SENSITIVITY OF SHEAR PROCESS IN METAL CUTTING TO THE DEVELOPMENT OF RESIDUAL STRESS

Young W. Park
Department of Industrial and Manufacturing Systems Engineering
Iowa State University
Ames, IA 50011

Paul H. Cohen, and Clayton O. Ruud
Department of Industrial and Management Systems Engineering
The Pennsylvania State University
University Park, PA 16802

INTRODUCTION

Machining processes are widely used for producing a component by material removal. Material is removed in the form of chips through the action of the wedge-shaped cutting tool. As the tool proceeds, the material is first elastically deformed, and then plastically deformed. The mechanism of plastic deformation in metal is dislocation movement. Typical machining processes include turning, milling, drilling, shaping and grinding. It is known that the chip formation process in metal cutting is quite unique in many ways [1]. First, the process is a localized, asymmetric deformation that takes place at very large strains and exceptionally high strain rates in a small deformation zone. Typical values for strains and strain rates range 2 to 5 and 10^4 to 10^9 per second, respectively. Second, it is relatively unconstrained in that the only external constraint is the length of contact between tool and chip on the rake face of the tool. On the rake face there may be seizure as well as sliding friction. Machining introduces a large amount of plastic deformation in the workpiece material and chip. This plastic strain is nonuniform, and therefore residual stresses are induced in the workpiece surface and subsurface throughout, and slight below, the depth of plastic deformation. Thus, residual stresses are often an undesirable but unavoidable by-product of machining.

In turning, tensile residual stresses are dominant in the machined surface [2-5]. Residual stresses in milling tend to be compressive in the machined surface [2,6]. In grinding, residual stresses are dominantly tensile at the surface, which is followed by low values of compressive stresses deeper into the material [2,7]. Residual stress can adversely affect the important properties of mechanical and electrical components. Some of them include dimensional stability, static and dynamic strength, fatigue strength, corrosion resistance, wear resistance and magnetization.

The objective of this paper is to investigate how sensitive the development of residual stress is to the mechanisms in metal cutting experimentally.

EXPERIMENTS

Three types of Al 3003 plates (W x D x H: 9 x 248 x 711 mm (3/8 x 9 3/4 x 28 in.), i.e., H12, H14 and H19, were used as workpiece materials manufactured and donated by Reynolds Metals Company. The chemical composition of the workpiece material used for this investigation is given in Tables 1. Fig. 1 shows the shape and dimensions of a typical workpiece. Workpieces were prepared from the plates using several manufacturing processes, such as band sawing, milling, turning, electropolishing, etc. The cutting direction was designed to be parallel to that which the workpiece material was rolled in its prior processing. A step and gradual thinning of the workpiece were made at the end where the cutting tool approached. These are helpful to reduce initial impact loading and subsequent vibration.

The cutting speed, depth of cut, rake angle, and amount of cold work were chosen as the four independent variables due to the results in the literature, and in the case of the amount of cold work, it has not been investigated before. Strain-hardening due to cold working and/or cold drawing results in tremendously different shear angle [8]. Selecting levels of each variable are based on the study objectives, material availability, and capability of the lathe. Dry orthogonal cutting with a quick-stop device was performed on a 20-HP LeBlond 1610 lathe, based on an orthogonal array of the experimental design. The tool was mounted on a Kistler three-component piezo-electric dynamometer. The data collection and processing were performed by using a Tektronix 2630 Fourier Analyzer. Fig. 2 shows the schematic diagram for machining experiments.

A Ruud-Barrett Position Sensitive Scintillation Detector (R-B PSSD) XRD instrumentation with single exposure technique (SET) was used to measure residual stresses. A CrK_α X-ray beam was used to obtain the peaks on (222) Miller indices planes of aluminum at 78. 49 degree of Bragg angle. The angle between the incident beam and the surface normal was set to 30 degree. The power supply of the X-ray tube was set to 40 KV and 20 mA. Before machining, the original surface of the workpiece material to be cut was characterized by using the R-B PSSD XRD instrumentation. After machining was completed, residual stresses were measured on the machined surface by using XRD. The direction of cutting was aligned with the translational axis of the x-ray head. The measurements were made at five positions in two directions, i.e., cutting direction and opposite direction to the cutting. After a set of measurements were completed, 0.0005 in. (0.0127 mm) of the surface were electropolished away, the depth of the removed material measured by a Numerex CMM, and the subsequent XRD measurements performed. This procedure was repeated with varying depths of electropolishing, depending upon the plastic deformation gradient, until the depth where residual stress extant in the as-received state of the material was detected. The location of the x-ray head was continuously monitored and minor adjustment was made if necessary by means of a position control stepper motor.

Table 1 Chemical Analysis (%) of Al 3003.

