Metal cutting theory foundations of near-dry (MQL) machining

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Abstract: The costs of maintaining and eventually disposing of metal working fluids (MWF), combined with health and safety concerns, have led to a heightened interest in either eliminating MWF altogether or limiting the amount of MWF applied. The former process is known as dry machining while the latter is referred to as near-dry machining (NDM) or minimum quantity lubrication (MQL). This paper points out that non-system approach to NMD applications and misunderstanding of the metal cutting theory foundations of NDM significantly slowdown implementations of these seemingly attractive and cost-effective technologies. It reveals two major stages in implementations of NDM. It argues that the cutting theory stage should precede NDM application considerations. The fundamental problems associated with the reduction of the total energy required by the cutting system have to be solved at this first stage. The paper pointed out the principal directions in the future studies on NDM are discussed.

Keywords: metal machining; metal working fluids; MWF; near-dry machining; NDM; minimum quantity lubricant; MQL; machining; energy spent in machining; reduction of energy required by the cutting system.

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1 Introduction challenges with metal working fluids

Metal working fluids (MWF) have undergone intense regulatory scrutiny during the last 20 years. The United Auto Workers petitioned the Occupational Safety and Health Administration (OSHA) to lower the permissible exposure limit for metalworking fluids from 5.0 mg/m^3 to 0.5 mg/m^3. In response, OSHA established the Metalworking Fluid Standards Advisory Committee (MWFSAC) in 1997 to develop standards or guidelines related to metalworking fluids. In its final report in 1999, MWFSAC recommended that the exposure limit be 0.5 mg/m^3 and that medical surveillance, exposure monitoring, system management, workplace monitoring and employee training are necessary to monitor worker exposure to metalworking fluids. Eventually, this recommendation became mandatory requirement in the automotive industry.

In the current, competitive manufacturing environment, end-users of MWF are looking to reduce costs and improve productivity. As a result, a closer look at the cost of MWF was taken. Surprisingly, it was found that MWF represent a significant part of the manufacturing costs. Just two decades ago, MWF accounted for less than 3% of the cost of most machining processes. These MWF were so cheap that few machine shops gave them much thought. Times have changed and today MWF account for up to 15% of a shop production cost (Graham, 2000), while some European automotive companies reported 16.9% (Brinksmeier et al., 1999). The costs of purchase, maintenance and disposal of MWF are more than two-fold higher than the tool-related costs, although the main attention of researchers, engineers and managers has been focused on the reduction of the cutting tools-related costs. Moreover, MWF, especially those containing oil, have become a huge liability. Not only does the Environmental Protection Agency (EPA) regulate the disposal of such mixtures, but many states and localities also have classified them as hazardous wastes.

The costs of maintaining and eventually disposing of MWF, combined with the aforementioned health and safety concerns, have led to a heightened interest in either eliminating MWF altogether or limiting the amount of MWF applied. The former process is known as dry machining while the latter is referred to as near-dry machining (NDM) or minimum quantity lubrication (MQL) machining. However, non-system considerations from the management standpoint and misunderstanding of physics of MWF actions in the cutting process significantly slowdown implementations of these seemingly attractive and cost-effective technologies.

Generally speaking, NDM known also as MQL machining is machining with the supply of very small quantities of lubricant to the machining zone. It was developed as an alternative to flood and internal high-pressure coolant supply to reduce MWFs consumption. In NDM, the cooling media is supplied as a mixture of air and an oil in the form of aerosol (often referred to as the mist). An aerosol is a gaseous suspension (hanging) into air of solid or liquid particles. In NDM, aerosols are oil droplets dispersed in a jet of air. Aerosols are generated using the process called atomisation, which is the conversion of a bulk liquid into a spray or mist (i.e., a collection of tiny droplets), often by passing the liquid through a nozzle.

