms in the wedge-shaped space between the cutting edge and the workpiece surface. This is distinctly different to the mechanism proposed elsewhere to account for observations made when cutting under normal conditions i.e. when the depth of the removed layer is large compared to the cutting edge radius. The present paper establishes that notwithstanding observations made during these simulated cutting experiments, events observed in normal cutting are entirely consistent with a mechanism in which a thin layer of workpiece material is first extruded below the tool and subsequently recovers elastically thus establishing contact between the workpiece and a portion of the tool clearance face.

NOMENCLATURE

The following nomenclature is in addition to that given in the text:

F_c	cutting force component in the cutting speed direction
F_v	cutting force component perpendicular to the cutting speed direction
Φ	Merchant shear plane angle
S	shear stress which acts on the lower boundary of the primary deformation zone
p_1	mean normal stress which acts on that part of an artificial lower boundary which lies in the cutting speed direction (see [3])
H_0	hardness of the uncut workpiece material
$(h_m)_s$	hardening resulting from workpiece transit through a tensile region ahead of the tool
Δ_s	depth of hardening associated with $(h_m)_s$
Δ	depth of sub-surface workpiece hardening

INTRODUCTION

SARWAR and Thompson [1] have concluded that in sawing the depth of workpiece removal per tooth, t_1, is often considerably less than the tooth cutting edge radius, R. More recently [2] they have considered the extent to which the modes of workpiece deformation in the vicinity of the cutting edge (which have been mooted for cutting when $t_1 \gg R$) are applicable when $t_1 < R$. Among the proposals they considered is one by Connolly and Rubenstein [3] according to which it is suggested that a thin layer of workpiece material is extruded below the cutting edge and then recovers elastically, thus establishing contact with the clearance face for a distance commensurate with full recovery (Fig. 1).

In order to determine which, if any, of the several proposals is applicable to removal when $t_1 < R$, Sarwar and Thompson performed cutting tests using tools of cutting edge radii of the order of 30 times greater than those usually found on cutting tools. With radii of such magnitude they calculated that readily measurable heights of recovery would occur *if* the extrusion–recovery mechanism were operative.

In the event, they found that a dead-metal cap formed ahead of the cutting edge and that no measurable recovery occurred (Fig. 2) i.e. the extrusion–recovery phenomena did not occur under their experimental conditions. [Unfortunately, their experimental conditions differed from those usually adopted not only in that the cutting edge radius was greatly increased but that, simultaneously, the cutting speed was greatly reduced; accordingly we cannot know the extent to which the observed phenomena are to be attributed to a decrease in the t_1/R ratio or to a decrease in cutting speed. For the purposes of the present considerations, we will assume that provided the reduction in

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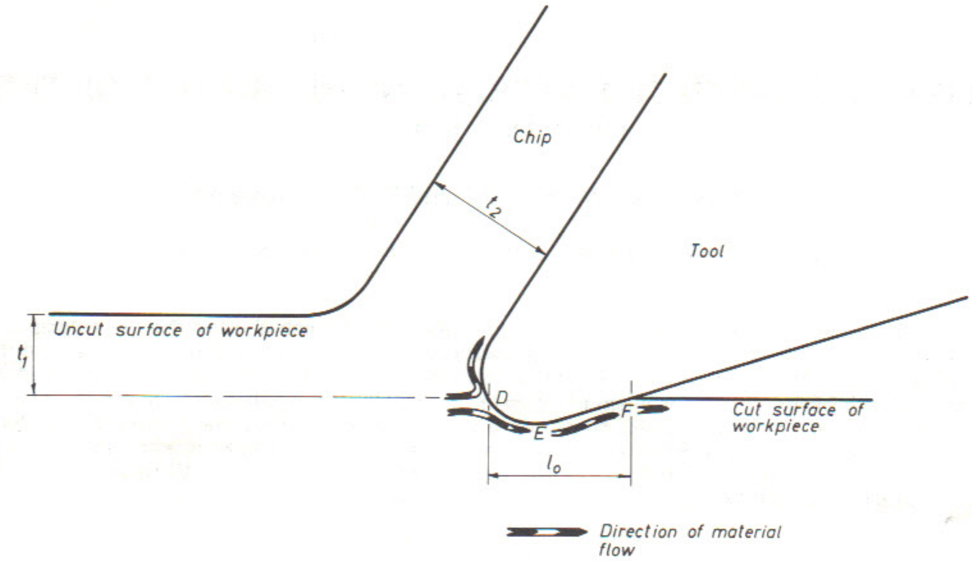

FIG. 1. Illustration of the "extrusion–recovery" mechanism in the vicinity of the cutting edge proposed for cutting when $t_1/R \gg 1$.

