An opening historical note

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Abstract: This paper argues that despite its obvious economic and technical importance, machining remains one of the least understood manufacturing operations due to low predictive ability of the machining models. Analysing the development of various models of metal cutting, the paper points out that specialist and practitioners in the field still use the obsolete single-shear plane model, a significantly inferior model by the author's opinion. This important issue, having the greatest theoretical significance and wide practical application must be addressed in metal cutting research. This paper suggests that the first metal cutting law (Makarow's law) should prevent more attention of specialists. It should be used in experimental studies of metal cutting and in practical optimisation of metal cutting operations. This paper emphasises that successful Finite Element Method (FEM) requires vigilance and the same visual knowledge and intuitive sense of fitness that successful researchers have always depended on when making critical conclusions.

Keywords: metal machining; history; models of metal cutting; experimental research; finite element modelling.

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Biographical notes: Dr. Viktor P. Astakhov received a PhD in Mechanical Engineering from Tula Polytechnic University, Tula-Moscow, Russia in 1983. He was awarded a Dr.Sci designation in 1991 for his outstanding performance and profound impact on science and technology. His main research interests include theory of metal cutting and its applications; cutting tool design, assessment and optimisation; machinability of materials, new tool materials and coatings. He has also won awards for both his teaching and research. He has published books, book chapters and many papers in professional journals as well as papers in trade periodicals. He is a Guest Editor, Board Member, Reviewer and an Advisor for many international journals.

1 Introduction

Metal cutting, or simply machining, is one of the oldest processes for shaping components in the manufacturing industry. It is estimated that 15% of the value of all mechanical components manufactured worldwide is derived from machining operations. However, despite its obvious economic and technical importance, machining remains one of the least understood manufacturing operations due to low predictive ability of the machining models (Usui, 1988; Usui and Shirakashi, 1982).

Although many reviews of the best publications on machining discuss developments in chronological order listing and prizing the publications that support the reviewer's point (Komanduri, 1993; Merchant, 2003), the best reviews of the machining development always point out the major problems and/or set the goals for further developments (Byrne et al., 1993; Chisholm, 1958; Finnie, 1956; Jawahir and Van Luttervelt, 1993; Kobayashi and Thomson, 1962; Kobayashi et al., 1960; Usui, 1988; Van Luttervelt et al., 1998; Zorev, 1958). Analysing the development of metal cutting for the past 100 years, Finnie (1956) pointed out that basic relationships between many variables in metal cutting are still lacking solutions. Comparing the results of various models of metal cutting, Chisholm (1958) concluded that none of them is adequate to the experimental results. Evaluating the results of multiple machining test, Zorev (1958) concluded that no one known model is adequate. Usui (1988) argued that even though our understanding of metal cutting has been deepened in many respects, the only descriptive theories of low prediction ability have been developed. Discussing prediction versus understanding of metal cutting models, Shaw (1984, p.200) in his book concluded that it is next to impossible to predict metal cutting performance. Armarego (1996) pointed out that a recent survey by a leading tool manufacturer indicates that in the USA the correct cutting tool is selected less than 50% of the time, the tool is used at the rated cutting speed only 58% of the time and only 38% of the tools are used up to their full tool-life capability. Survey points out that one of the reasons for this poor performance is the lack of the predictive models for machining. The same level of performance was found in an earlier survey on cutting regime selection for CNC machine tools in the US aircraft industry.

2 Modelling

During the past 150 years, a considerable amount of research and development has been carried out on the machining of materials. Much of this has been concerned directly with the reduction of machining costs and the production of acceptable components with the necessary accuracy and surface integrity. Concurrently, a much smaller volume of research has been devoted to discovering the fundamental mechanisms which operate during the machining of materials and which has not been concerned with the solution of specific machining problems. This basic work has been growing in volume during the last 50 years, since it has been recognised how valuable a fundamental knowledge of the cutting process can be in helping towards the solution of practical machining problems even when an empirical test program is used (Jawahir, et al., 1997).

The model of chip formation constitutes the very core of the metal cutting theory. The single-shear plane model and practically all its 'basic mechanics' have been known since the 19th century after Time (1870) presented the results of his observations of the cutting process. Tresca (1873) argued that the cutting process is one of compression of the metal ahead of the tool so the chip failure should occur along the path of tool motion. Time (1877) provided further evidences that the material being cut is deformed by shearing rather than by compression. Zvorykin (1896) provided physical explanation for this model. In 1896 Briks (1896) justly criticised the single-shear plane model pointing out the major drawbacks of this model. Unfortunately, these conclusions were much ahead of this time so that they were not even noticed by the future researchers until the 1950.