	Si	Fe	Cu	Mn	Zn	Ti	Al
%	0.21	0.62	0.16	1.14	0.02	< 0.01	97.84

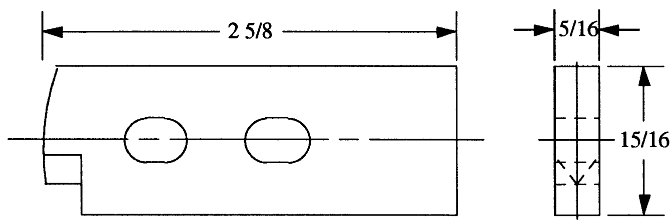

Fig. 1 The shape and dimensions of the workpiece (dimensions are inches).

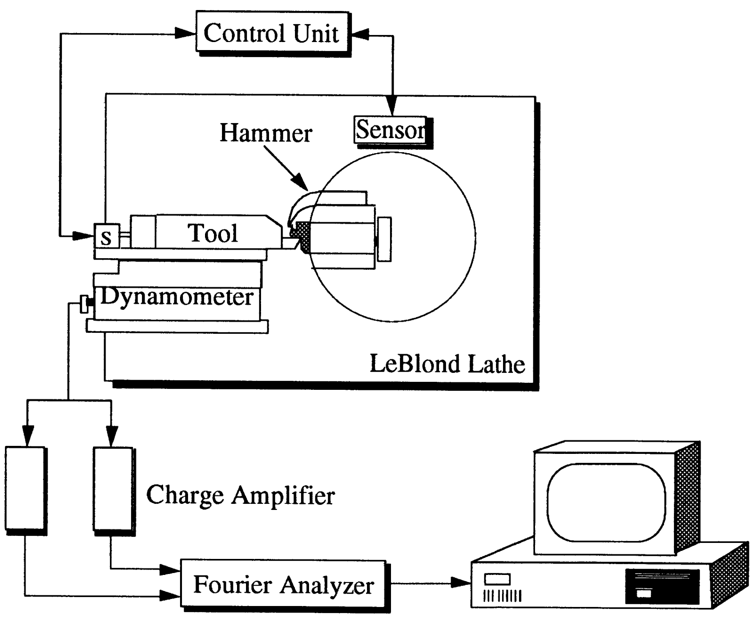

Fig. 2 Schematic diagram for machining experiments.

RESULTS AND DISCUSSIONS

A typical result of the residual stress distribution with the depth beneath the machined surface is shown in Fig. 3 with standard deviations. It was observed in earlier work that the surface residual stresses in turning were tensile. However, the experimental results show that the surface residual stresses were compressive. These contradictions can be explained as follows: A QSD was designed and used for the machining experiments. It is known that shear process during machining is preceded by radial compression ahead of the cutting tool and by radial tension behind it. If the radial tension is more than the radial compression, the resultant residual stresses are compressive and vice versa. In this study it is believed that the radial compression was more than the radial tension, thus the tensile residual stresses were generated in a machined surface. In addition, due to the small finite radius of the cutting edge, some material was forced under great pressure to flow beneath the tool and along the machined surface, then recovered elastically . After a length cut, the tool has to be removed from the workpiece material. Ideally, the tool has to be disengaged from the workpiece material without affecting the state of a machined surface. However, a rubbing can occur in the freshly machined surface [9]. This may be due to the relative motion of the workpiece material and tool, and due to the elastic recovery of the machined surface. These are equivalent to applying tensile stress to a shallow depth of the machined surface and consequently generate compressive residual stresses. The superposition of two stresses results in a distribution of residual stress observed in this study.

It is worth testing the sensitivity of residual stresses to a shear process, since machining is a shear process. The results are shown in Figs. 4 - 5. From Fig. 5, it is clear that the peak residual stresses in both directions are sensitive to shear strain occurring during cutting and that they are consistent over the range of the estimated shear strains. On the other hand, it is said that the surface residual stresses are characterized by considerable scatters. This can be explained as follows: The surface region experiences shearing first, and rubbing later. This complex phenomenon results in scattering of the measured values. The effect of rubbing is limited to the surface and near surface, and thus the peak residual stress is beyond the range of rubbing effect. It gives the clear trend of the measurements.

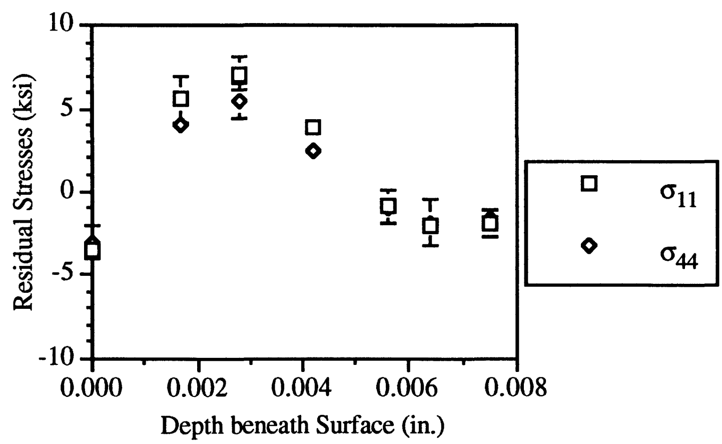

Fig. 3 Typical result of the residual stress distribution with the depth beneath the machined surface.

