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MANUFACTURING SCIENCE AND TECHNOLOGY

Introduction

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Metal cutting is clearly an engineering sector that is greatly impacted by rapidly changing technology and global competition. Recently, there has been dramatic increase, worldwide, in the number of studies which have applied different research techniques to various facets of the machining process. Unfortunately, a much smaller volume of research has been devoted to discovering the fundamental mechanisms within the metal cutting process, as opposed to seeking case solutions for particular machining problems. The ultimate objective of the science of metal cutting is the solution of practical problems associated with material removal in the metal cutting process. To achieve this objective, the fundamental principles governing the cutting process should be revealed. A knowledge of these principles makes it possible to predict the practical results of the cutting process and thus to select the optimum cutting conditions for each case.

This symposium includes contributions from researchers and industrial practitioners that address leading edge issues with regard to metal cutting. It is hoped that these papers help to identify a focused metal cutting research agenda for the next century. The symposium consists of a total of 30 papers, that underwent a rigorous peer review process. The symposium includes excellent papers authored by researchers from Canada, France, Greece, Poland, R.O.C., Singapore, Ukraine, and USA. The papers cover topics such as: modeling of machining, evaluation of machining, materials behavior, and stability of machining. The symposium includes a keynote paper titled "Material Properties as Indicators of Machining Behavior" by R. Stevenson from the General Motors Research and Development Center.

A large number of individuals deserve recognition for their efforts related to putting this symposium together. Foremost among these are the researchers who submitted their works for publication and agreed to present and discuss their results and the reviewers who provided timely and critical reviews. Finally, we would like to thank the ASME Manufacturing Engineering Division for their support of the symposium.

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IMPLEMENTATION OF THE LATEST BREAKTHROUGH IN THE PHYSICS OF MATERIALS IN METAL CUTTING: ANALYSIS AND PRELIMINARY RESULTS

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ABSTRACT

Everyday practice of cutting process planning requires reliable cutting force estimates, which currently can be obtained only from process-dependent machinability databases. The greatest obstacle to developing a more basic, efficient approach is a lack of understanding of material behavior under unique deformation conditions of cutting. The metal cutting process has been defined by the authors earlier as the purposeful fracture of workpiece material and, therefore, a new way to minimize the energy consumption per unit volume of the layer to be removed in cutting should be revealed in order to predict metal cutting performance. Unfortunately, the traditional mechanical metallurgy has too little to be used for such a purpose. This paper deals with practical applications of the equation of state of a solid to the metal cutting process. It is shown theoretically and proven experimentally that the energy consumed in cutting can be effectively controlled by applying external force fields to the workpiece.

1. INTRODUCTION

In many machining operations the work material is a major machining factor over which the manufacturing engineer has the least control. He can, in many ways adapt the cutting tool, the machine tool, the cutting fluid to a specific job, select the cutting kinematics, the cutting regime, the tooling (jags, fixtures, adaptors, etc.). That is to say that he/she can design a machining operation completely. However, the work material as specified on a design drawing and then on a process sheet can seldom be changed, even if machining proves very difficult and expensive. Therefore, in view of costly work materials, tight work schedulers, and difficult machining, the fullest possible knowledge of materials properties involved in machining is of high importance. The problem here is how to select relevant properties and then how to use the selected properties in the design of machining operations.

The properties of metal have been studied ever since Man discovered that he could change the hardness of steel by heating it to a bright cherry red and then quenching it in water or other suitable media. What happened to the metal was first theorized, but then, as instruments for study improved, facts replaced theory. Mechanical metallurgy as a fact-based science has been developed. For a long time since then, it was an impression that, with progress in physics of solids, the development of a physically-based theory of plastic deformation of metals was just a matter of time. However, it has not yet happened. In spite of great accomplishments in the investigation of the nature of deformation, strength, and fracture of solids, a lot of problems related to the physics of these phenomena remain unresolved. It seems that within the scope of the conventional ideas their solutions are not possible.

One of the most impressive developments has undoubtedly been dislocation theory which accounts for many of the characteristics of crystalline solids, in particular the behavior during plastic deformation. The concept of dislocation was proposed independently by Taylor, Orowan and Polanyi in 1934 (Dieter, 1986) . Although in the last 20 years extensive research had developed a variety of techniques for observing and studying dislocations in real materials, no practical way to apply the theory of dislocation behavior to study plastic deformation of polycrystalline aggregate were suggested. Several comprehensive books have been written on this subject, but there seems to be definite need for a text which systematically describes the actual behavior of metals and alloys during various types of deformation, and attempts to explain this as far as it possible in terms of dislocation theory. The known attempts (for example [3]) are of academical rather than practical concern.

The theories of elasticity and plasticity describe the mechanics of deformation of most engineering solids. Both theories, as applied to metals and alloys, are based on the experimental studies of the relation between stress and strain in a polycrystalline aggregate under simple loading conditions . Thus they are of a phenomenological nature on the macroscopic scale and, as yet, pertain little to the structural knowledge of a metal.

