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FOREWORD

The organization of this symposium started during a sabbatical year that Klaus Weinmann spent at the University of Minnesota. Discussion about the issues and results in machining process research led to two realizations. The first was that machining research is still a lively activity and new, important results are being produced. In the course of discussing the development of this research, the seminal role of Branimir F. von Turkovich became clear. The general impression of the importance of his work became increasingly explicit. Major contributions to process understanding and the intellectual growth of many people in the machining research community changed from a general appreciation to specific instances and particular cases. With this basis the symposium was organized with two goals. It is intended to provide a view of current research in machining and so indicate the issues and directions set by the research community. It is also an attempt to recognize the contribution of Brani von Turkovich in bringing about the current state of research and researchers.

Taking stock of a research area usually leaves out the personalities involved since the convention is to publish only definite results. This is especially true in an indirect approach such as this compilation of current research works. There is, in fact, no commonly available way to pay adequate tribute to individuals. Rather than listing a series of accomplishments here and producing an obituary-like Foreword, we only note that many professional and personal lives have been positively influenced by Brani von Turkovich. Of this there is no doubt and to this there are many witnesses. This symposium is dedicated fondly to Branimir F. von Turkovich.

B. E. Klamecki
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CONTENTS

THE METAL CUTTING RESEARCH OF B. F. VON TURKOVICH

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INTRODUCTION

The intent of this paper is to review one area of the research work of Branimir F. von Turkovich. The work of interest is that concerned with metal cutting theory. The specific work reviewed is further limited to that published in widely available sources. The narrowing of subject and source is not confining because of the high quality and large amount of research performed. Also the talent, approach and insistence on completeness seen in this body of work indicates the high quality of research in other areas and sources.

In addition to tracing the development of process models of the metal cutting chip formation process, an interpretation of the development direction is interjected. The hope is that what emerges is a description of a major body of work and of a unique view of how problems should and can be studied. The distinctive von Turkovich view of process modeling materializes as demanding appropriate physical foundations, completeness in including all aspects of the process into the model and rigor in development of the problem set forth.

DISLOCATION BASED CHIP FORMATION MODELS

In 1963, two papers by von Turkovich and Trigger were published which show a unique view of the metal cutting process and the modeling of it. The first of these two papers, von Turkovich and Trigger (1963), starts with the development of a model of the shear zone. What may at first sight appear to be a logical extension of the shear plane model quickly moves in a new direction. Considerations of shear zone geometry and forces lead to study of the shear stress in the shear zone. In a list of starting assumptions labeled (a) - (j) is (d) which introduces the ideas of dislocation density and configuration. An argument is sketched for the variation of shear stress through the shear zone in terms of dislocations.

The issues of dislocation generation, motion and annihilation along with cutting conditions and material characteristics controlling these processes are raised. Most of the formalism presented is along phenomenological lines with a plasticity analysis but an offshoot appears when the analysis proceeds with the use of a "τ." In addition explaining this shear stress in fundamental physical process terms was raised. The central role of work material strength variation in determining machining/process characteristics means that this material based approach can put process understanding on a fundamental basis.

The companion paper, Trigger and von Turkovich (1963b) presents machining test data and is most interesting in the choice of experimental variables. Cutting forces were measured for various workpiece materials and purity and initial temperature. These factors are expected to have large influences on dislocation processes. Such fundamental processes are discussed with regard to explaining measured chip hardness.

The written discussions of these two papers are striking in that they consider and complement the experimental work and phenomenological description of the chip formation process while ignoring the fundamental physical processes introduced. This may be due to the interests of the discussers. It may also be due to the lack of detailed development of the dislocation based deformation model in this initial work. This latter situation changed rapidly.

The atomistic approach to describing the machining process was clearly put forward in a pair of papers, von Turkovich (1967) and von Turkovich and Calvo (1968). The detailed development of a dislocation mechanics description of the deformation in chip formation started and phenomenological plasticity was left behind. With prediction of the shear stress as the goal, the first of these papers starts with cutting tool motion imposing a strain, γ, on the workpiece which implies dislocation generation. The dislocation formation energy, E_d, is the energy rate supplied to the process

$$\tau\dot{\gamma} = \dot{\rho}E_d$$

By expressing $\dot{\gamma}$ in terms of ρ the stress was shown to be

$$\tau = KGb\rho^{1/2}$$

with K a constant and G, b and ρ the shear modulus of the work material, the Burger's vector and the dislocation density. Estimates of the shear stress value compared well with measured values from cutting tests.

