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SOME ASPECTS OF DAMAGE MANAGEMENT FOR CUTTING TOOL MATERIALS

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Abstract

There are two concepts in the title that can be seen as "foreign" to the usual technical language. Both can have several meanings and thus we adapted them "flexibly" to the current needs. One way to understand the term “management” is through its functions: planning (defining purpose and means), organizing (defining tasks and methods), and direction (guidance, controlling), inspection (testing, comparing). It can also mean among other things, standpoint, circumstance, respect, or even character. Regarding the expression “damage management” the intended meaning here is reducing or to preventing damage to the tool, also improving the resistance of the tool material to damage, which besides material selection issues also has design, technology and operational aspects. This article gives an overview of some of these.

Keywords: *tool material, machining, damage resistance, wear, fracture.*

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1. Cutting tool materials and their characteristics

In the realm of tool materials – especially when it comes to machining technologies – the need for increased productivity makes necessary the use -besides of tool steels - of hard alloys, ceramics and superhard materials (**Table 1.**).

Through an appropriate alloying of tool steels we can obtain a decrease in the critical cooling speed that is dependent on the steel’s composition (instead of water cooling, a more desirable oil or air cooling is possible), also the ideal critical diameter can be increased. Furthermore, we obtain those primary and secondary carbides that increase (also at higher temperatures) wear resistance. While primary carbides are obtained through crystallization from the melt, secondary ones are separated during the alloying annealing, the quantity, dispersion and size of these has a defining role in the tool’s hot hardness, damage resistance (wear and annealing resistance) that can be obtained through these. In the case of machining – as a process through which material is removed by using a wedge-like tool – these define the tool life (the machining ability) of the machining tool [1–3].

Table 1. *A possible classification of tool materials*

Tool steels	Hard alloys and false alloys	Ceramics	Superhard materials
Structural steels that can be used as tool materials (case hardenable. alloyable, nitridable, ball bearing steels) and iron casts Unalloyed tool steels, cold shaping tool steels, ledeburite steels, hot shaping steels, high speed steels Austenite ageable steels, martensite anti-corrosion steels, maraging steels	Iron, nickel or cobalt based hard- or super-alloys Powder metallurgy quick steels Hardenable hard metals Hard metals Cermets	Oxide ceramics Compound ceramics Composite ceramics	Cubic borone nitride Artificial diamond Natural diamond

The machining ability of a cutting tool material is understood as its capacity to keep its geometry for a long enough time while under the mechanical and thermal stress caused by machining. Naturally, the machining ability also depends on the working conditions of the cutting wedge, especially on the kind of material that is being machined, the cutting speed, the feed, the depth of cut, the tool geometry and the cutting environment (cooling, lubrication, corrosive effect). **[4]**.

There is a strong connection between the quantity of hard phases that are present in the material and the maximum allowed cutting speed. It is desirable to increase the proportion of hard phases in tool materials, but this direction of development has its limits, therefore besides the quantity of hard phases their quality is also a priority. These on one hand increase hardness, on the other hand, according to the materials that are to be processed, require the use of hard phases that are less likely to dissolve in the workpiece. Another direction in development is the tendency to use the tool materials and the tools for the specific purpose for which they were made **[2]**.

For instance, we can expect High Speed Steels to have good heat conductivity, increased toughness (through Co alloying), hot shapeability (as in the case of twist drills), easy to process, to harden and harden through, increased hot hardness and wear resistance (annealing resistance up to 600 °C), minimal tendency to crack. Therefore, besides the usual steel production techniques, high speed steels are also produced by powder metallurgy (sintering). In steels produced by sintering the quantity and the quality of the hard phases can be more freely determined, therefore they have an increased hot hardness, compressive strength, wear resistance and, due to powder metallurgy technologies, have adequate toughness and shapeability **[1]**.

Interstitial (made up by larger metal atoms and smaller sized non-metal atoms) ceramic compounds are very rigid and therefore very brittle. The characteristics that are important from a practical point of view can be utilized if their hard granules are embedded in a tough material or if they are made into a thin surface layer:

- The first solution is represented by hard metals and cermets. While hard metals are usually WC-based, Co-bonded, cermets (CERamic METals) are typically TiC based and Mo-bonded powder metallurgy false alloys. Hardenable hard metals have a higher wear resistance due to their significant iron and carbon content, their processability comparable to that of tool steels and their carbide content. In fact their characteristics place them between tool steels and hard metals **[1]**.
- A good example for the utilization of the latter is the wear-resistant TiN layer produced through PVD (Physical Vapour Deposition) on the surface of ready made or renewable tools **[5]**.