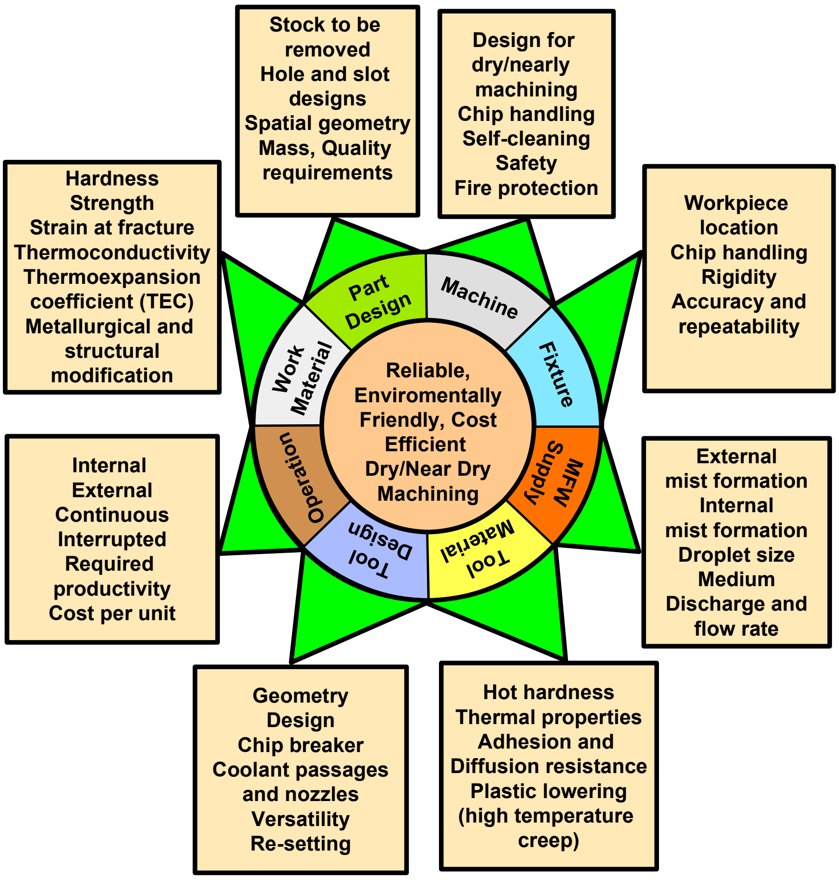
An atomiser is an atomisation apparatus; carburettors, airbrushes, misters and spray bottles are only a few examples of atomisers used ubiquitously. In internal combustion engines, fine-grained fuel atomisation is instrumental to efficient combustion. Despite the name, it does not usually imply that the particles are reduced to atomic sizes. Rather, droplets of 1–5 microns are generated. Because MWF cannot be seen in the working zone and because the chips look and feel dry, this application of MQL is called NDM.

This paper aims to discuss the cutting process side of NDM laying down the fundamentals of this process suing the advanced metal concepts.

2 NDM as a system: process and technology

Experience of implementing of NDM shows that this technology can be successful if and only if the whole NDM system of components is considered and special attention is paid to each and every component individually while maintaining the coherence of the system. Figure 1 shows such a system. Therefore, a 360° analysis of all components listed in Figure 1 is a prerequisite before any consideration on practical implementing NDM. Unfortunately, this is not the case in practice.

Figure 1 Components of the NDM system (see online version for colours)



The author's analysis of the implementation practice of NDM reveals that the most common mistake made by many professionals and practitioners in the field is to use the existing machines, tool, tooling, controllers and part designs for NDM without understanding the physics of machining and thus the system consideration of the whole machining process. This has been resulting in multiply failures of this seemingly attractive technology. Although the blame should be equally shared by academia and industrial scientists, the major share in the discrediting of this technology belongs to NDM apparatus and accessories manufacturers because they used the full power of their sales force to promote their products without much care about the end result. In their sales presentations, they show:

a idealised pictures of NDM principle similar to that shown in Figure 2 where oil droplets mysteriously fly only to the cutting tip of the tool

b pie-charts, where the MFW application cost triples that of the tooling cost

c OSHA and EPA requirements on MWF exposure limits and MWF disposal.

Normally, it does not take much time to convince an inexperienced end-user that his/her company can be 'lean and green' in short time and at reasonable cost. In reality, however, it happens rather rare.

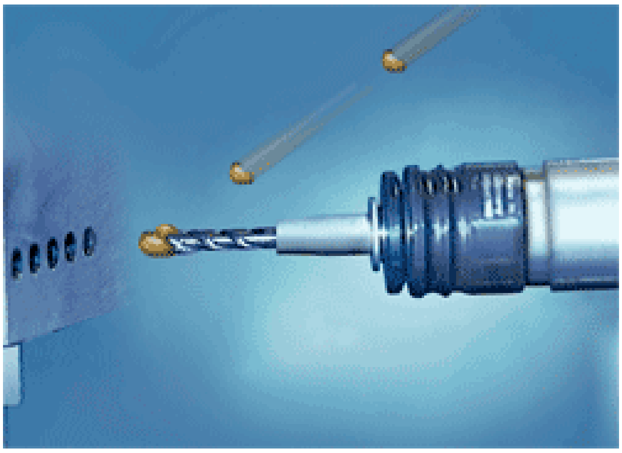
To solve this problem and thus to make NDM technology more user-friendly and to reduce the failure rate in applying this technology, a system analysis of its applicability should precede any implementation commitment. Regardless of the scope of a particular NDM project, this analysis should always include two principal stages:

1 Cutting theory stage where the work material, parameters of the machining regime, cutting tool design and material, workpiece design, tolerances (including spatial) are considered together in order to assess feasibility of NDM in principle on one hand, and to understand what has to be changed (optimised, redesigned, etc.) to implement NDM on the other hand.

2 Practical NDM setup and apparatus. At this stage, a particular NDM type, aerosol components and parameters should be selected and tested in terms of their suitability for the considered project (Astakhov, 2008). NDM stability should be verified and the data for the efficiency analysis should be collected for critical machining operations, tools and work materials to be involved with NDM.

This paper provides some guidance for the first stage, it hopes that this stage will be further developed by various researches and practitioners as almost no information on this stage is available today. In the author's opinion, this is the major hurdle in practical implementation of NDM.

