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MACHINING AND GRINDING -- HIGH RATE DEFORMATION IN PRACTICE

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Introduction

Machining and grinding are well-established material-working operations involving highly non-uniform deformation and failure processes. A typical machining operation is characterized by uncertain boundary conditions (e.g.,surface interactions), three-dimensional stress states, large strains, high strain rates, non-uniform temperatures, highly localized deformations, and failure by both nominally ductile and brittle mechanisms. While machining and grinding are thought to be dominated by empiricism, even a cursory inspection leads one to the conclusion that this results more from necessity arising out of the complicated and highly interdisciplinary nature of the processes tnan from the lack thereof.

One aspect of machining and grinding operations that is clear is that they both involve highly non-uniform, large strain, and high strain rate deformation mechanisms. Chip formation during orthogonal cutting is described as a localized shearing process involving shear strains of between 2 and 4 and strain rates on the order of 10^5 s^{-1} [1, 2]. Grinding is reported to involve similar strains and strain rates coupled with higher surface temperatures than found in normal machining operations.

With these conditions in mind, the purpose of this paper is to outline the current understanding of strain rate effects in metals.

Rate Effects in Plastic Deformation

Deformation is accommodated in many materials by the generation and motion of defects. In metals, these can be dislocations or deformation twins. The kinetics of deformation processes are defined by the thermally activated interactions of defects with the crystal lattice or with other defects. There are many possibilities for accommodation mechanisms; the rate controlling mechanism depends on the temperature, strain rate and defect population at any instant.

The high strain rates attributed to machining and grinding tend to restrict the options for deformation behavior. For instance, at these strain rates deformation can be assumed to occur under adiabatic rather than isothermal conditions. However, creep mechanisms that require bulk transport (diffusion) are unlikely – even at the increased temperatures reached during machining – due to the limited time available for these processes at high strain rates.

The high strain rate deformation literature contains many references to a transition to viscous drag controlled deformation at strain rates exceeding 10^3 s^{-1} or so. Viscous drag deformation is characterized by a linear dependence of flow stress on strain rate – an exponent of 1 in a power law relation whereas the exponent at low strain rates is found to be closer to 0.1. A rate dependence of this magnitude, if it were to occur, would dramatically affect flow stress levels as well as the tendency toward strain localization. Recent work, however, has shown that this transition is unlikely except during shock loading [3].

With these restrictions, estimates of adiabatic stress strain curves at the strain rates reported for machining and grinding can be made according to models that describe thermally activated deformation in metals. While simple models for plastic deformation in metals are available, descriptive constitutive laws for machining and grinding need to accurately represent the strain hardening, strain rate dependence, and temperature dependence of the flow stress. Because of the very unique and severe conditions found in machining and grinding independent experimental verification is not always possible, which places a high premium on the foundation used to establish a constitutive relation.

We have developed one model that is capable of describing adiabatic deformation under large strain and high strain rate conditions. It is not the intent in this paper to describe in detail this model, which has been described previously [4,5]. Instead we would like to illustrate the trends predicted by such a model for conditions typical of machining and grinding. Figure 1 shows adiabatic stress strain curves in an austenitic stainless steel at a high strain rates and several initial temperatures. For comparison, a single room temperature (isothermal), quasi-static stress strain curve is included. The adiabatic nature of deformation at high strain rates leads to pronounced "thermal softening" in this material.

