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THE ROLE OF WORKPIECE MATERIAL IN BRITTLE TOOL FAILURE DURING INTERRUPTED CUTTING

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Abstract

The mechanism of brittle tool failure is extremely complex and is influenced by such factors as tool material, tool geometry, workpiece material and cutting conditions. This paper looks in particular at the role of workpiece material.

Following a general review of brittle tool failure in interrupted cutting it is shown that workpiece materials can be classified into four main groups, each of which exhibit different tendencies with respect to whether failure occurs or not.

Strategies for the selection of optimum cutting tools and cutting conditions are proposed for each of the workpiece material groups.

Nomenclature

- b - width of cut
- i = $\gamma + \omega/2 - \upsilon$
- r - distance of stress element from tool point
- Fa - resultant cutting force in two dimensions
- Ff - feed component of cutting force
- Fv - velocity component of cutting force
- V - cutting velocity
- V_1 - cutting velocity at which rake face pitting ends
- V_2 - cutting velocity at which cutting edge chipping commences
- λ = $\tan^{-1} Ff/Fv$
- β - negative shear angle
- γ - rake angle
- δ - angle of stress element from tool wedge axis
- θ - tool exit angle
- σ_r - radial stress in tool
- σ_{tr} - transverse rupture strength of tool material
- ω - tool wedge angle
- υ = $\tan^{-1} Fv/Ff$

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1. Introduction

It is generally accepted that cutting tools reach the end of their useful life by either a gradual wearing process or some form of catastrophic failure. The former is progressive with time and reasonably predictable, and is therefore, preferred. Cutting tool failure is often unpredictable and is therefore, undesirable, particularly when using automatic or computer controlled machine tools.

Two main modes of cutting tool failure have been identified, brittle and plastic. Plastic tool failure is normally associated with cutting at high material removal rates with tools having little resistance to thermal softening eg high velocity cutting of carbon steels with high speed steel (HSS) tools. On the otherhand brittle failure is normally associated with the use of brittle tool materials for cutting high strength materials eg the cutting of hardened steels with carbide cutting tools. Plastic failure normally occurs during continuous cutting operations which often produce high steady state values of stress and temperature on the tool rake face. While brittle tool failure can occur during continuous cutting under extreme conditions such as the cutting of ultra high strength steels with carbide tools(1), it normally occurs during interrupted cutting and it is this aspect of brittle tool failure which is considered in this paper.

As indicated above, brittle tool failure is normally associated with the cutting of high strength or hard materials during interrupted cutting. There are however, occasions, particularly under certain conditions, when brittle tool failure occurs during the interrupted cutting of relatively low strength materials. The work presented here looks at four main groups of workpiece material and considers whether or not, and under what conditions, brittle tool failure occurs. Some consideration is also given to how a knowledge of the role workpiece material plays in brittle tool failure during interrupted cutting can be used to establish appropriate strategies for the selection of cutting tools and cutting conditions during computer controlled cutting.

2. Brittle Tool Failure During Interrupted Cutting

2.1 Basic Mechanism of Brittle Tool Failure

The mechanism of brittle tool failure is generally regarded as the initiation and propagation of cracks in the cutting tool material which lead to chipping at the cutting edge. The resulting damage can be on a macro or micro scale. In the former case the cutting edge is damaged to such an extent that effective cutting can no longer continue. With chipping on a micro scale cutting is often still possible for some time and the result can be regarded as an acceleration of the normal tool wear process. However, once micro chipping occurs, cutting forces and hence stresses increase which often leads to macro chipping and instant failure. It is pertinent to note that when interrupted cutting the flank wear scar on the tool often exhibits the evidence of some form of micro chipping and in these cases whether the tool reaches the end of its useful life by virtue of the level of flank wear or macro chipping depends on the cutting conditions and the geometrical configuration of the tool and workpiece.