Figure 2 Idealised image of NDM (see online version for colours)



3 Major objective of the first stage

The first stage should start with understanding the subject. To begin, one should ask himself a few simple questions: Why NDM works at all? Why it shows somehow better results than flood or even high-pressure MWF supply? In other words, how is it possible 'physically' as flood or high-pressure MWF definitely removes much more thermal energy? Why aerosol containing oil and air mixture has (according to all NDM research and promotional papers) greater cooling ability than that of water soluble MWFs although the heat capacity of water is ten times greater than that of oil and much greater than that of air keeping in mind that heat removal due to oil droplets evaporation is negligibly small (Astakhov, 2006) because of inherent oil properties and tiny oil flow rate (30–60 ml/h)? Through finding physically – justifiable answers to these simple questions, one easily finds that the aerosol used in NDM cannot physically provide the same cooling action of flood and especially high-pressure MWF supply techniques regardless of ungrounded claims used in many sales and promotion materials, which unfortunately found their way even to some research papers.

Therefore, the overall objective of the first stage is the reduction of energy required by the cutting system in machining though the reduction of the power spent in the separation of the layer being removed from the rest of the workpiece and friction powers at interfaces and secondary contact surfaces to the level where NDM becomes feasible, reliable and cost beneficial. Although this first stage is not concerned with chip removal and aerosol delivery, it reveals the parameters to be dealt with at the second stage, namely defines the machining regime, tool geometry, place of aerosol application (location of aerosol outlets), aerosol parameters (concentration, flow rate, type of oil used, size of droplets, etc.). This stage also concerns with the minimisation of part thermal distortion through defining parameters and sequence of the machining operations.

4 Metal cutting theory fundamentals for the first stage

At the first stage, one should clearly realise that all energy supplied to the cutting system converts into the thermal energy, which flows in the form of heat into the components of the cutting system. To make NDM feasible, one needs first to understand energy partition in the cutting system. Then, practical measures to reduce the energy required by the cutting system for its existence should be developed using the available theoretical, computational (modelling) and experimental results. It sets a request to the metal cutting research community to provide such results. International, national grant-issuing bodies as well as technical and technological societies and large manufacturing (including cutting tool) companies should provide funding for research projects aiming to provide such results. To coordinate such scientific efforts, an international (national) advisory body should be established.

4.1 Energy required by the cutting system and energy partition

Using the model of energy partition in the metal cutting system, Astakhov (2006) and Astakhov and Xiao (2008) proposed the power balance in the cutting system as

$$P_c = F_c v = P_{pd} + P_{fR} + P_{fF} + P_{ch} + P_{mn-ce} \quad (1)$$

where P_{pd} is the power spent on the plastic deformation of the layer being removed, P_{fR} is the power spent on the tool-chip interface, P_{fF} is the power spent on the tool-workpiece interface, P_{ch} is the power spent in the formation of new surfaces, P_{mn-ce} is the energy spent due to the combined influence of the minor cutting edge.

Analysis of the energy partition using this model carried for steel E52100 and aluminium alloy 2024 T6 (Astakhov and Xiao, 2008). Figures 3–5 present some results for steel E52100.

The relative impact of the cutting speed on the energy partition is shown in Figure 3. As seen, the power required for the plastic deformation of the layer being removed in its transformation into the chip is the greatest. However, the greater is the cutting speed, the greater powers on the rake and flank faces of the cutting tool. When the cutting speed is 1 m/s, the power of the plastic deformation, P_{pd} is 67%, while the power spent on the tool-chip interface, P_{fR} is 18% and the power spent on the tool-workpiece interface, P_{fF} is 9%. When the cutting speed is 4 m/s then P_{pd} is 45%, P_{fR} is 25% and P_{fF} is 22%, i.e., the sum of powers spent on the tool-chip and tool-workpiece interfaces (P_{fR} and P_{fF}) is greater than the power spent for the plastic deformation P_{pd}. This result signifies the role of tribology in high-speed machining (Astakhov, 2006). The power spent in the formation of new surfaces P_{ch} is 6% in both considered case although the frequency of chip formation is much greater when v = 4 m/s.