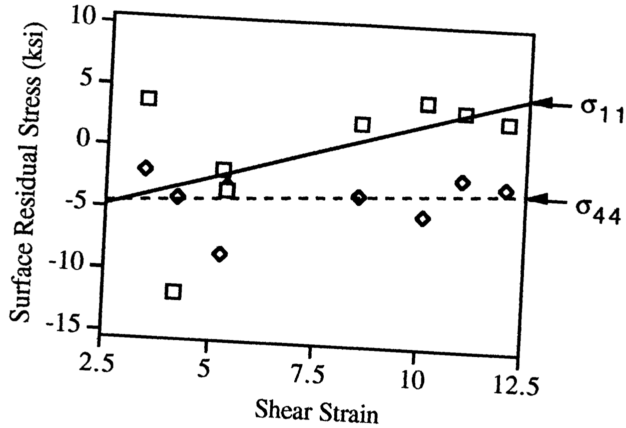

Fig. 4 Sensitivity of surface residual stress to shear strain.

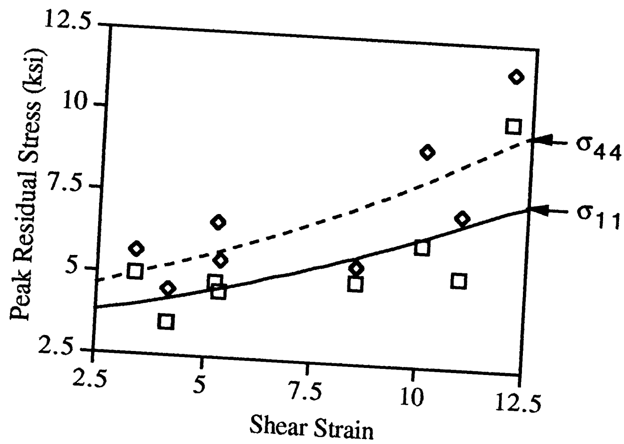

Fig. 5 Sensitivity of peak residual stress to shear strain.

CONCLUSIONS

It can be concluded that compressive residual stress generated in the machined surface of 3003 aluminum for this study is the combination of radial compression due to the cutting tool, and radial tension due to rubbing. It also can be concluded that the peak residual stresses are sensitive to shear process, while the surface residual stresses are confusing due to the complexity of process happened at the surface.

ACKNOWLEDGMENTS

The authors thank to National Science Foundation, General Motors Corporation, and Ford Motor Company for their financial support and to Reynolds Metals Company of Richmond for material support.

REFERENCES

1. P. H. Cohen and J. T. Black, "Strain, Stain Rate and Shear Velocity Measurement in Metal Cutting", Journal of Engineering for Industry, Vol. 106, p.271 (1984)
2. J. F. Kahles and M. Field, "Surface Integrity Guidelines for Machining", SME Technical Paper No. IQ71-240 (1971).
3. P. Leskovar and J. Peklenik, " Influences Affecting Surface Integrity in the Cutting Process", Annals of the CIRP, Vol. 31/1, p. 447 (1982).
4. H. K. Tonshoff and E. Brinksmeier, "Optimization of Computer Controlled X-Ray Stress Analysis", Annals of the CIRP, Vol. 30, p.509 (1983).
5. Y. C. Shin, S. J. Oh, and C. O. Ruud, "Feasibility Study on Machining Condition Monitoring by an X-Ray Diffraction Method", Transactions of NAMRI/SME, p.136 (1991).
6. M. M. El-Khabeery and M. Fattouh, "Residual Stress Distribution Caused by Milling", International Journal of Machine Tools and Manufacturing, Vol. 29, No. 3, p. 391 (1989).
7. S. O. A. El-Helieby and G. W. Rowe, "Quantitative Comparison between Residual Stresses and Fatigue Properties of Surface-Ground Bearing Steel", Wear, 58, p.155 (1980).
8. J. E. Williams, E. F. Smart, and D. R. Milner, "The Metallurgy of Machining", Metallurgia, Vol. 81, p.3 (1970).
9. J. T. Black and C. R. James, "The Hammer QSD-Quick Stop Device for High Speed Machining and Rubbing", Journal of Engineering for Industry, Vol. 103, p.13 (1981).