In the use of ceramics, higher temperatures are allowed and shifts in temperature also occur more frequently. Compound ceramics are not as heat resistant in oxidizing environments as oxide ceramics (since those cannot be oxidized, or burnt any further) but they withstand shifts in temperature more effectively. This is also due to their low heat expansion coefficient (they don't crack when cooling down) and their relatively large heat conductivity (they don't heat up too much from friction).

2. Utilization and damage of tools

The mechanical and thermic effect of tools increases through technological development. On one hand there's an ever increasing choice of materials and, therefore, of the available materials that can increase the mechanical load of the tool. On the other hand, the need for increased productivity requires more intensive processing which in turn increases mechanical load and, more importantly, thermic stress. Finally, new processing technologies are being developed that themselves increase the stress on the tools **[2, 4]**.

The surface layer of the tools encounters a mechanical stress equal to the shaping resistance of the material that it comes in contact with and the tension in the surface layer of the workpiece. We expect tool materials to be both wear resistant and tough. These are characteristics that play out against each other and as such they are in an inversely proportional relationship to each other (**Figure 1.**) **[2]**.

Besides mechanical stress, heat stress also defines the life span of tools to a great extent. The surface temperature of machining tools varies but many non-machining tools and casting tools are also exposed by large, mostly impulse-like heat stress. The attrition of processing tools happens in two principal ways: an unexpected, premature fracture or wear or, a wear that's consistent with its use. Premature fractures can be traced back to two main causes: lack of necessary toughness or a decrease in the yield point at higher temperatures.

Statistical analysis performed on several thousands of tools have shown that wear, loss of sharpness is twice as often the cause of the damage than fracture (chipping). In the case of the more tough quick steel and hard metal, fragmentation and chipping occur almost equally often, because for higher dynamic purposes quick steel is used normally. An improvement in the fact that in a third of the cases the tool is damaged suddenly and in an unpredictable way, is especially necessary in the case of automatic or less supervised (NC, CNC) processing machinery [2].

The martensite transformation-based hardening of tool steels often yields heat treatment cracks. The cause of this lies in the micro-structural mechanisms of crack formation and the inner tensions caused by the heat, both of which depend on the shape and size of the tool. A too rapid and non-uniform heating, a too high austenite heat, an excessive heating and a rapid cooling can also contribute to the formation of cracks. Hardening cracks propagate in an inter-crystalline fashion along the original austenite granule borders. In hardened pieces the cracks often only form during mechanical or chemical post-processing because additional tensions can be caused by whetting, granule dispersion, calendering or curing, which contribute to the cracking of the material [2, 3].

If the degree of wear on a machining tool is too high, the tool can suffer damage due to the fracture or elastic deformation of the leading edge (Figure 2.). Fracture damage is defined as chipping, splintering or cracking. Deformation damage is a change in the shape of the leading edge due to elastic deformation. At machining temperatures it is possible that the material of the leading edge becomes softer than the material that is being machined. In such cases the leading edge is deformed elastically, its material being stripped off by the material of the workpiece. This happens most often in tools made of tool steels but in extreme conditions it can also happen to tools with a hard metal edge [4].

Deformation energy and the friction energy on the front and back surfaces of the tool produces heat during machining. The three deformation zones (Figure 3.) in the chip's root correspond to three sources of heat. The heat generated here advances towards the colder areas, the chipping, the leading edge, the workpiece and it is dissipated into the environment (cooling medium)[4].

At the beginning of the machining, both the workpiece's material and the leading edge are at the same temperature as the environment. From the primary deformation region heat is eliminated through conductivity, radiation but most of all with the material flow. In this region heat always affects new, cooler volumes of materials therefore in the primary deformation region temperatures are relatively low.