Figure 3 Relative impact of the cutting speed on the energy partition

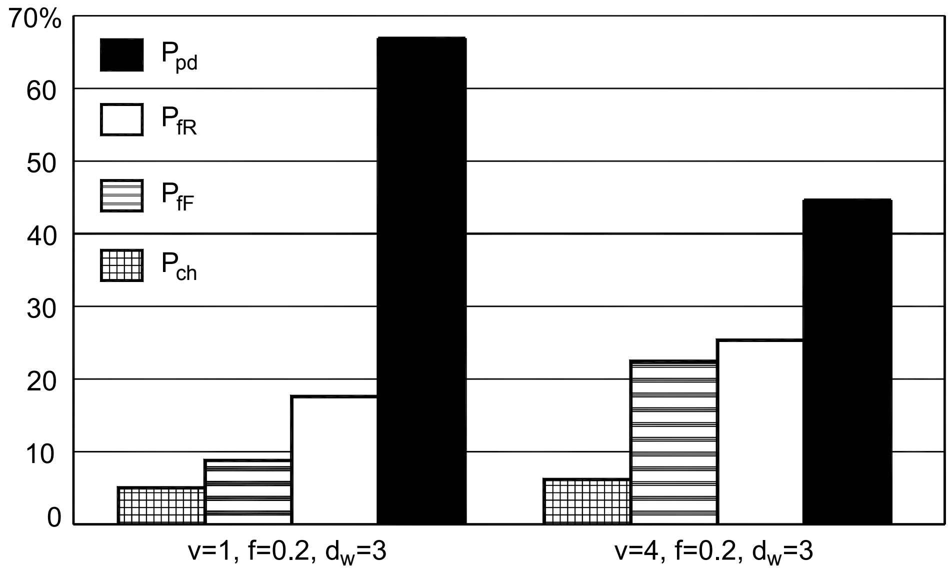


Figure 4 Relative impact of the depth of cut on the energy partition

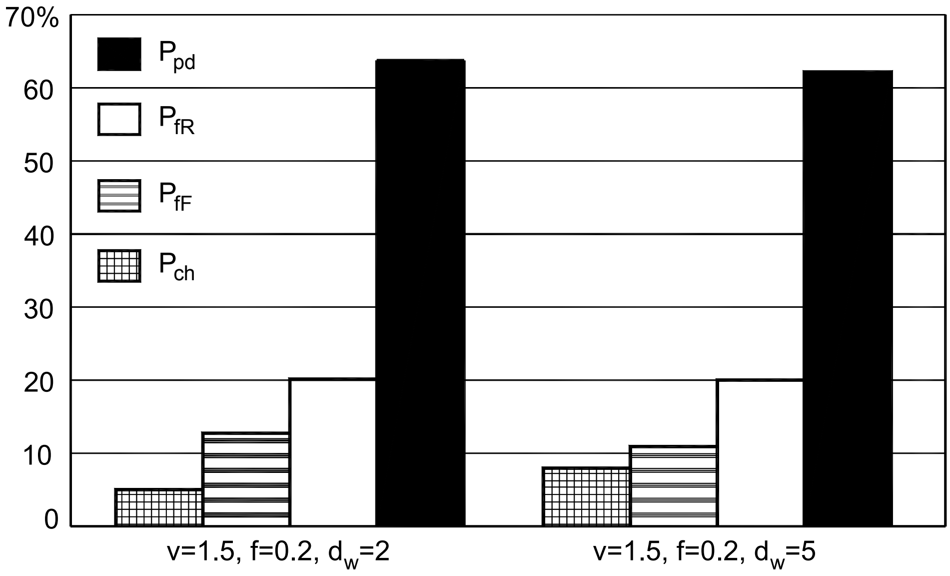
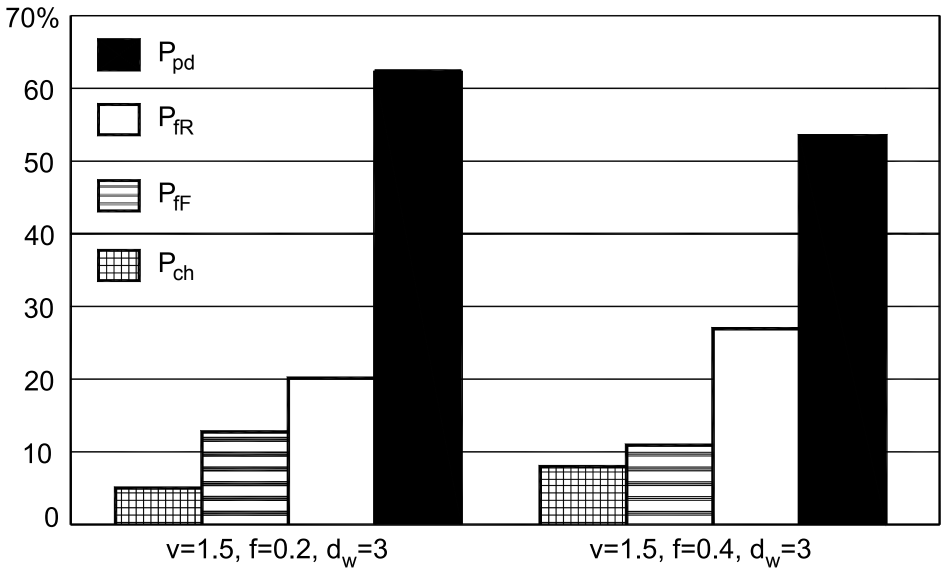


Figure 5 Relative impact of the cutting feed on the energy partition



The relative impacts of the depth of cut and the cutting feed are shown in Figures 4 and 5. As seen, a 2.5-fold increase in the depth of cut does not affect the energy partition. A two-fold increase in the cutting feed reduces P_{pd} from 62% to 54% while P_{fR} increases from 20% to 27%.

Practically, the same results were obtained for aluminium. When the cutting speed is 1 m/s, the power of the plastic deformation, P_{pd} is 67% while the power spent on the tool-chip interface, P_{fR} is 20% and the power spent on the tool-workpiece interface, P_{fF} is 6% and P_{ch} is 7%. When the cutting speed is 7 m/s then P_{pd} is 50%, P_{fR} is 25% and P_{fF} is 25% and P_{ch} is 6%.