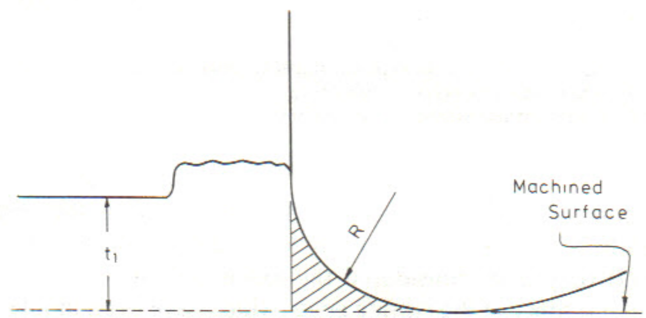

FIG. 2. Illustrating the "dead-metal" cap observed in simulated cutting when $t_1/R \sim 1$.

cutting speed (and hence, in cutting temperature) does not result in the workpiece exhibiting brittle characteristics, any changes in workpiece deformation behaviour are to be attributed, primarily, to changes in t_1/R.]

The observation made by Sarwar and Thompson is consistent with one of two conclusions viz., either

(a) the extrusion – recovery mechanism does occur when $t_1/R \gg 1$ but does not occur when $t_1/R < 1$, or

(b) the extrusion – recovery suggestion is invalid for all values of t_1/R.

Sarwar and Thompson do not consider this point explicitly, nor is it clear from [2] to which view they incline.

Fortunately it is relatively simple to decide between these alternatives for if we can show that phenomena observed in cutting with $t_1 \gg R$ are completely consistent with the extrusion – recovery mechanism then (a) must be true — otherwise (b) is true. In fact, the crucial question is "does or does not recovery occur?" Since recovery manifests itself as tool/workpiece contact over part of the clearance face, this question can be re-phrased as "are cutting phenomena sensitive to changes in tool clearance angle and, if so, is the observed dependence on clearance angle consistent with the extrusion – recovery model?" The experiments and results reported here are aimed at answering these questions.

THEORY

The extrusion – recovery model has been fully described in [3] and need only be briefly reviewed here. Experiments performed with a set of cutting tools having rake angles in the range 0° to −75° have revealed that there exists a rake angle (the critical rake angle, α_c) so negative that chip formation becomes impossible and workpiece material is extruded [4]. For narrow tools, material is thrown to the side but if the tool is wide, material flows below the tool as well.

No cutting tool can be perfectly sharp and the cutting edge can be represented as an arc of a circle of radius R (Fig. 1). If D is the point on the cutting edge contour at which the tangent makes an angle α_c with the vertical, then the horizontal line through D represents the partition boundary; all material above the line becoming, eventually, part of the chip while the thin layer below D flows below the cutting edge.

We may regard this as an extrusion process, the two faces of the "die" being the lower face of the tool and the bed of the machine. Since the layer passing below the tool is very thin (5×10^{-7}m) while the workpiece is very much thicker, this corresponds to extrusion at a very low reduction ratio — for example, if the workpiece thickness were only 25 mm, this would represent a reduction ratio of 2×10^{-5}. Under such circumstances the plastic field will be localised (in the region immediately below the tool) and will be entirely surrounded by an elastic field so that after emerging beyond E, the point of greatest constriction, recovery will be complete, the workpiece losing contact with the clearance face of the tool at the point F.

The horizontal projection of the contact length DEF is $l_o = R \operatorname{cosec} \beta[1 - \sin(\alpha_c - \beta)]$ where β is the tool clearance angle. For clearance angles sufficiently small that

$$\sin \beta \simeq \tan \beta$$

we may write

$$l_o \simeq R\,[\cos \alpha_c + (1 - \sin\alpha_c) \cot \beta] \tag{1}$$

Assuming that there exists a hydrostatic pressure, p_m, acting over the tool/workpiece contact region and that the extruded layer is in frictional contact with the tool (coefficient of friction = μ) it was shown [3] that for an unworn tool in orthogonal cutting, a cutting force element would arise by virtue of this extrusion – recovery mechanism which would have components F_c' and F_v' along and perpendicular to the cutting direction. These are given by

$$F_v' = p_m W l_o$$
$$F_c' = \mu p_m W l_o$$

where W is the width of tool/workpiece engagement.

Subsequently [5,6] it was shown that if the extrusion – recovery mechanism applies then both the surface hardness, H_m, and the depth of sub-surface workhardening, Δ, of a workpiece cut orthogonally would be attributable, in part, to this mechanism. In this way contributions to the surface hardening $(h_m)_o$ and to the depth of hardening Δ_o would arise, both of which were shown to be proportional to l_o.