The leading edge comes in contact with already heated material parts. In the beginning of the process the cold leading edge still cools them down and it can still dissipate the friction heat. On the contact surfaces the temperature of the leading

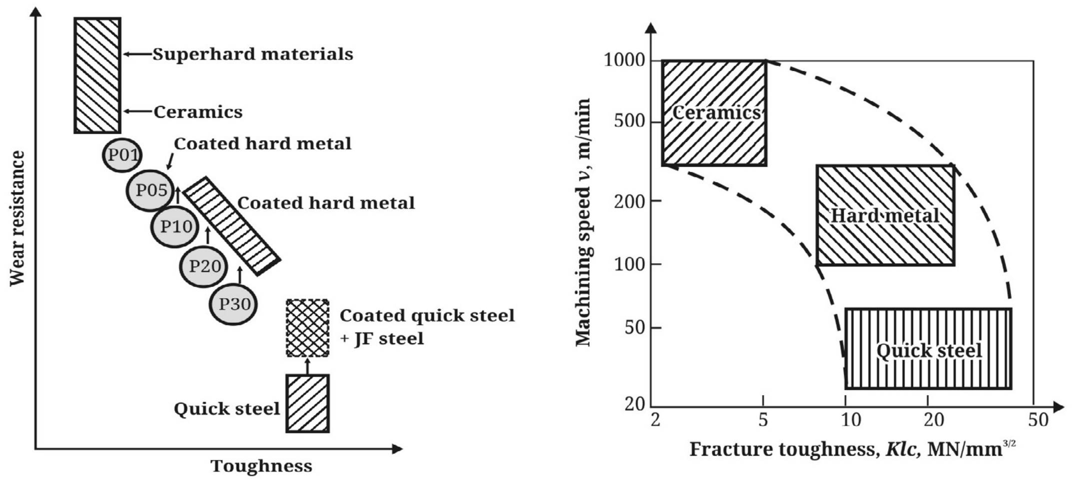


Figure 1. *The relationship between the toughness and wear resistance, also the maximum allowed cutting speed of tool materials*

edge increases quickly and it reaches the surface temperature of the cutaway material parts. Because of the friction, the temperature of the contact surface keeps increasing until it reaches a state of equilibrium.

The maximum temperature place depends on the manner of the chip formation. When cutting tough materials we obtain flowing chips, the heat zone is significantly influenced by the friction heat. Maximum temperatures can be found on the front surface at a given distance from the leading edge. With more rigid materials fractured chips are obtained which break away from the front surface. The friction of the chip with the front surface is moderate and the environment „has good access" to the place of the machining. Therefore the maximum temperatures are on the leading edge or its immediate proximity. The temperature of the leading edge and that of the workpiece is different in the various places on the chipping's root. it is important that we use annealing-resistant tool material and a coolant-lubricant that is effective and prevents undesirable changes in the material structure.

The classification of undesirable differences in continuity that are created during fabrication, processing and usage and that define lifespan can be seen in **Table 2.** Of these planimetric (plane-like, 2D) deviations are especially dangerous as they can become capable of spreading and thus cause fracture **[6]**.

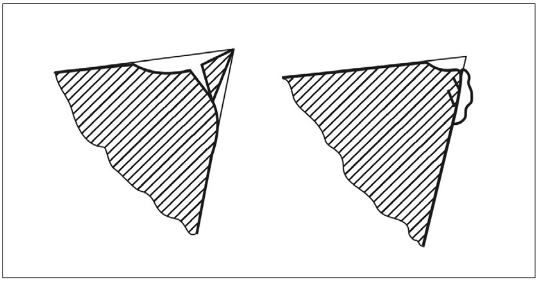


Figure 2. *Fracture (l) and deformation damage (r) of machining tool*

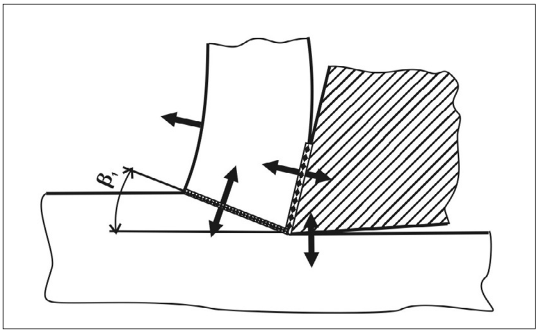


Figure 3. *Places where heat is generated and its dissipation paths in the chip's root*

Figure 4. illustrates the typical mechanical and thermal damage of machining tools pointing out the possible causes and the necessary countermeasures **[7]**. Among these there are suggestions regarding material choice, construction, technology and utilization.

