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Development of localized compressive hydrostatic stress-assisted cutting method – Examination by molecular dynamics simulation and microcutting experiment

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Abstract
In the precision machining of metals, suppression of unnecessary plastic deformation such as the burr formation is of considerable importance. On the other hand, hydrostatic stress has no relation with the plastic deformation and reduces the density of defects represented by voids and microcracks. Such characteristics are expected to be useful for achieving higher machined surface integrity. This study aims to develop a cutting method, which enables to generate a localized compressive hydrostatic stress field around the cutting zone to improve the machined surface integrity without causing unnecessary plastic deformation. A molecular dynamics simulation of such a cutting process for a monocrystalline Al workpiece was performed using a developed cutting tool equipped with a planer jig for giving a localized compressive hydrostatic stress field. A microcutting experiment was also conducted on a monocrystalline Cu workpiece by using a similar cutting tool as the simulation and compared with the simulation result. Consequently, decreases in the burr formation were successfully observed in both results.

Keywords: cutting, tool, hydrostatic pressure, plastic flow, burr, molecular dynamics

1. Introduction

In the machining of metals, unnecessary plastic deformations such as the burr formation occurs in the machined surface and subsurface, because such a process is mainly achieved by the plastic deformations. Therefore, suppression of such unnecessary plastic deformations is important. On the other hand, it is known that the hydrostatic pressure does not concern the plastic deformations [1], even though it affects deformation behaviours of metals. The yield stress and the ductility of metals increase under a high compressive hydrostatic pressure [2]. A high compressive hydrostatic pressure also reduces the density of lattice defect such as voids and cracks, and inactivates the mobility of workpiece atoms [3]. These characteristics are expected to improve the machined surface integrity, and some papers reported that an improvement in the machined surface integrity can be realized for brittle materials when the cutting is conducted under a high compressive hydrostatic pressure [4]. However, relatively large equipment is needed to give such a high pressure to the workpiece and it is an issue for practical use.

In this study, a cutting method by making use of localized hydrostatic stress has been developed by just using a simple cutting tool attached with a planer jig [5]. In this report, a molecular dynamics (MD) simulation and a microcutting experiment are performed by using the developed cutting tools, and both results were compared.

2. Molecular dynamics (MD) simulation of cutting process

2.1. Molecular dynamics (MD) simulation model

The developed MD Simulation model is shown in Figure 1. In the simulation, the workpiece is assumed to consist of monocrystalline Al, and both the tool and the planer jig for giving compressive hydrostatic stress are assumed to consist of rigid diamond, respectively. A Morse potential functions existed [6, 7] are applied to a pair of Al atoms and an Al-C atoms pair, respectively. For giving a lubrication effect, the potential between an Al-C atoms pair is reduced by 10% by lowering the cohesive energy. Newton's motion-equations are solved by leapfrog method with the time step of 3 fs. In the cutting process, the cutting tool is slid horizontally on the workpiece at the speed of 200 m/s after indenting it into the workpiece to the depth of 2 nm with the same speed as the cutting. Broken arrows in Figure 1 show the tool trajectories.

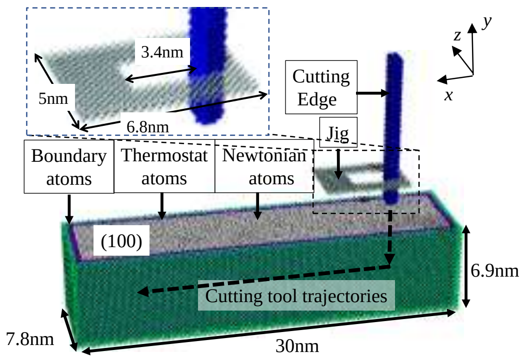


Figure 1. MD simulation model for developed cutting process

2.2. Simulation results and discussion

Figure 2 shows the snapshots of atomic arrays of half space and traveling distance of Al atoms from initial position after 15 nm long cutting. In Figure 2, results by (a) normal and (b) developed cutting tools are shown for comparison.