2.2 General Influence of Entry/Exit Conditions

It was observed by researchers at an early stage that, compared to continuous cutting under the same conditions of velocity, feed and depth of cut etc, interrupted cutting led to a shorter tool life and/or a greater incidence of catastrophic failure. It was initially thought, particularly with respect to tool failure, that the main cause was the initial impact as the tool contacted the workpiece on entry. Fig.1 depicts the entry into the workpiece of a milling cutter and indicates that, depending on tool geometry and the orientation of the tool and workpiece, initial contact between tool and workpiece can be at a point, along a line or over an area. Experimental results obtained during face milling suggested that the tool life was

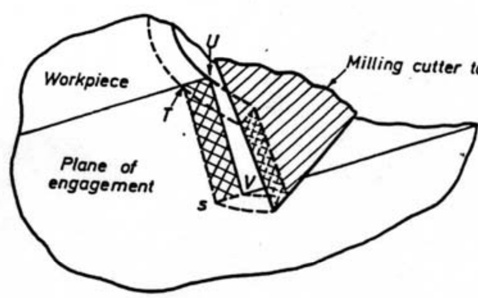


Fig.1 Entry of Milling Cutter into Workpiece

influenced by the entry angle of the cutter and was attributed to the form of initial contact between tool and workpiece. Kronenberg(2) explained his results by introducing the concept of the 'partial time of penetration' while Opitz and Beckhaus(3) obtained a correlation between face milling cutter life and the so-called 'partial area of engagement'. Gilbert(4) suggested that the exit conditions ie how the tool exits from the work also influence tool life/tool failure during milling. Consideration of the experimental conditions used by Kronenberg and Opitz and Beckhaus reveal that as they changed the tool entry angle and hence the conditions of initial contact between tool and workpiece, other parameters, including tool exit angle were also changed. Yellowley(5) recognised this and conducted a series of tool life tests when peripheral milling a titanium alloy which showed that when taking all other factors into consideration and maintaining the tool exit angle constant, tool life was not influenced by the entry conditions. He also observed that when milling many high strength thermal resistant materials tool life was reduced or catastrophic failure occurred when the chip was adhered to the rake face of the tool, a phenomenon he referred to as 'chip stick'.

Other workers including Takayama and Yamada(6) also indicated that the exit conditions could influence tool life in milling. The mechanism normally suggested for the reduction in tool life was the stress amplification at tool entry by the presence of deformed chip material adhering to the tool resulting in the tool chipping. Yellowley postulated that in the final stages of cutting before tool exit tensile cracks form as depicted in Fig.2. He went on to suggest that the processes involved in the latter stages of cutting before

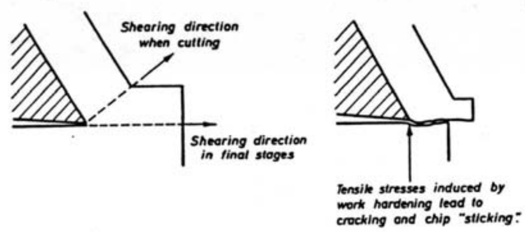


Fig.2 Shearing in Final Stages of Interrupted Cutting as proposed by Yellowley(5)

tool exit are similar to those involved in the blanking and piercing operations, an analysis of which has been carried out by Noble and Oxley(7). Pekelharing(8) studied the influence of tool exit angle on tool life in some detail and showed that not only could the shear plane in the final stages of cutting move to a horizontal position as suggested by Yellowley, it could also move to below the horizontal, a condition he referred to as 'negative shearing'. The resulting chip formation process was referred to as 'foot forming'.

2.3 Negative Shearing/Foot Forming

While Pekelharing noted the influence of the tool exit angle on negative shearing he made no attempt to predict under what conditions negative shearing would occur. Kamaruddin(9) analysed the phenomenon of negative shearing using an approach similar to that used by Merchant in his classical approach to the mechanics of cutting problem. He used the model for interrupted turning depicted in Fig.3 from which he derived the following equation for the

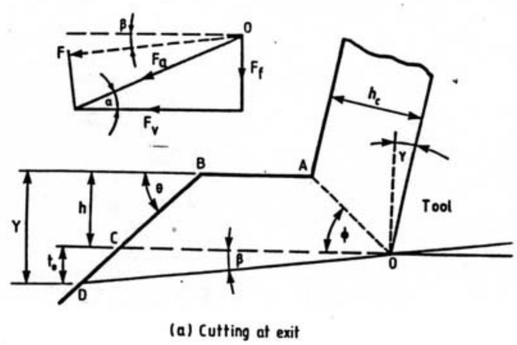


Fig.3 Geometry at Exit in Interrupted Turning

negative shear angle β

$$\text{ie} \quad \beta = \frac{\theta + \alpha - \pi/2}{2} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