It follows that if, as suggested in [3], the extrusion – recovery model is a valid representation of events occurring during cutting leading to continuous chip formation then F_c', F_v', $(h_m)_o$ and Δ_o should all be proportional to l_o, where l_o is given by equation (1).

Albrecht [7] has shown that the cutting edge radius ground on cutting tools depends on the included angle of the tool so that for a set of tools all having the same rake angle but having different clearance angles, the length l_o will decrease as the clearance angle increases both directly [via the change in the cot β term of equation (1)] and indirectly [via the change in R]. In practice we cannot express l_o in terms of β since we lack the functional relation between R and β. Fortunately this is not particularly detrimental since our present objectives will be attained if we can show that F_c', F_v', $(h_m)_o$ and Δ_o

(i) each decrease as the clearance angle increases, and
(ii) are proportional to each other (since each must be proportional to l_o if the extrusion – recovery phenomenon occurs).

The primary aim of the present work is to examine the validity of (i) and (ii) — thereafter ancillary evidence will be adduced.

EXPERIMENTAL DETAILS

The experimental procedure adopted in the present work is virtually the same as that fully described in Haslam and Rubenstein [5] so that only a brief description of the method will be given here. Specimens of the workpiece material, aluminium alloy B.S. 1476, HE9 WP (the specification of which is given in the reference cited), in the form of rectangular plates are ground, lapped, polished, and annealed. They are then clamped together, in pairs, and are subjected to a one pass orthogonal planing operation at a cutting speed of 2.25 m min^{-1} using a 30° rake angle H.S.S. tool. The specimen holder is rigidly fixed to a dynamometer so that the cutting force components are recorded and the chips are collected for chip thickness measurement.

After being cut, the specimens are parted and a micro-hardness survey is conducted in the surface region on the "inside" surface of one of the plates. By extrapolation, the Knoop hardness at the surface (H_m) and the depth of the zone of workhardening (Δ) are obtained.

RESULTS AND DISCUSSION

It follows from theoretical considerations [3,5] that the following relations are to be anticipated when a ductile workpiece is cut orthogonally:

$$F_c = F_c' + WSt_1 (\cot \Phi + 1) \quad (2)$$

$$F_v = F_v' + Wp_1t_1 (\cot \Phi - 1) \quad (3)$$

$$H_m = H_o + (h_m)_o + (h_m)_s \quad (4)$$

$$\Delta = \Delta_o + \Delta_s. \quad (5)$$

The terms $(h_m)_s$ and Δ_s are each proportional to $t_2 \sec \alpha$ where t_2 is the chip thickness and α is the tool rake angle. Since the chip thickness ratio is fixed if the rake angle and cutting speed are constant, it follows that for the cutting conditions adopted in the present work $(h_m)_s$ and Δ_s are each proportional to the uncut chip thickness, t_1, so that equations (4) and (5) become

$$H_m = H_o + (h_m)_o + K_h t_1 \quad 4(a)$$

$$\text{and } \Delta = \Delta_o + K_d t_1 \quad 5(a)$$

where K_h and K_d are proportionality factors. In Figs (3 – 6) empirical data are presented in accordance with equations (2), (3), (4a) and (5a) respectively and can be seen to be in accordance with theoretical expectation.

The intercept values determined from these graphs give, respectively, values for F_c', F_v', $H_o + (h_m)_o$ and Δ_o and since $H_o = 216$ MPa, we can determine the values of $(h_m)_o$.

In Fig. 7, the empirical values of F_v', $(h_m)_o$ and Δ_o are presented against F_c' from which it can be seen that

(i) each decreases as the clearance angle increases and
(ii) they are proportional to each other

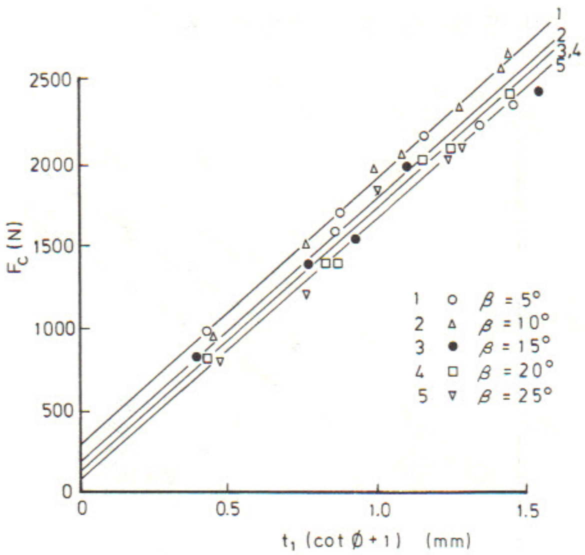

FIG. 3. Orthogonal cutting data presented in accordance with equation (2). Workpiece: Aluminium alloy, tool: H.S.S., cutting speed: 2.25 m min^{-1}, rake angle: 30°, clearance angle: varied.