In most cases in which there is a combination of a unique view of problem solving and real insight into a process, relatively uncomplicated process descriptions result. In this case the shear stress depends on an atomic binding characteristic, G, a fundamental structural characteristic, b, and a measurable, physically meaningful quantity, ρ.

Dislocation annihilation processes which come with dislocation motion were introduced in the 1968 paper. Again, the starting place is a phenomenological description and the intent is to attach a fundamental physical meaning to it. Workpiece temperature depends on the energy supplied, $\tau\gamma$, and workpiece heat capacity and thermal conductivity. The question raised is the description of the energy conversion process. The dislocation annihilation rate was calculated as dependent on vacancy generation rate and movement. The result is a detailed, dislocation based model of work material recovery.

Dislocation generation and annihilation processes correspond to the macroscopic concepts of work hardening and recovery. Further, the rates of the two opposing processes have implications in chip formation deformation. Adiabatic instability is mentioned and this along with nonuniform deformation and chip segmentation appear on the horizon.

With the use of dislocation mechanics to describe plastic deformation, the need for an extended physical space for these material processes is recognized in a study of shear zone models, von Turkovich and Micheletti (1968). Flow zone models are considered in detail and research needs described.

Nonuniform or inhomogenous deformation was of direct concern in work published in 1970, von Turkovich (1970). The paper describes dislocation processes along a shear plane and not only advances the state of process description but also makes contact with macroscopic manifestations of dislocation events. The ends of the shear plane are dislocation generation sites. Dislocations move and interact on the shear plane with dislocation velocity decreasing with increasing dislocation density. When the dislocation creation and annihilation processes are modeled taking into account the density-velocity relationship regions of varying strain result.

Relatively narrow bands of high strain are followed by wider regions of lower strain. This general result is seen to be the case in observations of chip structures. In addition the model can explain changes from strain hardening to strain softening behavior in terms of macroscopic stress-strain characteristics. What has become available then is the possibility of testing and using the models in macroscopic settings. It is not necessary to measure dislocation density to test the models - they predict macroscopic consequences. Conversely, adequately tested models can be used to describe microscopic events. The natural questions are then, are the dislocation mechanics concepts useful and the resulting models valid? Experimental study is called for but it must be able to address dislocation level processes.

PRIMARILY EXPERIMENTAL WORK

Dislocation densities are very high in workpieces being deformed in machining processes. But large density is no real help in process model evaluation since density measurement is difficult regardless of density level. What is easier to assess is change in dislocation density and happily the metal cutting process produces widely varying extent of deformation even in so-called steady-state machining.

Nonuniform deformation along the chip was predicted in the 1970 paper. In the same year a paper, von Turkovich and Black (1970), appeared which showed a definite, apparently ubiquitous chip structure. Metal cutting chips show narrow regions of intense shear alternating with wider regions which are less deformed. The extent of deformation and deformation variation provide a curious chip structure calling for an explanation and against which explanations can be measured. A goal is the prediction of the spacing between the regions of intense shear in the inhomogeneously deformed chip.

Two machining situations which may help clarify issues related to deformation in chip production are the initial stages of engagement of the tool with the work and macroscopically non-steady-state cutting. The Weimann and von Turkovich (1971) work shows an interest in the development of the shear zone. Microhardness measurements and recrystallization studies were performed for varying degrees of initial tool-work engagement. The fully developed shear zone is where the deformation processes take place and so its boundary conditions need to be specified. What also comes out of this work is an indication of the extent of deformation before a fully formed chip emerges. Extending these results to a chip formation criterion is an important, fundamental material behavior issue. Machining is a material separation process and while analysis of it and analysis techniques have advanced in sophistication, significant questions remain about how to describe the material separation process itself and how to describe it in analyses.