Negative shearing will commence when $\beta > 0$, hence the exit angle at which negative shearing commences is given by

$$\theta = \pi/2 - \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

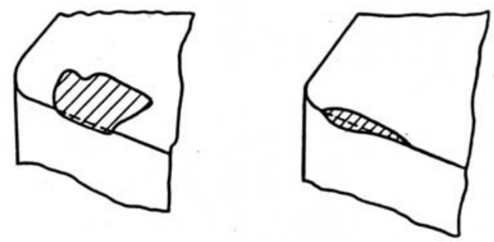
In interrupted turning with a given tool and workpiece the cutting force ratio α is simply a function of the feed per revolution. When cutting carbon steels at relatively low feed rates eg 0·2 mm/rev the value of α is approximately 30° which means that the exit angle θ should be less than 60° if negative shearing is to be avoided. As shown in **(10)** similar expressions to those in equations 1 & 2 can be developed for milling indicating again that exit angles in excess of approximately 60° lead to negative shearing.

When negative shearing occurs the normal cutting process ceases before the tool actually exits from the work. During the very short period of time immediately prior to exit the shear direction changes from along the normal shear plane to along another weaker plane and the remaining part of the chip is effectively stationary on the rake face which facilitates adhesion. The chip at exit when negative shear occurs resembles a human foot, hence the term 'foot forming'.

2.4 Cutting Edge Failure

Brittle tool failure has been correlated with the occurrence of foot forming by a number of workers **(8,9,11,12,13,14)**. However, as indicated by Ghani and Barrow**(14)** it is possible to have foot forming without causing tool failure and the actual form of tool failure often varies. Early tool failure can also occur without foot forming. Whether or not tool failure occurs and the actual form of tool failure when it does occur depends on the tool and workpiece combination and the cutting conditions.

Ghani and Barrow**(14)** showed that when turning a 0·4% C Steel (BS 970 En 8) with an ISO P10 carbide tool failure occurred at all velocities tested when severe foot forming occurred. However, the form of tool failure was distinctly different at low and high velocities. At low velocities the failure mode was referred to as rake face pitting while at high velocities it was termed cutting edge chipping. Both these failure modes are shown schematically in Fig.4. At the lower velocities, it was considered that the



(a) Rake face pitting (b) Cutting edge chipping

Fig.4 Different Modes of Tool Failure when Turning a Carbon Steel.

temperature and pressure in the chip-tool contact zone was such that, during the short period the chip was stationary relative to the tool during the foot formation process, a strong weld was formed between chip and tool. As this weld broke down either when the chip was thrown off at exit or forced off at the next entry, pieces of the tool material were removed. At the higher velocities where the chipping occurs at or near the cutting edge failure was attributed to stress reversal. It is believed that, as postulated by Shaw**(15)** the compressive stress in the tool wedge reverts to a tensile stress on exit due to sudden unloading. The magnitude of the tensile stress being equal to the compressive stress for sufficiently fast unloading rates.

The stress in a wedge shaped cutting tool can be calculated, assuming a concentrated load at the wedge apex, by the well known expression**(16)**

$$\sigma_r = -\frac{2Fa}{b\,r}\left\{\left(\frac{\cos i\,\cos\delta}{\omega + \sin\omega}\right) + \left(\frac{\sin i\,\sin\delta}{\omega - \sin\omega}\right)\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Typical values for σ_r on the rake face when turning a 0·4% carbon steel are shown in Fig.5.

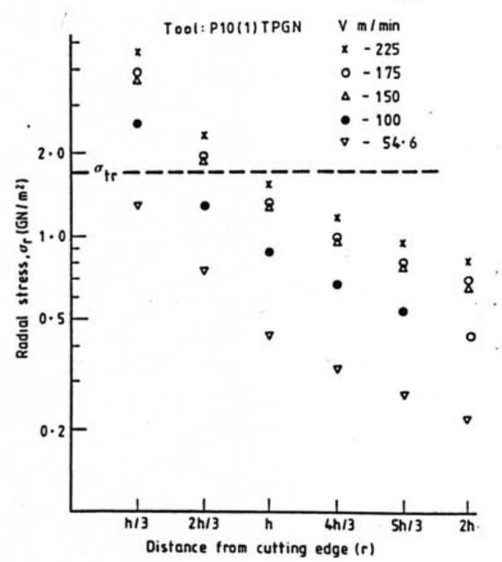


Fig.5 Predicted Radial Stress on Rake Face

It is generally accepted in interrupted cutting that the transverse rupture strength σ_{tr} is a reliable indicator of a tool material's strength. The value of σ_{tr} for a ISO P10 carbide is superimposed onto Fig.5 which indicates that if the compressive stress is reversed failure can occur close to the cutting edge.