In 1900, Reuleaux (1900), a famous German engineer, reported the presence of a crack ahead of the tool and concluded that the cutting process was similar to splitting wood. Although he presented the results of his well-prepared tests in a convincing manner, the specialists in the field could not accept them as a common belief in those times was that metal cutting was accomplished by pure shearing so that a crack cannot form in principle. Finnie (1956) stated that the 'crack' idea was immediately refuted by Kick (1901) in a paper a year after Reuleaux's publication. Although many books on metal cutting (e.g. Black, 1961; Boothroyd, 1975; Boothroyd and Knight, 1989) considered the publication by Reuleaux as a backward step, it was never explained why Reuleaux's result was a step backward (from which reference and established by whom?) or who, when and how disproved this result. Conducting a very detailed study of chip formation, Itava and Ueda (1976) proved the existence of such a crack. Moreover, they concluded that the continuous chip forms only under relatively specific (or, exotic) cutting conditions such as when pure single crystal aluminium is machined. Similar phenomena were observed by Astakhov (1998) and Didjanin and Kovac (1997). One of the most prominent specialists in materials behaviour and fracture Professor Atkins in his book (Atkins and Mai, 1985) stated (Section 10.5 Cutting, p.773) "Whether fracture of chip occurs into discontinuous chip formation is subsidiary issue … fracture is inherent is *continuous* chip formation in all material-removal (separation) process". Recently, Atkins (2003) in his excellent paper provided a methodology to account for the energy associated with crack formation in metal cutting.

Komanduri (1993) in his detailed review pointed out that although the type of chip formation under various condition for different materials was reported by many researches as, for example by Boston (1926), Ernst (1938) presented classification of the three types of chip formation that finally became the common definition in the today's metal cutting literature. Although these chip types were identified by Merchant (1944) as 'classical' and this classification is still widely used today in many books on metal cutting (DeGarmo et al., 1997; Dieter, 1976; Gorczyca, 1987), no one pays attention to neither the way these chip types were obtained (cutting regime, tool and work materials, tool geometry, etc.) nor to the physical characteristics of these chip types.

As well known (Armarego and Brown, 1969; Astakhov, 1998; Childs et al., 2000; Oxley, 1989; Shaw, 1984; Trent and Wright, 2000; Zorev, 1966), the shape of the chip depends primarily on the work material, cutting regime and on the tool material and its geometry. According to Ernst (1938), these chip types were obtained in pure orthogonal cutting at extremely low cutting speed (2 in/min = 0.05 m/min) using very specific work materials (high lead bronze and low carbon, medium nickel chromium steel SAE 3115) and cutting tool (rake angle 23°). As conclusively proven by the results of numerous experiments presented by Zorev (1966), cutting physics and mechanics of the machining are entirely different at low and at high cutting speeds as well as the appearance, shape and metallurgy of the formed chip. Physically grounded chip classifications are discussed in detail by Nakayama (1984) and Nakayama and Arai (1992), Jawahir and Zhang (1995), Jawahir and Van Luttervelt (1993) and Astakhov et al. (1997).

Using the so-called card model of chip formation due to Piispanen (1937) and making a number of assumptions (Astakhov, 2005; Shaw, 1984), Merchant (1944, 1945a,b) developed the first complete shear plane model of chip formation that included the deformation model, velocity diagram and force model (popularly known as Merchant's force circle diagram or a condensed force diagram (Komanduri, 1993; Merchant, 2003)). Although a number of other models are known to the specialists in this field (Armarego and Brown, 1969; Boothroyd and Knight, 1989; Finnie, 1956; Lee and Shaffer, 1951; Okushima and Hitomi, 1961; Oxley, 1989; Shaw, 2005; Stenphenson and Agapiou, 1996), the single-shear plane model has surpassed all of them and is still the foundation for metal cutting in students' textbooks (e.g. DeGarmo et al., 2003; Kalpakjian and Schmid, 2001), studies on metal cutting (Shaw, 2005), computer simulations programs including the most advanced Finite Element Analysis (FEA) packages (e.g. Systems, 2004). A simple explanation for this fact might be that the single-shear plane model is easy to teach, to learn and to be incorporated in simplified numerical examples to calculate cutting parameters for student's assignments (Gorczyca, 1987). Although it is usually mentioned that the model represents an idealised cutting process (Shaw, 1984) and that quantitatively the shear-angle relationship has been found to be inaccurate (Armarego and Brown, 1969, p.48), no information about how far this idealisation deviates from reality is provided. It is also interesting to recount the history of this model which was the first model developed (Time, 1870), rejected (Zorev, 1966), then widely accepted in the early 1950s and remains as 'a paramount' today (Astakhov, 2005). Even though a number of more realistic models of chip formation have been developed and verified (e.g. Fang and Jawahir, 2002; Fang et al., 2001; Jawahir and Zhang, 1995; Jawahir et al., 1997), specialists and practitioners in the field still use the single-shear plane model, a significantly inferior model by the author's opinion (Astakhov, 2005). This important issue, having the greatest theoretical significance and wide practical application in the optimisation of various cutting process, must be addressed in metal cutting research.

3 Experimental studies

The era of methodological experimental studies in metal cutting began in 1907 when Frederic W. Taylor published his milestone work "On the art of cutting metals" (Taylor, 1907). Summarising a great body of experimental results, he proposed the following relation between the cutting speed and tool life known today as the Taylor's tool life formula

$$vT^n = C_T \tag{1}$$

where v is the cutting speed, T is tool life in minutes, C_T is a constant into which all cutting conditions affecting tool life must be absorbed known as 'Taylor Constant' (Kronenberg, 1966), which is the cutting speed for a tool life of 1 min, n is an exponent which depends on the properties of the work material.