Another example of a different, insightful approach to problems is the work of Pleck and von Turkovich (1973). The machining process was studied using an apparatus in which the work was driven by a falling weight. Engagement of a cutter with the work results in a work velocity change determined solely by the chip formation process. Measurement of cutting forces and chip thicknesses as functions of freely decreasing cutting speed were made. Interpreting specific results is difficult but a subtle, overall strategy is seen. It seems that an attempt was made to get at the basic mechanical processes occurring in machining by letting the process run freely. This is in contrast to other chip formation research in which a constant cutting speed is imposed and so material deformation rate is, at least in part, set by the machine used not by the fundamental processes of chip formation. As in the case of chip formation criteria implications that arise in reading the Weinmann and von Turkovich paper, very basic issues and concepts materialize when reading Pleck and von Turkovich. For example, the typical Merchant type model of chip formation has been used in many forms to both describe the process and predict shear angle. The principle used for predicting process behavior is an energy minimum idea. The use of such a principle in model development or verification of models based on it seem to be more appropriate in the situation of a freely running, unconstrained process. Chip formation will be determined by material response not by material response under imposed deformation conditions.

Much of the experimental work shows real insight into both the machining process and material deformation and a unique view of how the study of these processes should proceed. How the work did proceed was by the development of process models using fundamental physical process concepts. The path is the generalization of basic concepts to the description of chip formation and the use of experimental results for confirmation of model validity. The approach of generalizing experimental results to process models and model development strategies was not followed.

FURTHER PROCESS MODEL DEVELOPMENTS

The primary experimental observation that carries over into further quantitative process description development is the nonuniformity of deformation evidenced in chip structure. Since some regions of the chip are severely deformed over very small regions separating wider, less deformed areas the prediction of deformation zone spacing is the obvious challenge. Given] the apparent content and style of earlier work such a prediction should probably be viewed as a validation of the process modeling procedure used and the model developed not as the goal. But the results are definite and do indicate nearness to a complete model, von Turkovich (1972, 1974).

The 1972 paper directly addresses the questions of adiabatic shear in chip formation. A continuum, energy balance formulation was employed to describe heat flow in a parallel sided shear zone. The model is made specific to chip formation in the heat generation term. The energy rate input is $\tau\dot{\gamma}$ and $\dot{\gamma}$ is expressed in terms of τ. The resulting shear zone temperature behavior is considered in terms of whether the heat generation rate is sufficient to increase temperature faster than it is lowered by conduction. The solution obtained is the critical shear layer thickness at which this type of temperature effect makes the deformation process unstable. What is obtained is a parameter which depends on work material strength and thermal properties and shear zone thickness. A critical value of this parameter separating regions of steady state and unstable deformation was obtained. The 1974 paper starts with the continuum energy balance equation.

The power input, $\tau\dot{\gamma}$, is expressed using dislocation generation rate based constitutive relations. A process behavior controlling parameter is developed in the analysis and a critical value of it calculated for which the process is unstable. In this work process instability refers to the condition at which work strength decreases with increasing temperature to a level such that the work cannot support an applied stress. This condition is expressed in terms of shear zone size and hence spacing between intense shear regions on chips is available.

This last paper may be viewed as the real culmination of dislocation mechanics based description of deformation in chip formation. Further refinements will be seen but they are overshadowed by an interesting, unexpected turn in outlook and concept development.

REFLECTIONS AND FURTHER EXPERIMENTAL WORK

Publications in the early 1980's summarize the problem areas in the general task of describing chip formation. It is interesting that these opportunities to present a personal perspective of machining process research were used to point out disciplinary areas of study rather than to review results developed over the previous 20 years. In 1981, two papers appeared, von Turkovich (1981a, 1981b), listing research areas that needed to be developed in order to advance metal cutting theory. As by now expected the list is of true problem areas not a list of narrow, process specific problems. Chip formation as a specific, complicated process must still fit in an engineering science framework. The areas of mechanics, kinematics, thermal processes and materials are discussed. What emerges is an emphasis on thermo-mechanical process coupling and the role of the work material in providing the feedback paths for interactions between fundamental processes. In addition to general process governing principles material specific approaches are needed.

The second of these two papers opens in a distinctive way. The limited need for detailed chip formation is pointed out. Applications such as high precision machining and chip control are pointed to as areas in which detailed analyses are useful. Rather than discussing the importance of these applications, the paper goes on by noting that a wide variety of materials produce essentially the same kind of chip structure. This observation leads to questions about which basic principles govern a deformation process so varied as machining. Typically, synthesis and generalization are the rule.