Rapid tool unloading is associated with negative shearing and high velocities although Ma(13) using high speed photography did not observe particularly rapid transfer from positive to negative shearing at tool exit. However, there is no doubt that in interrupted cutting tool failure is influenced significantly by velocity as shown by Eldem and Barrow(17). Fig.6, which is taken from reference 17, indicates that at a velocity of approximately 175 m/min there was a dramatic reduction in tool life based on tool failure. Although Eldem and Barrow did not attempt to determine whether negative

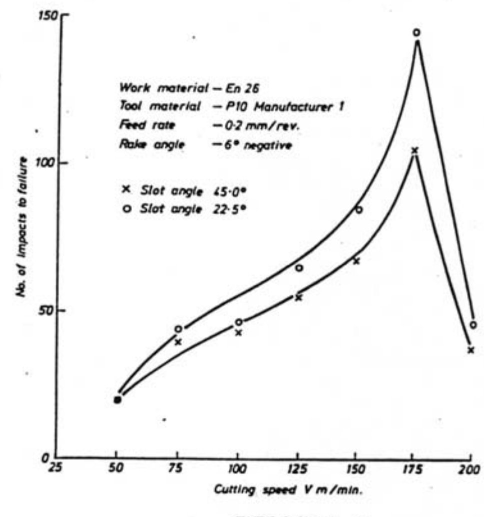


Fig.6 Influence of Cutting Velocity on Tool Failure

shearing occurred, there can be no doubt it was present as the workpiece material was a low alloy steel and the exit angle used 90°.

3. Workpiece Material Classification

As indicated previously four main groups of workpiece material have been identified, each of which exhibit different characteristics with respect to tool failure.

Group I

The main materials in this group are the light alloys (particularly Al alloys), brasses and many forms of cast iron. These materials produce relatively low tool stresses and do not form a particularly strong bond between chip and tool. In view of this even if foot forming occurs neither rake face pitting or cutting edge chipping will occur even when using relatively brittle tool materials. It is pertinent to note that

Kamaruddin(9) observed that while a grey cast iron (brinnel hardness 207) gave a very large negative shear angle there was no evidence of any tool damage at exit.

Group II

This group comprises the carbon and low alloy steels. There is a high incidence of tool failure, by rake face pitting and/or cutting edge chipping, if foot forming occurs. The group can be sub-divided as follows:-

i) Materials which, in the presence of foot forming, produce tool failure over the whole range of practical cutting velocities.

ii) Materials which exhibit rake face pitting at low velocities, no tool failure at intermediate velocities and cutting edge chipping at high velocities (see Fig.7).

iii) Materials which do not exhibit rake face pitting at low and intermediate velocities but give cutting edge chipping at high velocities.

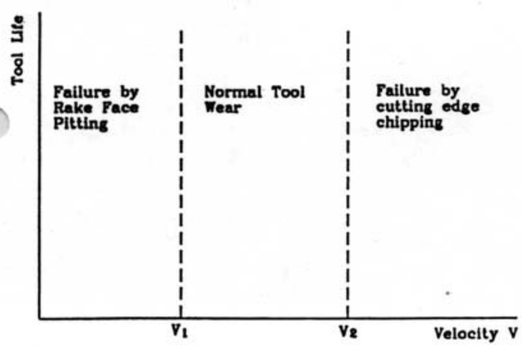


Fig.7 Influence of Velocity on Tool Failure/Tool Wear

For a given tool material rake face pitting is dependent on the strength of the bond between the adhered chip and tool rake face and will therefore vary with workpiece material.

In general those materials which exhibit a significant built-up edge will give problems with rake face pitting. Hence a 0·4% C steel (BS 970 En8) will give greater problems than a Ni-Cr steel (BS 970 En 30B). Kamaruddin (9) showed that in the presence of foot forming rake face pitting occurred at all velocities below V_2 (Fig.7) for En 8 ie $V_1 \geq V_2$ (Material Group II(i)) while for En 30B tool failure only occurred above V_2 ie $V_1 \approx 0$ (Material Group II(iii)). Since the strength of adhesion will decrease with temperature and hence cutting velocity, it is possible, as shown in Fig.7, for there to be a velocity range $V_1 \leq V \leq V_2$ where normal tool wear occurs (Material Group II(ii)).