Although it is recognized that during cutting processes many different phenomena occur: elastic and plastic deformations, external and internal friction, thermal phenomena, strain hardening and thermo-softening, phase transition, absorption, etc. and state of stress in the deformation zone is not uniaxial, the mechanical properties of workpiece material obtained in a simple tension test are used (sometimes with certain modifications accounting for high temperature, strain and strain rate in the deformation zone). The book on plasticity by Johnson and Mellor (1983) begins with the following quote (from the work by Orowan) "The tensile test is very easy and quick to perform but it is not possible to do much with its results, because one does not know what they really mean. They are the outcome of a number of very complicated physical processes. The extension of a piece of metal is in a sense more complicated than the working of a pocket watch and to hope to derive information about its mechanism from two or three data derived from measurement during tensile testing is perhaps as optimistic as would be an attempt to learn about the working of a pocket watch by determining its compressive strength." In other words, it is not clear how to correlate the properties obtained in the standard tensile test, where a uniaxial state of stress is the case, with those involved in deforming processes, where triaxial states of stress complicated by high strains and strain rates are common.

It seems that at the present stage of development, the predictability of a metal cutting theory depends entirely on the accuracy with which it accounts for the properties of workpiece material since the design and geometry of the cutting tool along with the properties of tool material are well-known and the cutting regime can be set at any desirable level and/or can be varied according to any defined sequence. However, it is arguable that the mechanical properties of workpiece material seem to be also well-known and tabulated in the corresponding reference books. Since the model for cutting is known, the prediction of metal cutting performance should not be a problem. In reality, this is not the case since it is unclear how to apply the know mechanical properties of workpiece materials in metal cutting studies and/or how to determine, if necessary, the additional relevant properties which are not tabulated.

This paper presents a new approach to material characterization in manufacturing. The approach is based on the derived physical equation of state of solids and new atomic-molecular (AM) concept of fracture. Our considerations cover the full range from the micro-level consideration of physical behavior of an AM-complex where the physical and mechanical properties of solids are formed to the macro-level and technological applications where the statistically averaged parameters of the AM-complex (such as strength, durability, temperature deformation, etc.) are interpreted.

Attention is diverted to the fact that known books on the subject (e.g. Pollock, 1993; Sutton, 1993; Felbeck and Atkins, 1996; Nishida, 1992; Hertzberg, 1989; Gitts, Zarka, Nemat-Nasser, 1987; Pettifor, 1995; Harrison, 1989, Atkins ans Mai, 1985; Smith, 1986) do not consider the physics of materials resistance to various external effects (external forces, fields, etc). Although these books consider a number of micro-level phenomena including the property of AM bonds, dislocations, etc., the micro-physics of materials is still poorly related to their macro-physics which actually defines their behavior. In contrast, the proposed approach explains and illustrates the practical relationships between the micro- and macro-properties as well as the use of these in fracture control. The latter means that, using the models, the fracture of a particular material can be promoted as it is desirable in metal cutting (Astakhov, 1998a) or delayed as it is desirable for machine parts and other structural elements. An issue of high importance here is that in either application, fracture can be reliably predicted.

2. PROPOSED APPROACH

The proposed approach is based on the solution of one of the most fundamental problems in technical physics, namely, the problem of physical state. This state is descried by the equation of state of solids proposed by Komarovskiy (Komarovskiy, 1997) in the following form

$$p\ V = \left[\mu_c \left(\frac{eT}{\Theta_D} \right)^3 - \mu_d \right] N_b \tag{1}$$

Equation (1) parallels with the known equation of state for gases

$$p\ V = n\ R\ T \tag{2}$$

where p is the pressure, V is the volume, n is the number of moles, and T is the temperature of the gas.

As seen, the universal gas constant $R = k\,N_a$ equal to the product of the Boltzmann constant k and Avogadro's number N_a is transformed into the functional shown in square brackets of Eq. (1).

Equation (1) establishes the correlation between the internal pressure p that keeps certain dimensions and shape of the body in a given volume V and that overstands the external effects which try to change these dimensions and/or shape, from one side, and the temperature T distributed over AM-bonds N_b according to the value of Maxwell-Boltzmann factor (eT/Θ_D) formed on solidification of the considered body, from the other side. Other designations are: e is the natural constant ($e = 2.718...$); μ_c and μ_d are chemical potentials of compression and dilation AM-bonds, respectively. They can be calculated as:

$$\mu_c = k\ T\ , \quad \mu_d = k\ (0.4\ \theta_D + T) \tag{3}$$

Θ_D is the Debye temperature (hereafter the D-temperature).

Solid, liquid, and gas states of matter differ in the kinetic energy of the atoms. These states are clearly separated by the freezing (melting) and boiling points of a substance. In our opinion the D-temperature should be added to these two points when a crystalline solid is considered. In contrast to the freezing (melting) and boiling points, the D-temperature does not change the state of a solid but changes it solid phase into two principle different solid states: compression and dilation. The structure of most metals and their alloys include mainly compression bonds and such material may be referred to as compression materials. Cast irons and other brittle materials have dilation bonds AM-structures and such materials are referred to as dilation materials. The D-temperatures for compression and dilation materials are found in different regions of the temperatures scale. This temperature is close to room temperature for the former and it is close to zero (in the Kelvin scale) for the latter. Due to this fact, compression materials can undergo solid state transformations in the external energy fields while dilation materials cannot. This explains the observed great differences in the studies of their behavior and physical-mechanical properties.

3. ANALYSIS OF THE EQUATION OF STATE OF SOLIDS

Equation (1) facilitates the understanding of the AM-mechanism of materials deformation and fracture. In this equation, parameter p, which defines the materials resistance to the applied external effects, has a vector nature causing orientation effects in structures under applied loads. Scale parameter V accounts not only for scale transformations (when the initial shape is preserved) but also for form transformations (when the initial volume is preserved). This statement can be easily explained if parameter V is expressed through the cross-section S and length l of a body as $V = S\ l$. After differentiating one can obtain