In a similar vein but with a different focus, the response of the tool and finished workpiece surface to the machining process are discussed in von Turkovich (1983). The limits of classical mechanistic analysis are pointed out leading to two conclusions. One is the need to broaden the engineering science base used in the studies of the cutting process. The other is that extensive experimentation is needed if the many aspects of the process are to be clarified and if process descriptions are to be adequately evaluated. This experimentation issue is picked up again in von Turkovich (1987). The argument is made that the importance of manufacturing is leading to the acceptance of manufacturing as a valid research topic and has resulted in a rapidly increasing number of research papers. The opinion expressed is that the number of high quality papers is decreasing. The reason given for this situation is that adequate processing research requires experimental work and there is a lack of equipment and laboratories for doing essential testing. Since new processes are being developed and there are gaps in the understanding of existing processes, experimental research is needed but is not being done at the level needed.

Contact between microscopic level deformation models and macroscopic machining processes was made on three fronts. Ramalingam and von Turkovich (1980) considered work material issues in linking machinability to work material structure. The effects of inclusions in the workpiece on tool wear are modeled and so the chip formation process is implicitly included in the analysis. While chip formation is not directly addressed there is a shadow of the earlier machining process modeling viewpoint. The effects of number of inclusions, their distribution and size are described. The inclusions are distinct, discreet entities and they are described by an integer just as number of dislocations was the basic variable in chip formation modeling.

More direct correspondence between deformation process models and macroscopic material behavior is seen in considerations of using machining as a material property test and in studies of chip structure. While not the first time metal cutting was suggested as a high strain, high strain rate property test the results obtained and reported in the work of Durham and von Turkovich (1983) and Brown, Durham and von Turkovich (1986) are unique. Two aspects of this work stand out. First τ–γ–$\dot{\gamma}$ curves are presented. The machining process is controllable enough and the analysis of it accurate enough to produce useable results. The second result is that at large strains and high strain rates shear stress decreases with strain. The occurrence of a maximum in the τ–γ curve and strain softening behavior was predicted in the process modeling work. An interesting description of the limits of material behavior as isothermal and adiabatic is used. These are precise definitions of deformation conditions but the use of them to describe deformation processes will be seen to refer to a new, more general approach to modeling the chip formation process.

The segmentation of machining chips is the topic in the papers by Komanduri and von Turkovich (1981) and the subsequent Komanduri et al. (1982) paper. Visual observations of chip formation and qualitative descriptions of it are presented in the first of these papers. Two clearly different deformation processes are expounded. A primarily compressive deformation likened to upsetting is followed by the growth of a narrow band of intense shear. These processes are cyclic and a chip with periodically varying degrees of deformation results. The second paper is concerned with explaining the shear localization process. No clear detailed explanation is evident probably due to the many possible explanations and the numerous authors so that all views get expressed. An important issue at the conceptual modeling level does emerge. With different deformation processes combining in the overall material removal process the description of chip formation as strickly shear deformation appears inadequate. Chip formation models must have the ability to describe many modes of deformation. The a priori assumption of a form of deformation should be avoided. The need is for very general modeling techniques and process descriptions. Also lurking is the problem of defining a chip formation criterion.

GENERALIZATION OF PROCESS MODELING TECHNIQUES

What might be the stirrings of some dissatisfaction with the generality of the process models developed is seen in a 1977 paper entitled, "Energy Conversion in Metal Cutting," von Turkovich (1977). The main theme of this work is the further refinement and extension of a dislocation based chip formation process model. The emphasis is on detailed description of the dislocation annihilation process and its usefulness in explaining constant stress and decreasing stress regions of $\tau-\gamma$ behavior. Energy dissipation concerns arise naturally in such considerations and the process is handled by starting with a very general energy balance. Mechanical work input is set equal to the energy rise of the workpiece and the analysis proceeds with describing the input in terms of dislocation processes. This first law of thermodynamics starting point is explicitly stated and may be the first mention of a different, broader view. The many relevant types of processes and problems - metallurgical, mechanical, thermal - are mentioned and it may seem possible to somehow integrate them in an energy based model. The von Turkovich (1979) paper takes this energy view a step further. On route to calculating shear zone thickness and adiabatic shear band spacing, plastic deformation and momentum change are expressed as energy balance and mechanical equilibrium. With respect to the initial problem formulation, two observations indicate a move toward a broader context in which to model the process. Continuum mechanics and energy balance equations appear explicitly and in fairly expansive form. Also, what seems to be a conceptually important step occurs. The general problem areas of mechanics, thermal effects and materials are included in the problem formulation in mechanical equilibrium, energy balance and dislocation mechanics equations. The last two of these are coupled as the mechanical power input for the energy balance equation is expressed in terms of mobile dislocation density. In a following paper, von Turkovich (1982), entropy is introduced into the analysis as an explicit variable. A very general process description is obtained which is cheated by calling it simply a thermodynamic model. It is a thermodynamic model in the full generality and power of this modeling approach. It includes mechanical, thermal and material property considerations explicitly. It provides the means for detailed, general description and analysis of chip formation as a particular case of material deformation.