Although Taylor's tool life formula is still in wide use today and is in the very core of many studies on metal cutting including the level of National and International standards (e.g. ASME Standard on Tool Life Testing, 1985), one should remember that it was introduced in 1907 as a generalisation of many-years experimental studies conducted in the 19th century using work and tool materials and experimental technique available at that time. Since then, each of these three components underwent dramatic changes. Unfortunately, the validity of the formula has never been verified for these new conditions. Nobody still proved that this model valid for any other cutting tool materials than carbon steels and HSS. Nowadays, more sophisticated assessments of tool life that account not only for the cutting speed but also for the cutting feed, tool geometry, depth of cut and many other parameters of the cutting system are used (Astakhov, 2004a,b; Kronenberg, 1966; Mills and Redford, 1983; Schey, 1983).

A real breakthrough in experimental studies on metal cutting was made by Makarow, who introduced a notion of the optimal cutting temperature. Analysing a great body of experimental data, Makarow (1976) formulated the law, which was presented as the first metal cutting law (the Makarow's law) by Astakhov (1998, 2004a,b):

For given combination of the tool and work materials, there is the cutting temperature, referred to as the optimal cutting temperature θ_{opt}, 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 pre-heated etc.).

As explained by Astakhov (1998, 2004a,b), the cutting temperature is understood as the mean integral temperature at the tool-chip and tool-workpiece interfaces as measured by tool-work thermocouple. As conclusively proven by Makarow (1976), this temperature is the most suitable parameter to correlate the tribological conditions at the tool-chip and tool-workpiece interfaces with tool wear. As this optimal cutting temperature is a function of only the work and the tool materials, it can be established once and then be used for the optimisation of cutting process in various cutting operations where the same work and tool materials are used.

Yet another aspect in metal cutting studies is the so-called high-speed machining. Today high-speed machining is in vogue. Some high-speed machining operations are becoming old hat. High-speed milling of aluminium, for example, is an application that is about 15 years old. But high-speed applications on other, tougher metals is still relatively new (Dudzinski et al., 2001). The concept of high-speed machining was conceived by Carl J. Salomon, who conducted a series of cutting speed on non-ferrous materials and reportedly found that the cutting temperature, reaching its maximum at certain cutting speed, then decreases with further speed increasing (King, 1985). Although no further researcher was able to repeat this test and thus obtain the same result, the idea of high-speed machining became very attractive for researchers and practitioners when high-speed machine tools and advanced tool materials become available and when the volume of machining of non-ferrous materials (e.g. aluminium alloys in the automotive industry) started to experience exponential growth. There are several challenges to getting to the bottom of this issue, not the least of which is trying to define 'high-speed'. It depends on the material, the type of machine, the type of insert, the type of application, etc. Today the common convention defines 'high speed' as any speed above conventional for any material. The concept of high-speed machining, however, is gradually overpowered by a new concept of high efficiency machining.

4 Numerical studies

As experimental studies on metal cutting are expensive and time-consuming, the numerical modelling was developed and applied as an alternative (Ceretti et al., 1996; Hoefler and Kumar, 1998; Huang and Black, 1996; Kim and Sin, 1996; Komvopoulos and Erpenbeck, 1991; Mackerle, 1999; Marusich and Ortiz, 1995; Shih, 1995; Strenkowski and Carroll, 1985). Amongst the numerical methods used to model metal cutting, Finite Element Method (FEM) is the most frequently used. The goal of the FEA is to predict the various outputs the metal cutting process as the cutting force, chip shape and its structure, levels and distributions of temperatures, stress, strain, heat, residual stress induced in the workpiece, tool-chip and tool-workpiece contact stresses, etc.

Although modelling of cutting process using sophisticated FEM software packages becomes popular and many researchers try to refer to the results of such a modelling as to something conclusively proven, there are many points of doubt in every complex computer program. It should be very clear that the FEM software incorporates many assumptions that cannot be easily detected by its users but that affect the validity of the results. There are several sources of errors, which can lead to poor approximation (or even a solution completely different) of the real case (Beer and Watson, 1992). Among them, the following are important in metal cutting:

1 poor input data due to the lack of information about the cutting process

2 oversimplified assumptions

3 improper modelling of the boundary conditions

4 numerical round-off (in solving the simultaneous equations) in the computer

5 discretisation error and

6 errors associated to remapping.

Successful FEM requires vigilance and the same visual knowledge and intuitive sense of fitness that successful researchers have always depended on when making critical conclusions. If we are to avoid calamitous conclusions, it is necessary for researchers to understand that such errors are not errors of mathematics or calculation, but errors of engineering judgement based on the lack of understanding the physical backgrounds, particularly machining. Mathematical models, including FEM models cannot output more physics than that was put into them. If a mathematical model used in computer-based simulation of machining is not based on the correct physical model then the results of such a simulation have no value.

The foregoing discussion suggests that the studies on metal cutting and machinability of engineering materials are very important to meet the challenging requirements of today's competitive marketplace.

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