3. Improving and analysing damage resistance

The most important options for decreasing wear or slowing down wear speed **[5]**:

- from a material choice viewpoint:
  - use of (tool) materials with increased hardness or elasticity modulus,
  - pairing of materials (tool + workpiece) that have less affinity (less propensity to adhere to each other);
- from a construction viewpoint:
  - optimizing the tool edge geometry to the task (workpiece material, its geometry, foldings...),
  - limiting the mechanical and the subsequent thermic stress to a necessary degree;
- from a technological viewpoint:
  - forming an optimal surface micro-topography,
  - use of surface treatment procedures adequate for the given task
- from a utilization viewpoint:
  - avoiding or decreasing unnecessary empty runs, vibrations,
  - assuring an adequate and continuous cooling-lubricating.

If the dominant type of damage is wear, by increasing the hardness of the surface Layers and their pressure flow border (resistance to small, permanent deformations) we can obtain a significant improvement in lifespan through better wear resistance and annealing resistance. This can be described relatively well by using data from a simple hardness measurement. If knowledge of the time frames of the wear process is necessary, then wear analysis – that simulates the real situation – can yield a volume loss measure number, or its reciprocal, the wear number (wear toughness) which can serve as a numerically expressed material characteristic. The latter and the hardness are in a linear function relationship **[5]**.

The rigidity (brittleness) of technical ceramics can be improved if during the sintering process

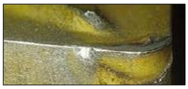
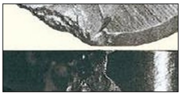
Type of tool damage			Cause	Countermeasure
Back wear			Tool material is too soft, machining speed is too high, too small back angle, extremely small feeding speed	A tool material with better wear resistance, decreased machining speed, increased back angle, increased feeding speed
Crater wear			Tool material is too soft, machining speed is too high	A tool material with better wear resistance, decreased machining speed, decreased feeding speed
Splintering			Tool material is too hard, feeding speed is too high, cutting edge is not solid enough, lack of handle- or structural rigidity	Tougher tool material, decreased feeding speed, increased sharpness (splintering instead of rounding off), using a bigger size
Fracture			Tool material is too hard, feeding speed is too high, cutting edge is not solid enough, lack of handle- or structural rigidity	Tougher tool material, decreased feeding speed, increased sharpness (splintering instead of rounding off), using a bigger size
Elastic deformation			Tool material is too soft, machining speed is too high, too deep cut and too high feeding speed, too high machining speed	A more wear resistant tool material, decreased machining speed, decreased depth and feeding speed, a tool material with an increased heat conductivity
Adhesion wear			Machining too slow, inadequate sharpening, inadequate material quality	Increased machining speed, increased front angle, a tool material with a lower affinity (coated, from powder metallurgy)
Heat cracking			Expansion or contraction due to machining heat, tool material too hard	Dry machining (with wet machining the workpiece has to be flooded with machining liquid), tougher tool material
Cutting			Hard surfaces such as raw surfaces, cooled parts and surface solidified layers, friction caused by unevenly shaped chippings (small vibrations)	A more wear resistant tool material, increased front angle in order to increase sharpness
Detaching			Bonding and adhesion of tool edge, bad chippings	Increased front angle in order to increase sharpness, increased machining pocket
Side wear fracture			Damage due to lask of solidity in the arched cutting edge	Increased charpness, tougher tool material
Crater wear fracture			Too soft tool material, too large cutting resistance and generated machining heat	Decreased sharpness, a more wear resistant tool material.

Figure 4. *Damage types of machining tools*

Table 2. *Classification of lacks in continuity*

Shape of undesirable differences in continuity	Created during production, casting of raw material	Created while elastic shaping	Created during heat treatment	Created during machining	Created during bonding (welding)	Created during assembling, repair	Created during shipping, storing	Created while in use
Linear	Surface cracking, hot cracking, cold cracking	Surface cracking, smithing cracking, flocculation	Hardening crack, hydrogen cracking, pitting		Cracking			Fatigue cracking
	Cold adhesion, faulty adhesion, flaking	Smithing sheeting, cylinder forming sheeting, layering, flaking	Splintering		Faulty bonding			
	Slag row				Slag row			
	Cutting	Cutting		Cutting	Faulty root, melting edge	Cutting	Cutting	
		Grooving		Grooving, Scratching		Scratching	Scratching	
Spherical	Pore, blister				Pore			
	Lunker, micro-lunker							
	Sand enclosure				Slag enclosure			
Branching off		Caused by overheated structure	Surface crack	Whetting crack				Caused by inter-crystalline corrosion, caused by tension corrosion

we use raw materials with a nanometer scale granule size. With ceramics of similarly fine, „nanophase” granules we obtain - besides an appropriate hardness - a better processability because the individual granules can slide on each other without causing cracking or fracture **[1]**.