Some important conclusions directly follow from the obtained results:

- The power required for the deformation of the layer being removed is the greatest in the metal cutting system within the practical cutting speed limits. Therefore, the major effort at the first stage of implementing NDM is to be spent on the reduction on this energy to the level where NDM becomes feasible.
- When cutting speed increases to the level regarded as high-speed machining, the relative impact of this power decreases while the powers spend at the tool-chip and tool-workpiece interfaces increase. At high cutting speeds, the sum of the later powers may exceed that required for the plastic deformation of the layer being removed. This result signifies the role of metal cutting tribology at high cutting speed (Astakhov, 2006). Therefore, there are three objectives at the first stage of implementing NDM for high-speed machining. The first and major is still the reduction of the power required for the deformation of the layer being removed. The second and the third concern with the contact processes at the tool-chip and tool-workpiece interfaces, respectively.

4.2 Power spend on the plastic deformation of the layer being removed

Analysis of the state of stress and deformation in the machining zone, Astakhov and Shvets (2004) showed that the power spent on the plastic deformation of the layer being removed, P_{pd}, can be calculated from the chip compression ratio and parameters of the deformation curve of the work material as follows

$$P_{pd} = \frac{K\left(1.15\ln\zeta\right)^{n+1}}{n+1} vA_w \tag{2}$$

where K is the strength coefficient (N/m^2) and n is the hardening exponent of the work material, ζ is the chip compression ratio that represents the strain at fracture in the cutting process as $\varepsilon = 1.151\mathrm{n}\zeta$ (Astakhov, 2006; Astakhov and Shvets, 2004), A_w is the uncut chip cross-sectional area (m^2)

$$A_w = d_w f \tag{3}$$

d_w is the depth of cut or drill radius (m), f is the cutting feed per revolution (m/rev).

As above-discussed, this energy is the larges part of the energy required by the cutting system for its existence. This energy defines the cutting force, tool life and other outcomes of the machining. It should be very clear that plastic deformation in metal cutting is a nuisance so that it should be reduced in order to increase the process efficiency and to implement NDM. The rule of thumb here is: the less the plastic deformation, the better the cutting process.

The author's analysis of equations (2) and (3) and available experimental results allow pointing out the principal direction in the reduction of the energy spend on plastic deformation of the layer being removed:

1 formation of a preferable state of stressing the deformation zone

2 using a preferable metallurgical state of the work material

3 achieving the optimal cutting temperature

4 enhancement of the embitterment (Rebinder) effect by the NDM

5 reduction of the volume of the material to be removed by cutting.

4.2.1 Preferable state of stress

The tool geometry directly affects the amount of plastic deformation in metal cutting as it defines to a large extent the triaxial state of stress in the deformation zone and the degree of triaxiality. The state of stress in the body, which undergoes plastic deformation affects the fracture strain, i.e., the extent of plastic deformation. One of the best parameter used to characterise the triaxiality of the state of stress in a deforming body is Π-factor (Johnson and Mellor, 1973) represented in the following form

$$\prod = \frac{3I_1(\sigma)}{2\sqrt{I_1^2(\sigma) - 3I_2^3(\sigma)}} \tag{4}$$

where $I_1(\sigma)$ and $I_2(\sigma)$ are the stress invariants, which may be expressed in terms of principal stress σ_1, σ_2 and σ_3 as

$$I_1(\sigma) = \sigma_1 + \sigma_2 + \sigma_3 \tag{5}$$

$$I_2(\sigma) = -(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) \tag{6}$$

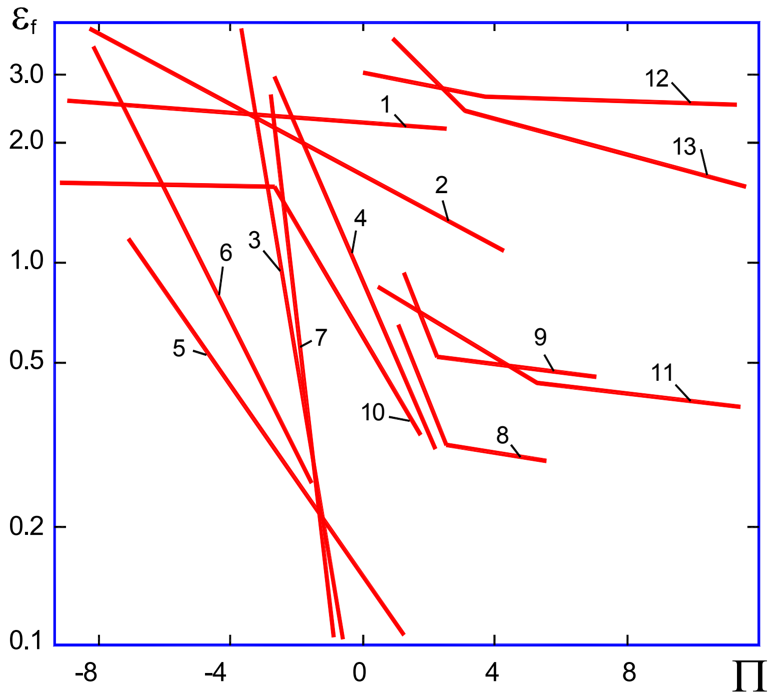
Figure 6 shows the relationships between the fracture strain and of the state of stress represented by Π-factor. As seen, the degree of triaxiality has great influence on the fracture strain. In the author's opinion, this is the major lead in the optimisation of the tool geometry, which can be thought of as having the objective function – the minimum fracture strain with the set of real-life constrains.