Group III

Materials in this group include the stainless steels, cobalt alloys, nickel alloys and titanium alloys. When using a relatively brittle tool material failure can occur regardless of whether foot forming is present or not. These materials exhibit very high adhesion between chip and tool and while cutting an austenitic stainless steel (BS 970 En 58C) Ghani and Barrow(14) observed that, in the presence of foot forming, the main cause of failure was chip-tool adhesion at all the velocities tested ie if stress reversal did occur the cutting edge chipping was overshadowed by the large scale pitting due to chip-tool adhesion. They found that when a 'foot' was present the weld between chip and tool was so strong that on leaving the workpiece the chip remained on the rake face with the 'foot' covering the cutting edge. On the next entry the 'foot' became trapped between the cutting edge and workpiece causing tool fracture. With no foot forming, while there was obviously no 'foot' to be trapped, the adhered chip on the rake face caused the tool to be inefficient by obstructing chip flow at the next entry. Ma(13) obtained similar results when cutting a martensitic stainless steel (BS 970 En 56B).

Group IV

Materials in this group are very hard (normally HB > 600) such as the ultra high strength steels and chilled cast iron. Failure can occur regardless of the exit conditions and may even occur during continuous cutting as indicated in (1).

4. Strategies for The Optimum Selection of Cutting Tools and Cutting Conditions

It is obvious from the foregoing that for all the material groups, including the difficult groups three and four, brittle tool failure can almost certainly be avoided by choosing a suitably tough cutting tool ie one whose transverse rupture strength σ_{tr} is sufficiently high. Unfortunately very tough tool materials such as HSS lack hardness and resistance to thermal softening and their use will lead to low material removal rates and hence productivity.

Recent work in the Manufacturing Division at UMIST had addressed the problem of cutting tool and cutting conditions selection in milling operations. This work has highlighted the need for a knowledge of the role the workpiece material plays in brittle tool failure as outlined previously. This work contributes towards the development of a technologically orientated system for the manufacture of milled components called TECHMILL. The system TECHMILL makes extensive use of a solid modeller for feature recognition etc and also of an extensive technological data base for the selection of cutting tools and optimum cutting conditions etc. It is therefore, possible to calculate such factors as tool compressive stress and exit angle in order to select the appropriate cutting tool and adjust the cutting conditions to avoid or minimize the influence of tool failure.

The overall procedure for selecting the optimum cutting tool and cutting conditions for milling operations in the TECHMILL system is extremely complex and a full description of the methods employed etc is beyond the scope of this paper. However, it is relevant here to consider the general strategies involved for the material groups under consideration.

Group I Materials

As indicated previously there are generally no problems with this group of materials and the appropriate cutting tool and cutting conditions can be chosen which produce optimum economic performance.

It is pertinent to note that in the past this group of materials has experienced the greatest industrial use under interrupted cutting conditions of relatively brittle tool materials such as carbide.

Group II Materials

The ideal strategy here is to avoid completely dangerous exit conditions. Although in milling any exit angle greater than 60° is likely to produce negative shearing and hence foot forming as predicted by equation 2, there are usually few problems with tool breakage at large exit angle where the actual cut thickness is small and no problems at an exit angle of 180° where the cut thickness is zero. While for a single straight cut it is possible, once the cutter has been completely engaged, to employ the down milling mode with an exit angle of 180°, this is not always possible in practice, particularly for complex workpieces, and a more complicated strategy is required.

Initially the 'best' tool based on possible material removal rates under ideal conditions is chosen from the data base and the corresponding optimum cutting conditions chosen. The next step depends on whether the workpiece material is in Group II(i), Group II(ii), or Group II(iii).

Group II(i) - In this case $V_1 \geq V_2$ so if the calculated velocity is less than V_1 (Fig.7), the exit angle is calculated and if severe foot forming is predicted an alternative tool is chosen. If the calculated velocity is greater than V_2 the maximum compressive stress on the tool rake face is calculated and compared to the σ_{tr} of the tool material. If σ_{tr} is exceeded then the exit angle is calculated and if severe foot forming is predicted an alternative tool is chosen. As indicated, for this group it is assumed that $V_1 \geq V_2$. However, to date the authors have obtained no definitive evidence, either from their own work or from the work of other researchers, that V_1 can be higher than the velocity at which stress reversal occurs ie $V_1 = V_2$ rather than $V_1 \geq V_2$. In any case the strategy proposed is considered to be adequate since, if severe foot forming occurs and the exit conditions cannot be changed, the only course of action is to select a tougher tool.