The mechanical properties of technical ceramics can be improved with some sort of secondary phase, most often in the form of threads, needle crystals or particles. The effect of the improvement can be further increased by decreasing the size of the added phase to 100 nm or less. In composites with a ceramic matrix, in order to decrease rigidity (increase toughness), obstacles are created with less rigid particles that can block the path of an eventual spreading crack (e.g. adding

SiC particles to Si_3N_4). The fracture toughness and bending solidity of Al_2O_3 also increases by adding finely dispersed ZrO_2 particles. The tetragonal-monocline transformation occurring at the at the ZrO_2 cracking edge generates a pressure tension that constitutes an adequate defense against the spreading of the cracks **[1]**.

There is no universally accepted, unique way to measure toughness. For example, during bending tests the maximum tension value or the energy consumed during impact tests is used to describe toughness, but these aren't universally accepted because experience shows that these don't always predict the behaviour of the tool during utilization. More precisely: they are not sensitive enough and often incapable of differentiating between the tool materials' real, often very different performance capacities in an industrial environment.

The special properties of ceramic materials – hardness, wear resistance, greater heat resistance – can be well utilized in technologies. This, as well as the fact that, as replacement materials, their significance is increasing, requires a more precise definition for their toughness. A characteristic of the ceramic materials is the fact that due to their rigidity the sizes of the critical faults that can cause unstable crack propagation falls into the order of the parameters that describe their micro-structure (granule size, structural inhomogeneities).

According to **Figure 5.** the cracks that start from the imprint of a simple and fast Vickers hardness measurement can describe deforming capacity or lack thereof (rigidity) **[8]**.

This kind of cracking pattern can only be taken into account in special circumstances (HV_{30} > 600, $F > F_{krit}$, diamond paste polished surface) and used in the fracture toughness formula for calculations.

$$K_{Ic} = k \cdot \frac{F}{c^{3/2}} \tag{1}$$

The value of "k" is a constant given by the material properties and the geometry of the diamond pyramid. For such analysis one can also use Knoop hardness measuring with a diamond pyramid with diamond shaped base instead of the square shaped one.

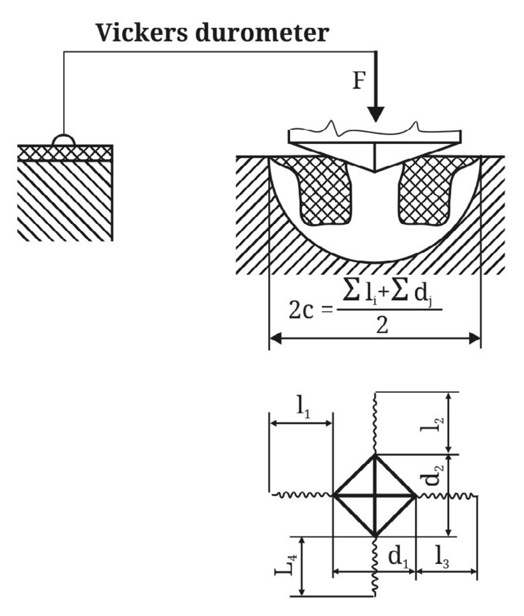


Figure 5. *Vickers-based fracture mechanics analysis*

Acoustic emission can adequately predict tool fractures, it also offers the possibility of continuous control. Sudden processes inside the material (such as forming of a crack, shifting of material at the limit of the elastic zone or a reorganizing of the grid due to a shift in state) generate acoustic emission signals that are situated typically somewhere between the audible range and the several 10's of MHz range **[9, 10]**. In practice, filtering the machine's trepidations, vibrations from the signals might be difficult.

4. Conclusions

Tool quality assured through adequate tool material, construction (edge geometry) and production technology cannot by itself guarantee the desired lifespan. One also has to consider the circumstances and conditions of utilization through which different wear and damage processes can occur, influencing the structure and properties of the materials, and also the geometric properties of the tool.

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