The list of the real-life constrains on the optimised tool geometry includes:

- Dimensional and form accuracy of the parts produced. This constrain should be specified for each and every tool because the tool geometry defines the direction and magnitude of the cutting force and its components that, in term, affect the deformations of the workpiece and its future, tool, tool holder, spindle and machine structure deformations.
- Surface integrity of the machined surface in terms of its surface finish, machining residual stress, etc.
- Properties of the tool materials. The optimised tool geometry should utilise the strong properties to the full extend while prevent the situation where the tool materials weaknesses can compromise tool performance and reliability.
- Efficiency of machining. One should realise that the optimum cutting process does not necessarily mean the most efficient one as the cutting tool and machining process are part of the machining system.

The quantitative analysis of the influence of the tool geometry parameters on the power spent in cutting should be one of the objectives of the future studies on NDM.

Figure 6 Effect of Π-factor of the fracture strain (see online version for colours)



Notes: 1, niobium; 2, iron; 3, tungsten; 4, molybdenum; 5, beryllium; 6, magnesium; 7, zinc; 8, tin alloy; 9, brass; 10, brass alloy; 11,tin bronze; 12 deformed lead; 13, cast lead

4.2.2 Preferable metallurgical structure

In the author's opinion, this aspect of machinability of materials and its influence on the power spent is cutting is the most neglected in industry even in state-of-the-art automotive plants. Drawings of the finished part indicate only the grade of the work material according to one of many standards (AISI, SAE, ASTM, etc.) and the final hardness (if it is important). There are a number of objections to this insufficient information on the properties of the work materials, particularly when NDM is to be used:

- Many standards on the work materials are outdated as they were developed long time ago. As a result, the allowable ranges of variation of the chemical composition of work materials are a way too great that result in great scatter in machinability, thus in energy spent in marching among different manufacturing batches of seemingly the same work material. A good example of the influence of minor components on the machinability of a grey cast iron widely used in the automotive industry was presented by Griffin et al. (2002). They found that within the range allowed for manganese (0.3–0.8%), the longest tool life corresponds to 0.3% and it reduces more than twice when the content of manganese is 0.8%. The same result was obtained for the allowable range of tin. Even more pronounced influence of volume percent of hard inclusion was found in this study.

- In modern manufacturing, the part may undergo one or even several heat treating operations in its manufacturing process. As such, not much attention is paid to the structure and hardness of the blanks (bar stock, castings, forgings, etc.). For example, steel bar stocks of the same materials are supplied at different metallurgical state: as rolled, cold rolled, annealed, normalised, etc.

Moreover, according to the common notions stated in practically all textbooks on metal cutting, the hardness and/or strength (yield or ultimate) define machinability of a materials and thus the amount of energy spend in machining. As a result, part and process drawing include only this information on the work material. In the author's opinion, this is simply incorrect because everyday practice of machining shows that these notions do not much reality. For example, as discussed by Astakhov (2006), machining of medium carbon steel AISI 1045 (tensile strength, ultimate σ_R = 655 MPa, tensile strength, yield $\sigma_{y0.2}$ = 375 MPa) results in much lower total cutting force, greater tool life, lower required energy, cutting temperature, machining residual stresses than those obtained in the machining of stainless steel AISI 316L (σ_R =517 MPa; $\sigma_{y0.2}$ = 218 MPa). The prime reason for that is that any kind of strength of the work material in terms of its characteristic stresses cannot be considered alone without corresponding strains, which determine the energy spent in deformation of the work material (Astakhov and Shvets, 2004; Astakhov, 1998, 1999). Only when one knows the stress and corresponding strain, he can calculate other parameters-outcomes of the metal cutting process (Astakhov and Shvets, 2004).

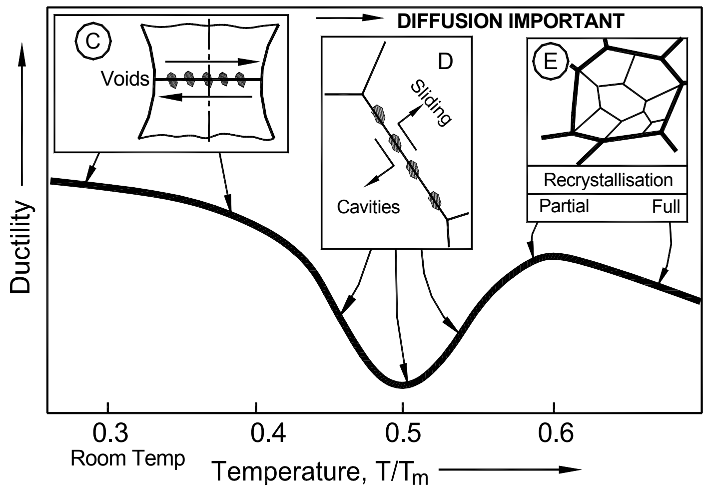
Although a preferable metallurgical structure of the work material should be dealt with on the case-to-case basis, a good start in the selection of this preferable structure is the minimum of the product of the strain and stress at fracture of the work material. As such, both should be known. Therefore, the objective of the future studies in this direction is to obtain these characteristics.