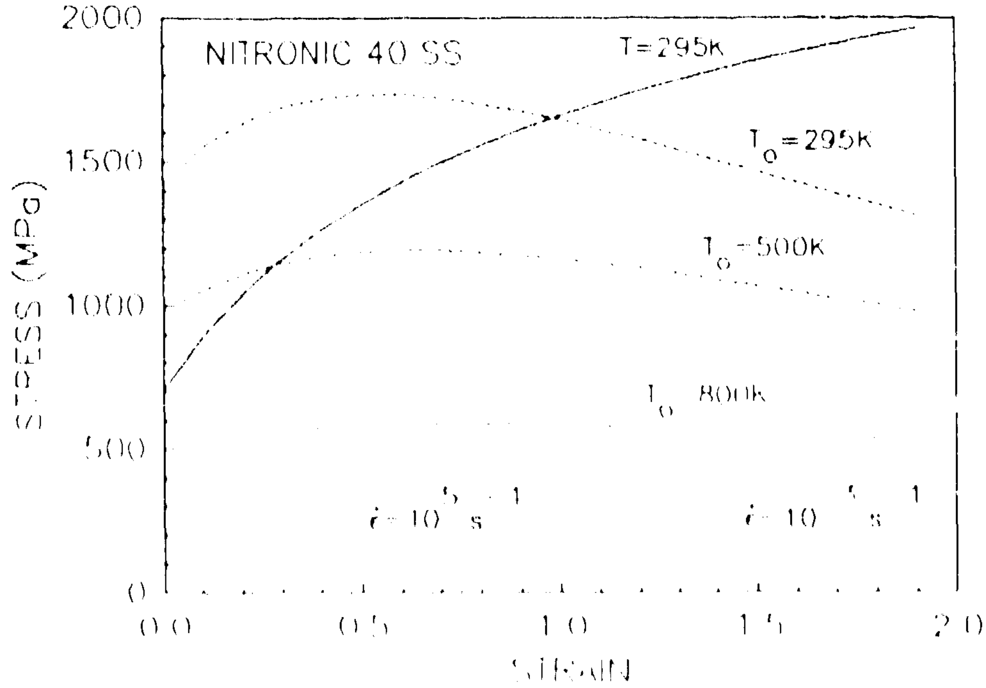

Figure 1: Predicted adiabatic stress strain curves in Nitronic 40 stainless steel at strain rates and temperatures typical of machining and grinding operations.

Strain Localization

In a sense, deformation is always localized due to the crystallographic origin of microstructural deformation mechanisms. Under the appropriate conditions, these microscopic shear localizations can develop into macroscopic shear banding. Metal removal in a machining operating appears to favor a shear localization process. This follows from i) the highly non-uniform stress states and the stress concentrations that exist in the vicinity of the tool/workpiece interface and ii) the adiabatic nature of deformation in machining. The latter is particularly important because the tendency toward shear localization is opposed by the strain hardening ability and strain-rate sensitivity of a material but is assisted by a strongly temperature dependent flow behavior under adiabatic conditions.

Predictions of the initiation of localized straining have proved to be very difficult. Except in a few cases, these necessitate the use of numerical methods. The use of constitutive laws that describe the instantaneous strain, rate, and temperature dependence of the flow stress is essential in analytical or numerical simulations of complicated strain localization behavior.

In general, predictions of the actual failure event in machining operations is very difficult. By failure, we mean the actual mechanism and criteria for formation of the new interfaces making up a chip. However, when localized shearing is severe, this is not as much of a problem as it might appear since the failure plane is well established and the models tend naturally toward a zero stress level as more and more strain (and, thus, heat) builds up in a shear band. This further supports the need to apply descriptive constitutive laws to machining calculations.

Fracture

While machining and grinding mostly involve a localized shearing mechanism, there has always been a need to machine very brittle materials. Because surface cracks are detrimental to the performance of brittle materials considerable effort has gone into the development of grinding and machining operations for these materials. Grinding has been preferred to cutting because i) the higher surface temperatures reached during grinding take the surface above a brittle to ductile transition and ii) the individual "cuts" taken in grinding involve a considerably smaller volume than those taken in machining. In fact, recent work by Puttick has shown that ductile machining response in nominally brittle materials is possible if the depth of cut is maintained below approximately 100 nm [6].

In general, high strain rates lower the ductile to brittle transition temperature, i.e., high strain rates assist brittle fracture behavior, through the associated increased stress levels that can drive cracks at higher velocities. The volume effect seen by Puttick and others may have more to do with the microstructural scale and the probability of encountering flaws or microstructural features that can initiate critical cracks. That is, ductile response in nominally brittle materials is possible if the scale over which deformation is imposed is smaller than the microstructural scale of inherent flaws or crack initiation sites.

Conclusions

Machining and grinding are industrial material-working operations that combine several aspects of plasticity, e.g., strain localization and multiaxial deformation, that remain at the forefront of current research. Strain rate and temperature dependent plastic flow are essential aspects of the detailed material removal mechanisms operative during machining and grinding. Successful application of advanced processing modeling and control in these operations will require the use of descriptive constitutive laws.

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