Group II(ii) - As indicated previously it is possible to have this intermediate material sub-group, which exhibits a velocity range V_1 to V_2 where no tool failure occurs. However, for the work/tool combination tested by the authors to date, few combinations fall in category II(ii) and the range V_1 to V_2 for reasonable tool life values (≥ 10 mins) is very small. Hence $V_1 \simeq V_2$ and the Group II(ii) materials can for practical purposes be considered to be identical to Group II(i).

Group II(iii) - If the calculated velocity is less than V_2 then the tool is retained.

If the calculated velocity is greater than V_2 then the procedure is similar to that for Materials II(ii) with $V > V_2$ except that in this case if there is severe foot forming there is the option of using the same tool at a velocity $V < V_2$.

While, as indicated above, procedures are adopted which check whether the exit conditions are such as to produce severe foot forming, it should be remembered that in practice, particularly for complex components, the geometrical situation will be such that the cutting geometry will vary as the cutter traverses the work. In view of this part of the cutter traverse will be undertaken using 'safe' exit conditions while part will be undertaken using 'dangerous' exit conditions. While software routines within the TECHMILL system have been developed to optimize the cutter path with respect to exit conditions, in some cases 'dangerous' exit conditions may still occur for a short period of time. Under these circumstances either a less favourable tool will have to be selected or the cutting conditions altered in order to avoid premature tool failure.

As indicated previously using a very tough tool material is likely to lead to significant reductions in material removal rate and this course of action should only be considered when the 'dangerous' exit conditions occur over the majority of the total cutter path. In those cases where the

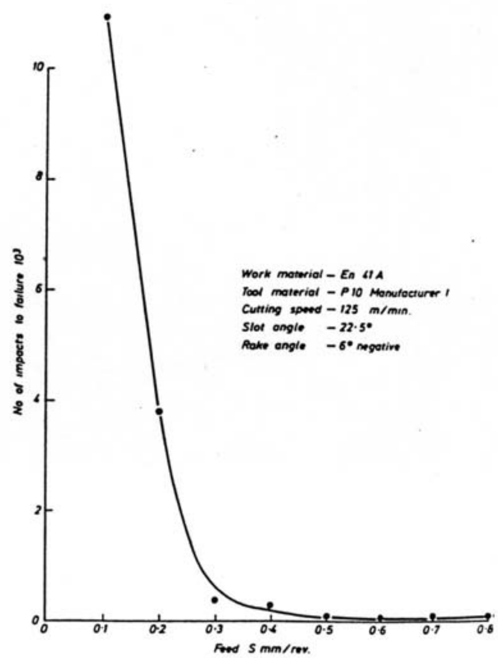


Fig.8 Influence of Feed on Premature Tool Failure

'dangerous' exit conditions only occur over a relatively small proportion of the cutter path length it is better to consider a reduction in feed rate. As indicated in Fig.8 which presents results when interrupted turning with severe foot forming (exit angle = 90°) a reduction in feed significantly reduces the incidence of premature tool failure. In Fig.8 the tool life at a feed of 0·1 mm/rev is approx 6·0 minutes which is quite acceptable if the 'dangerous' exit conditions are only present for a relatively short period of the total time the tool is used.

Group III Materials

Since with this group of materials brittle failure occurs even when negative shearing does not occur there would appear to be little point in checking for negative shearing and foot forming. However, the work of Kamaruddin(9) indicated that when cutting an austenitic stainless steel the chip adhesion and entrapment tended to be more severe when foot forming occurred. Yellowley(5) noted that when using a carbide tool to down mill a martensitic stainless steel at an exit angle of 180° satisfactory tool life was obtained but that the tool life became progressively shorter as the exit conditions became more severe. While the problem of early tool failure can, to a certain extent, be alleviated by reducing feed rates the benefits are marginal, particularly under severe foot forming conditions. In view of this if down milling with an exit angle of 180° cannot be employed it is often necessary to use a very tough tool material such as HSS. In this connection it is pertinent to note that HSS is still the predominant tool material in the aero-engine industry for the miling of such materials as stainless steels and the Co, Ni, and Ti alloys etc.

As pointed out by Kamaruddin(9) the main problem with this group of materials is the obstruction, due to strong adhesion, of adequate chip flow and in this connection positive rake angles give a better performance than negative rake angles. In addition Ma(13) found that strengthening the cutting edge by using a negative land was not a solution as the increased cutting edge strength was more than offset by the increased obstruction to chip flow.