4.2.3 Achieving the optimal cutting temperature

To comprehend the concept of the optimal cutting temperature, the essence of the first metal cutting law (the Makarow's law) should be fully understood. This law (Astakhov, 1998, 1999, 2004) states that for a given combination of the tool and work materials, there is the cutting temperature, referred to as the optimal cutting temperature, at which the combination of minimum tool wear rate, minimum stabilised cutting force and highest quality of the machined surface is achieved. This temperature is invariant to the way it has been achieved (whether the workpiece was cooled, preheated, etc.).

The physics behind this law can be explained as follows. According to Atkins and Mai (1985) and Komarovsky and Astakhov (2002), there is a marked decrease in the strain at fracture under a certain temperature specific to a particular work material. The physics of this phenomenon is discussed by Astakhov (2006) for carbon steels as follows. At temperatures approximately 0.45 T_m (T_m is the melting point), grain boundaries act principally as barriers inhibiting cleavage and causing dislocation pile-ups (Figure 6). The regions of intense deformation, which are contained within the grains at lower temperatures, now shift to the grain boundaries themselves. Voids are nucleated and cracks then develop on the grain boundaries. Shear stresses on the boundaries cause relative sliding of the grains and voids are reduced in region of stress concentrations. Therefore, around this temperature, region can be referred as the ductility valley. Experiments showed (Makarow, 1976) that the reduction of plasticity may reach two-folds and even more for high alloys.

Figure 7 Plasticity valley



The presence of the plasticity valley is the physical cause of the existence of the optimal cutting temperature. The cutting conditions that cause this temperature should be regarded as the optimal cutting conditions as the work of plastic deformation of the layer been removed in at minimum from the metal physics' point of view. As the cutting speed is the major contributor to the cutting temperature, the cutting speed that cause the optimal cutting temperature should be regarded as the optimal cutting speed (Astakhov, 2006). Thus, an efficient NDM should be carried out at the optimal cutting speed assuring the minimum plastic deformation from the metal physics' point of view while the optimum cutting geometry creates the preferable state of stress that further reduces this strain and thus energy spend on the separation of the layer being removed. The coupling of these two effects brings the best result.

4.2.4 Enhancement of the embitterment (Rebinder) effect by the NDM

Surprisingly, very little explanations are provided to clarify why NDM works. The known explanations of the efficiency of NDM came from the oil mist principle that was developed by a bearing manufacturer in Europe during the 1930s. Today, this method of lubricating is applied to all types of other machine tools, web and sheet processing equipment, belt and chain conveyors, rolling mills, vibrators, crushers, centrifuges, kilns, pulverisers, ball mills, dryers and liquid processing pumps. Boundary lubricating layer of extreme pressure (EP) additives and accurate delivery of the lubricant to the contact surface just before they engaged into a contact plush cooling by oil droplets evaporation were 'borrowed' to explain the effectiveness of NDM in metal cutting.

One of the feasible and physics-based explanations is the so-called embrittlement action of the cutting fluid that reduces the strain at facture of the work material. This action is based on the Rebinder effect (Astakhov, 2006). Rebinder's studies were directly concerned with the metal cutting process. Conducting a great number of cutting tests under different cutting conditions and with different cutting fluids, he observed microcracks formation and 'healing'. The latter was particularly pronounced in machining ductile materials where great plastic deformation of the layer being removed is observed. The results of Rebinder's study showed that the absorbed films prevent microcracks closing (healing due to plastic deformation of the work material). Because each microcrack in the machining zone serves as a stress concentrator, smaller energy was required for cutting. Pursuing this direction, Epifanov found (Graham, 2000) that the penetration of the foreign atoms (from cutting fluid decomposition) produced an embrittlement effect in a manner similar to hydrogen embrittlement. He concluded that this is facilitated by a resulting decrease in plasticity. Our current understanding of the Rebinder effect is the alternation of the mechanical and physical properties of materials due to the influence of various physiochemical processes on the surface energy (Astakhov, 2006).

As above-discussed, the work of plastic deformation of the layer being removed in metal cutting is the greatest. After this work is done, it is too late to bear the consequences using inferior (in terms of cooling ability) NDM as it cannot compete against the cooling ability of a flood or a high-pressure though tool water soluble MWF (Astakhov, 2008). The only feasible way for NDM to work in metal cutting is to increase embitterment of the layer being removed and thus to reduce the work of plastic deformation done in transformation of the layer being removed into the chip (Astakhov, 2008). Available information about the practice of NDM suggests that atomised oil possesses great ability to enhance the Rebinder effect. In the author's opinion, this explains the effectiveness of NDM. Because the lowering of the surface energy of a solid that leads to alternation of its mechanical properties can be achieved as the result of adsorption, chemisorption, surface electrical polarisation, surface chemical reactions (Astakhov, 2006), research, selection of NDM designs and parameters as well. It sets clear objectives for the future development studies and implementation of application specific oils, aerosol preparation and delivery techniques used in NDM.