Difficulties and complications arise in many process behavior descriptions when qualitative behavior changes can occur in the actual process. Failure of the process model to predict or even to be able to predict real behavior shows the model to be inappropriate or incomplete. The localization of deformation in chip production and the predictive description of it has been a concern running through a large portion of the research reviewed. It appears that the ability to describe the complex behavior resulting in nonuniform deformation has been a test of the process models developed. The most complete of these models is in von Turkovich (1986) which bridges the extremes of isothermal and adiabatic processes by introducing time explicitly into the model formulation. Along with force balance, energy conservation and material constitutive relations, an instability criterion is included. What is satisfying and distinctive about this criterion is that it is based on the existence of solutions to a set of characteristic equations. This is in contrast to the more typical adoption of a single material or process variable as somehow embodying all the relevant processes giving rise to an overall process instability.

AN OVERVIEW

Compressing the portrayal of the body of research above to a typical, few sentence summary does the work reviewed an injustice. The review probably does the same.

The interpretation given starts with a break from phenomenological plasticity descriptions of the deformation in chip formation. Very basic, physical aspects of plastic deformation were chosen and dislocation based process models developed. While this aspect of the process became more detailed, other factors were included expanding both the depth and scope of the models. In its full form the most developed model might be called a general thermodynamic formulation and development. At first glance, this may seem a return to a phenomenological viewpoint. A different, more considered view is that the very general process models defy the term phenomenological. The number of processes included and the dislocation based constitutive relations used are a unique blend of fundamental concepts and a distinctive view of process description. This may be a case where the increasing of the size of the problem resulted in a change in form of the process model. An unwillingness to settle for an incomplete or region-of-validity model has resulted in a general, useful model and real results.

A CONTRIBUTION

A large part of von Turkovich's metal cutting research has been concerned with dislocation based description of the chip formation process. The following is presented in the spirit of this work which has typically taken a unique and very basic view of physical processes.

In the research reviewed the terms dislocation generation, breeding rate and annihilation were used and suggest dislocation populations and population changes. This suggestion and the recent popularity of using population models as examples of iterated mapping was the starting point for a study of changing deformation in the shear zone.

In the typical two-dimensional representation of metal cutting processes a cutting tool moves through the workpiece and the chip is formed in a shear zone of area A extending from the cutter edge to the workpiece free surface. For present purposes, it is assumed that a rigid cutter moves through the work at a constant rate. Any power required is available and an incremental advance of the cutter produces a strain increment $d\gamma$. As described by von Turkovich (1970) the ends of the shear plane (zone) are dislocation generation sites. For the unit strain increment $gd\gamma$ dislocations are introduced into the shear zone. Existing dislocations breed at rate a so that the increase in dislocations due to n existing dislocations multiplying as a result of $d\gamma$ is an.

The imposed strain also causes dislocation motion and annihilation. In the extreme case each of the n dislocations can interact with the other (n-1) dislocations. Such interactions can result in dislocation annihilation by vacancy generation and motion resulting in dislocation climb as argued by von Turkovich (1970). The number of dislocations annihilated is a fraction b of the number of interactions and is bn (n-1). Combining the dislocation number increase and decrease for a strain increment the number of dislocations after strain increment i is

$$n_{i+1} = gd\gamma + am_i - bm_i^2 \qquad (1)$$

where n(n-1) is set equal to n^2 since number of dislocations is large. Dislocation density is n divided by the shear zone area A.