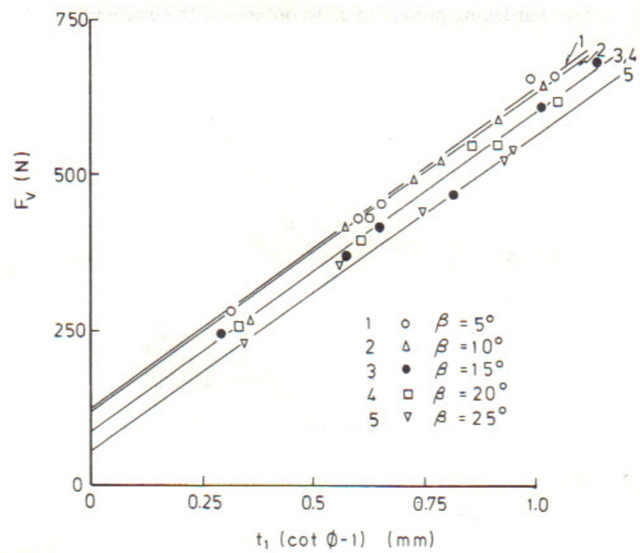

FIG. 4. Orthogonal cutting data presented in accordance with equation (3). Conditions as for Fig. 3.

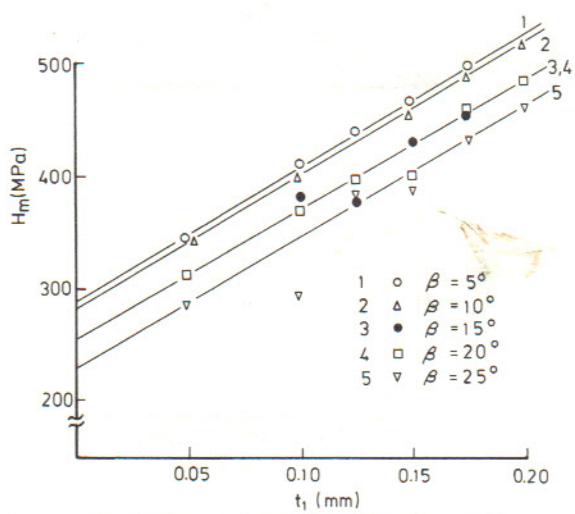

FIG. 5. Surface hardness data presented in accordance with equation (4a). Conditions as for Fig. 3.

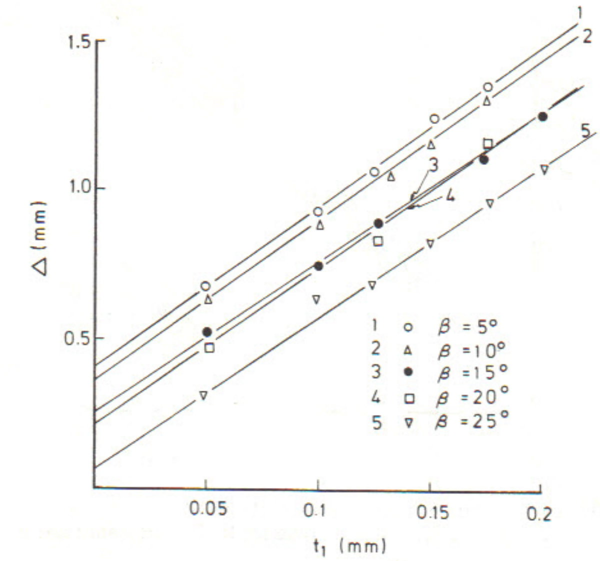

FIG. 6. Depth of sub-surface hardening presented in accordance with equation (5a). Conditions as for Fig. 3.