4.2.5 Reduction of the volume to be cut

It directly follows from equation (2) that the energy spend on plastic deformation of the layer been removed is proportional to the volume to be removed. It can be achieved if the near-net-shape blanks are used. It may require to redesign blanks and to use different processes to produce these blanks (forging, extrusion, cold-forming, etc.). For example, in the automotive industry when die castings are used as blanks, one of the possible and feasible ways is to use the so-called cored holes, i.e., holes made in castings with some stock to be removed by reaming. Besides reduction of the energy needed to produce the finishing holes, this dramatically reduce the amount of the chips generated thus makes hole-making operations much more suitable for NDM. This also eliminates the need in drilling so that the two- or three-pass hole-making operations (two or three cutting tools) can be substituted by single-pass operations with a finishing reamer. However, a number of problems have to be solved to make core hole reaming practical and reliable (Bhattacharyya et al., 2006a, 2006b; Atabey et al., 2003; Lee et al., 2001).

Today, two-flute reamers are used for the finishing pass in hole-making operation in the automotive industry. The known attempts to use the same tools to machine cored hole failed because such tool have no tendency to straighten cored holes as they follow inherent eccentricity of such holes. Therefore, new application-specific tool designs capable to handle the known misalignment, shape errors, non-uniformity of the stock to be removed, position errors, etc. have to be introduced. To achieve this, a number of models should be developed and verified experimentally. Among them, two are of prime importance:

- Model that is capable to predict the cutting forces for an arbitrary reamer geometry. Inputs to the model include: tool geometry, feed, speed, initial hole geometry and process faults including parallel offset run-out, spindle tilt, their respective locating angles and tool/hole axis misalignment. Given these input parameters, the model should predict torque, thrust and radial forces. Model validation tests should be conducted to assure that model predictions confirm the corresponding experimental data with reasonable accuracy. The effects of process faults on cutting forces, tool life and quality of machined holes should also be examined. Effects of parallel offset run-out, spindle tilt, spindle tilt locating angle and tool/hole axis misalignment as well as part thermal distortion are to be studied. A range of suitable tool geometries and designs, tolerances on cored hole locations in die castings and castings location in the machine fixture are some important outcomes of this research and development efforts.
- One of the important factors affecting the quality of a surface manufactured by reaming is chatter. This is especially true in reaming core holes. That is why the automotive industry is reluctant to used cored hole reaming regardless of many advantages of chip operation. Therefore, chatter should be investigated by means of a numerical non-linear stability analysis so that the mode of vibration of the cutting tool will be revealed and the tool design will be altered to reduce the mentioned chatter to the acceptable level within the inherent allowable inaccuracies of cored holes in die castings.

5 Need for a new materials model

The first stage of NDM implementation can be significantly simplified if suitable modelling software that formalised the knowledge and results available is developed. The core of this modelling tool (regardless of its nature) is the so-called materials model which describes the behaviour of work material in machining.

Equation (2) has been derived using the simplest material constitutive model as the power law named after Hollomon (Dieter, 1976). Although its results are of reasonable accuracy for steel-like materials, the main drawback of this equation is that it may not fully suitable to describe deformation behaviour of composite materials as for example, automotive high-silicon Al-alloys. Therefore, development of a new much more general model is needed.

Several material constitutive models are used in FEM of metal cutting, including rigid-plastic, elasto-plastic, viscoplastic, elasto-viscoplastic, etc. These models take into account high strain and temperature reportedly found in metal cutting. Among others, the widest use has the Johnson-Cook model (Astakhov, 2002) which is a thermo-elasto-visco-plastic material constitutive model. Today, this model is used exclusively as such a model in all theoretical and numerical studies (Moufki and Molinari, 2005a, 2005b; Deshpande et al., 2006; Mackerle, 1999, 2003) as well as in commercial metal machining FE programs as for example, developed by Third Wave (http://www.thirdwavesys.com) or DEFORM (http://www.deform.com/) companies.

The most severe problems with the use of the Johnson-Cook model are discussed by Astakhov and Outerio (2008). There are three other important issues with this model particular to metal cutting that have never been addressed in metal cutting studies:

- The model does not account for the formation of cracks and fracture which is always the case in metal cutting and particularly profound in metal matrix composites (MMC) as high-silicon Al-alloys.
- The behaviour of work materials, particularly MMCs is very sensitive to a particular state of stress (Slater, 1977), which never been considered in material modelling and process/tool design in metal cutting.
- The model coefficients are very sensitive to any change in the metallurgical conditions of the work material. According to the existent standards on the composition and properties of various work materials, their properties vary significantly even within the same grade not to mention heat treatment, grain size, residual stresses and many other factors. Unfortunately, the many known FEM of metal cutting used the coefficients of the Johnson-Cook model taken from the literature sources. As such, the discussed particularities of the work material are not studied or even mentioned.

For NDM modelling including FEM, an entirely new model based on the physics of strength of work materials should be developed, verified and then used in the further research on metal machining. The developed model must account on the real structure of work materials including the presence of the real-world defects as interfacial cracks, porosity and inclusions so it can be used to determine an optimal balance between the machinability (efficiency of machining) and costs of work material processing (rolling, forging, die castings, etc.).

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