Ignoring g initially enables the use of well known results from population dynamics. With g = 0 and using z = (b/a)n equation (1) becomes

$$n_{i+1} = rz(1-z) \qquad (2)$$

in which $r = (a^2/b)$. One of five different kinds of population change behaviors results depending on the value of r which is the ratio of existing dislocation generation rate squared to the dislocation annihilation rate. In this case the rates are changes of number of dislocations per unit strain increment. For $0<r<1$ the initial population decreases monotonically due to the dominance of the death rate b. Changes in breeding and/or death rate so that $1<r<3$ produce monotonic population growth to a constant level. Oscillatory population behavior occurs for $3<r<3.4$. In the range $3.4<r<3.57$ so-called period doubling occurs and for $r>3.57$ erratic population changes occur. These last two types of behavior are said to be chaotic in that population behavior changes are deterministically described but so sensitively dependent on initial conditions that individual states of the population evolution are unpredictable.

Returning to equation (1), numerical simulations for a large number of cases showed oscillatory dislocation population behavior corresponding to nonuniform deformation behavior in the shear zone as predicted and observed in much of von Turkovich's work. A particularly simple example which shows the typical results obtained is for g = 1, a = 2 and varying value of b, Figure 1. The iteration increment is a strain increase which produces a unit increase in number of dislocations or in dislocation density for a constant two-dimensional shear zone area. For small values of b a constant population level is achieved after only a few strain increments. Oscillatory population behavior of increasing complexity is seen as b increases. Three observations are worthy of special note. Distinct oscillatory behavior over large numbers of iteration steps is seen for a large range of annihilation rate. Even for the complex behaviors a sort of periodicity over large imposed strain is seen. Making the large leap from this simple model to the physical process it seems that some type of oscillatory deformation behavior will be seen over a large range of dislocation annihilation rate. Finally, for values of b larger than 2 (at which population growth and decrease balance) varying population behavior is obtained before invariably the population goes to zero.

It is realized that this model does not consider the effects of dislocation population or density on the growth and annihilation rates. This issue is addressed overtly by adopting a variable strain increment assumed to produce a unit increase in dislocation generation at the shear zone ends.. Even in the simple model developed satisfying results are obtained. These show nonhomogeneous deformation which seems to be the hallmark of machining chip formation.