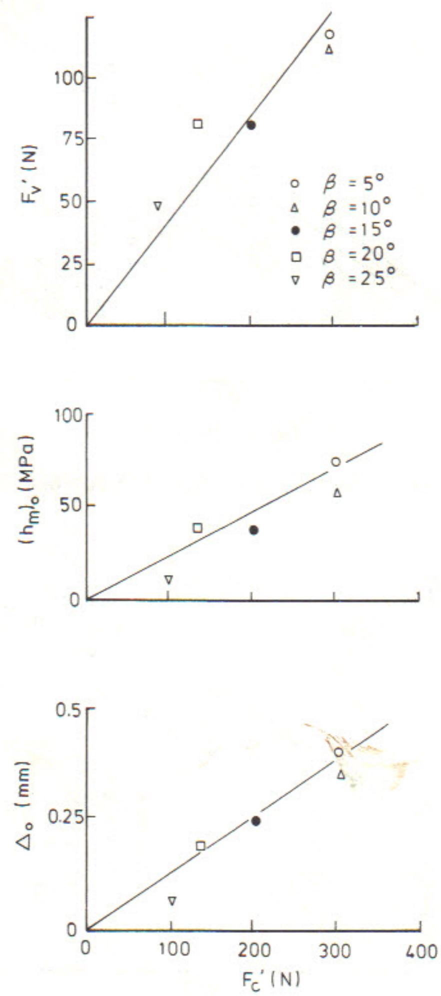

FIG. 7. Values of F_v', $(h_m)_o$ and Δ_o each presented against the corresponding value of F_c'. Conditions as for Fig. 3.

i.e. F_v', F_c', $(h_m)_o$ and Δ_o all behave in exactly the manner to be anticipated if the extrusion – recovery mechanism occurs.

Thus, notwithstanding the observations made by Sarwar and Thompson when cutting under conditions such that $t_1/R < 1$, empirical observations made when cutting such that $t_1/R \gg 1$ are entirely consistent with the conclusion that the extrusion – recovery mechanism is occurring.

It is instructive at this point to examine data presented by Sarwar and Thompson in their Fig. 9b [2]. Extrapolating the curves for the "sharp tool" to $t_1 = 0$ gives $F_c' \simeq F_v' \sim$ 500N. Since we have seen that for a sharp tool (i.e. $t_1/R \gg 1$) the extrusion – recovery mechanism applies, it follows that zero removal corresponds to $t_1 \sim h$ where h is the depth of material extruded below the cutting edge i.e. $h = R(1 - \sin \alpha_c)$. Assuming that $\alpha_c \sim 65°$, $t_1/R \sim h/R \sim 0.1$. For comparison Sarwar and Thompson find that when cutting with tool for which $R \sim 0.8$mm (i.e. something like 30 times the cutting edge radius of a sharp tool) $F_v \sim 1700$N at $t_1/R \sim 0.1$.

It would seem reasonable to expect F_v to be proportional to R so that if the mechanism found to exist at $R = 0.8$ mm were to apply when cutting with a sharp tool we would anticipate that F_v would be of the order of $1700/30 \simeq 60$N. In contrast, as we have seen, Sarwar and Thompson's data indicate a value of 500N.

CONCLUSIONS

The considerations detailed above lead us to conclude that

(i) phenomena observed when cutting with a set of tools having clearance angles ranging from 5° to 25° are entirely consistent with the suggestion that under normal cutting conditions, a thin layer of workpiece material is extruded below the cutting edge which thereafter recovers elastically, thus establishing contact with part of the clearance face;

(ii) these observations are completely incompatible with the mechanism observed in [2] when "scaled-up" cutting tests were performed in which exaggerated cutting edge radii and t_1/R ratios less than unity were adopted;

(iii) the feed force component obtained in "normal" cutting tests is about 10 times that which would be expected if the "dead-cap" mechanism observed in "scaled-up" tests were to occur.

In consequence, the over-riding conclusion is that the mechanism observed to occur in "scaled-up" cutting tests with $t_1/R < 1$ is not that which occurs under normal cutting conditions, i.e. when $t_1/R \gg 1$ and R is of the order of 25 μ.

REFERENCES

[1] P. J. Thompson and M. Sarwar, *Proc. 15th Int. MTDR Conf.* p. 217 (1975)
[2] M. Sarwar and P. J. Thompson, *Proc. 22nd Int. MTDR Conf.* p. 295 (1981).
[3] R. Connolly and C. Rubenstein, *Int. J. Mach. Tool Des. Res.* **8,** 159 (1968).
[4] C. Rubenstein, F. K. Groszman and F. Koenigsberger, *Proc. Int. Industrial Diamond Conf.*, Oxford, 1966, Vol. 1, p. 161. Industrial Diamond Information Bureau, London (1967).
[5] D. Haslam and C. Rubenstein, *Ann. C. I. R. P.* **18,** 369 (1970).
[6] W. S. Lau and C. Rubenstein, *Israel J. Tech.* **9,** 305 (1971).
[7] P. Albrecht, *Trans. Am. Soc. Mech. Engrs.* **82,** (Series B), 348 (1960).