Group IV Materials

These materials present particular problems during interrupted cutting due to their extreme hardness. Adhesion is not a problem here and the exit conditions do not appear to have any significant influence. In view of this there is no need to check the exit conditions. Problems can occur at entry and, as indicated previously, even during continuous cutting. The high hardness demands a tool which is both tough and wear resistant and in view of this a fairly hard and hence somewhat brittle tool material is often preferred. However, some form of cutting edge strengthening is usually required.

5. Concluding Remarks

There is no doubt that a better understanding of the way in which brittle tool failure occurs in interrupted cutting can lead to significant improvements in productivity. It is particularly important to understand the role, where appropriate, of exit conditions on tool failure and, even more importantly, to be able to predict the occurrence of 'dangerous' exit conditions. This allows the use of harder, more wear resistant, tools for those situations where 'safe' exit conditions are predicted.

The classification of workpiece materials into the four groups considered here has proved to be of considerable benefit in developing routines for the selection of cutting tools and the optimization of cutting conditions in milling operations. Using the classification proposed it is possible to reduce computational time by only doing complex geometrical checks of the exit conditions for those materials where exit conditions present a problem.

While, to date, the four material

groups proposed have proved adequate it may well be that further experience with other materials, particularly the many new materials currently being developed, will require the use of further groups or sub-divisions. At present whether or not chip-tool adhesion is sufficiently strong to cause tool failure can only be established by empirical means and further fundamental studies could prove useful.

Based, partly, on the findings reported here the Manufacturing Division at UMIST is currently developing alternative strategies for tool path generation in milling operations. The work to date indicates that these strategies will lead to significant improvements over the commercial tool path generation packages currently available.

REFERENCES

1. J Ellis and G Barrow 'The Failure of Carbide Tools when Machining High Strength Steels' Ann. CIRP Vol.21/1 (1972) p.25.
2. M Kronenberg 'Analysis of the Initial Contact of Milling Cutter and Work in Relation to Tool Life' Trans. ASME, Vol.71 (1949) p.217.
3. H Opitz and H Beckhaus 'Influence of Initial Contact on Tool Life when Face Milling High Strength Materials' Ann. CIRP, Vol.18 (1970) p.257.
4. W W Gilbert ibid. Discussion.
5. I Yellowley 'The Development of Machinability Testing Methods with Specific Reference to High Strength Thermal Resistant Work Materials' PhD Thesis, University of Manchester (1974).
6. H Takayama and A Yamada 'Face Milling of Carbon Steel 550C with Carbides' Study on Carbide Milling No.1, J.Soc. Precis. Mech. Japan Vol.26 (1960) p.674.
7. C F Noble and P L B Oxley 'Crack Formation in Blanking and Piercing' Int. Jnl. Prod. Res. Vol.2 (1963) No.4 p.265.
8. A J Pekelharing 'The Exit Failure in Interrupted Cutting' Ann. CIRP Vol.27(1) 1978 p.5.
9. A G B Kamaruddin 'Tool Life in Interrupted Cutting' PhD Thesis, University of Manchester (1984).
10. G Barrow 'Tool Life in Interrupted Cutting' Proc. 2nd IMCC Wuhan, China 1985.
11. A J Pekelharing 'The Exit Failure of Cemented Carbide Face Milling Cutters Part I Fundamentals and Phenomena' Ann. CIRP Vol.33/1 (1984) p.47.
12. C A van Luttlervelt and H R Willemse 'The Exit Failure of Cemented Carbide Face Milling Cutters Part II - Testing of Commercial Cutters' Ann. CIRP Vol.33/1 (1984) p.51.
13. Y S Ma 'An Investigation of Stress Distribution in Orthogonal Cutting and Tool Pre-Failure Mechanism in Milling Operations' MSc Thesis, University of Manchester (1989).
14. A K Ghani and G Barrow 'Tool Failure at Exit During Interrupted Cutting' Ann. CIRP Vol.34/1 1985.
15. M C Shaw 'Fracture of Metal Cutting Tools' Ann. CIRP Vol.28/1 (1979) p.19.
16. S Timoshenko and J N Goodier 'Theory of Elasticity' McGraw Hill 1951.
17. S Eldem and G Barrow 'Tool Life in Interrupted Turning Operations' Irr. J. Technol. Vol.14 (1976) p.172.