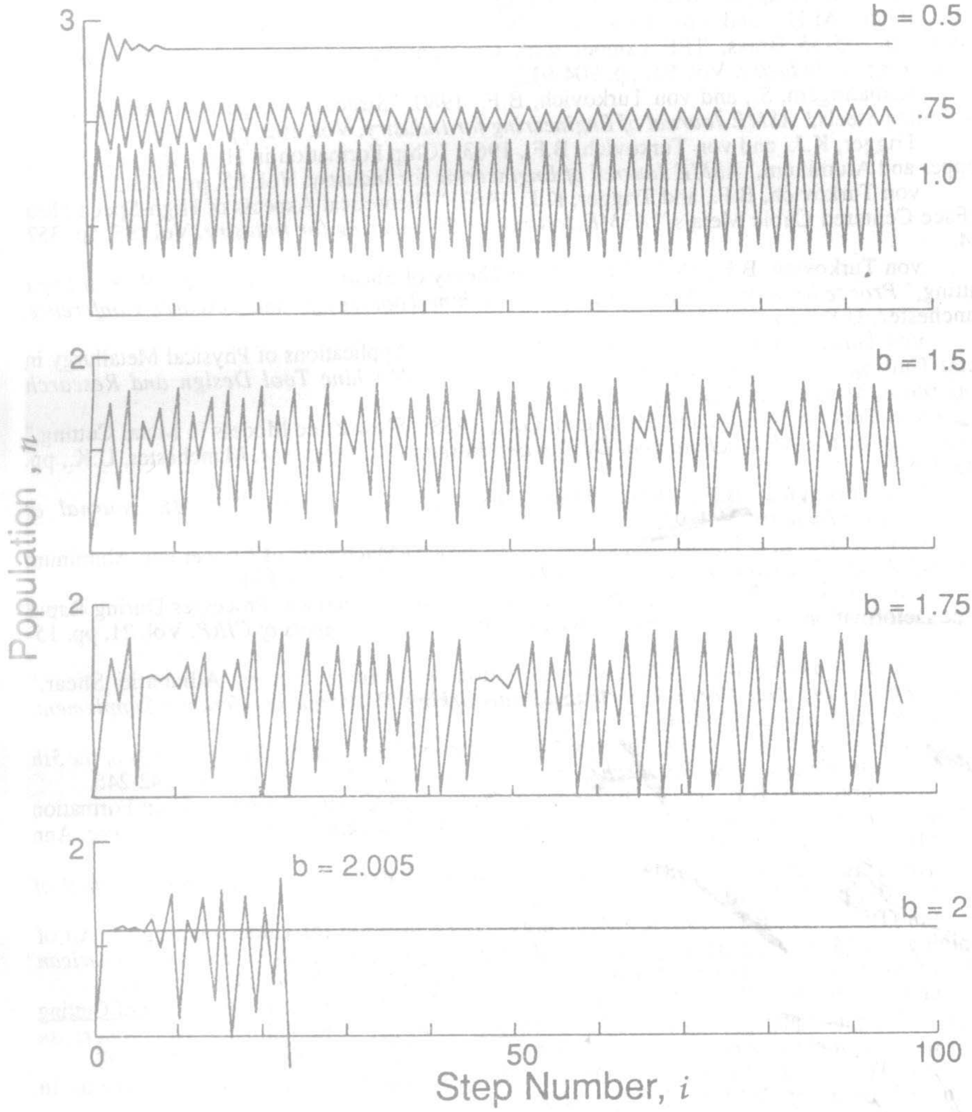

Figure 1. Dislocation population behavior with increasing strain for varying value of annhilation rate b.

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FINITE ELEMENT SIMULATION OF METAL CUTTING PROCESS WITH STRAIN-RATE AND TEMPERATURE EFFECTS

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ABSTRACT

The development and implementation of a finite element method for the simulation of plane strain orthogonal metal cutting process with continuous chip formation are presented. A four-node, eight degree-of-freedom, quadrilateral plane-strain finite element is formulated. The effects of elasticity, viscoplasticity, temperature, strain rate, large strain, and friction, which occur during the metal cutting process, are all included in the present finite element formulation. The separation criterion is based on the distance between the tool tip and the nodal point connecting the two elements ahead of the cutting tool. A local (near the tip of the tool) and a global mesh rezoning techniques are developed and used to enhance the computational efficiency and accuracy. The cutting and feed forces are calculated for the orthogonal cutting of a 1020 carbon steel sample. Under nominally identical cutting conditions, the cutting and feed forces are also measured experimentally. Comparisons between the experimental and finite element simulation results for cutting forces show good quantitative agreement. An order of magnitude agreement is also obtained for the depth of the plastically deformed zone. The versatility of the present finite element methods allows for displaying detailed knowledge of the metal cutting process, such as the distributions of temperature rise, yield stress, effective stress, plastic strain, plastic strain rate, hydrostatic stress, and deformed configurations, etc. at any instance during the cutting process.

1 INTRODUCTION

Metal cutting processes are widely used to remove unwanted material and achieve dimensional accuracy and desired surface finish of engineering components. In metal cutting process, the unwanted material is removed by the cutting tool which is significantly harder and more rigid than the workpiece. The width of cut is usually at least five times larger than the depth of cut and the chip is thus produced in a nearly plane strain condition (Shaw, 1984). In this study, a 2-D plane strain finite element method is developed and implemented to simulate the metal cutting process with continuous chip formation.

Experimental observations of the flow pattern in metal cutting with continuous chip (Boothroyd, 1975) show that the deformation of the work-material is concentrated around two deformation zones, as shown in Figure 1. The primary deformation zone extends from the tip of the cutting tool (A) to the junction between surfaces of the undeformed workpiece and the deformed chip. In this zone, the work-material is subject to large shear deformation at a high strain rate (usually around 10^3 to 10^5) (Oxley, 1989). The temperature rise in this zone is mainly due to heat generated by plastic deformation. In the secondary deformation zone, the chip is sliding along the interface between the work-material and the cutting tool. The strain rate is not as high in the primary deformation zone as in the secondary deformation zone but the temperature is higher, mainly due to the frictional heat generation. Based on experiments (Zorev, 1966; Boothroyd, 1975; Trent, 1984), the tool/chip interface is usually divided into a sticking (seized) and a sliding regions as shown in