Relatively large number of atoms in red can be seen around the cutting groove shoulder in Figure 2(a). These atoms constitute the burr. Such a trend is hardly observed in Figure 2(b), and this indicates that the developed cutting tool is helpful to reduce unnecessary plastic deformations. Number of atoms in the cutting chip in Figure 2(b) is much larger than that in Figure 2(a). This indicates that the developed cutting tool has an advantage in the smooth cutting chip formation.

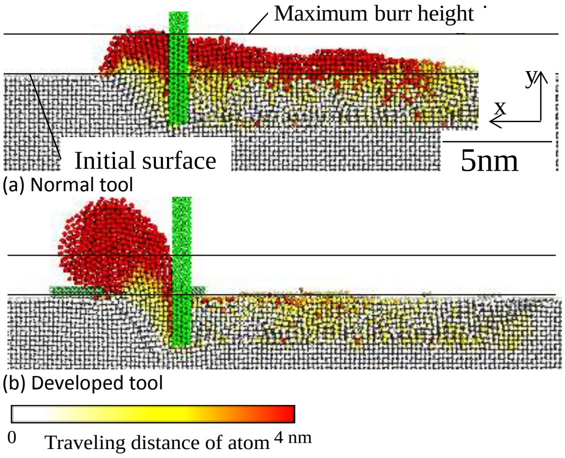
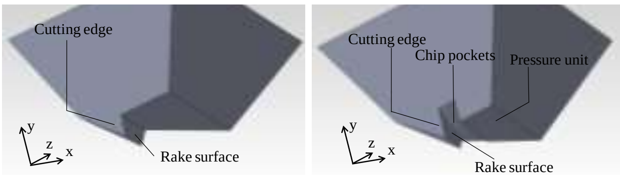


Figure 2. Snapshot of half space and traveling distance of Al atom

3. Microcutting experiment

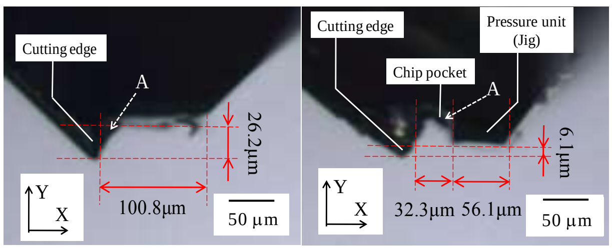
3.1. Experimental procedure

Figures 3 and 4 show designed tool models and observation results of fabricated diamond tools used in the microcutting experiment. In both figures, (a) and (b) indicate normal and developed cutting tools, respectively. Both tools were machined by a ps laser.



(a) Normal tool (b) Developed tool

Figure 3. Cutting tool model



(a) Normal tool (b) Developed tool

Figure 4. Optical micrograph of diamond cutting tool

As shown in Figures 3(b) and 4(b), the developed tool is composed of a cutting edge, a pressure unit for giving localized hydrostatic pressure and a chip pocket which has an inclination for smooth chip elimination, while the normal one just has a cutting edge (see Figures 3(a) and 4(a)). Their representative dimensions are also indicated in Figure 4, even though there are some issues in the accuracies.

Figure 5 shows the main body of microcutting/scratching equipment used in this study. When microcutting, both fabricated cutting tools are fixed by a cantilever with relatively low stiffness and are driven by a DC motor in the horizontal direction with the speed of 0.5 mm/s after indenting them on a pure Cu workpiece surface to the depth of around 6.1 μm.

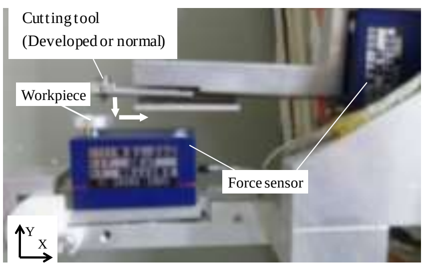
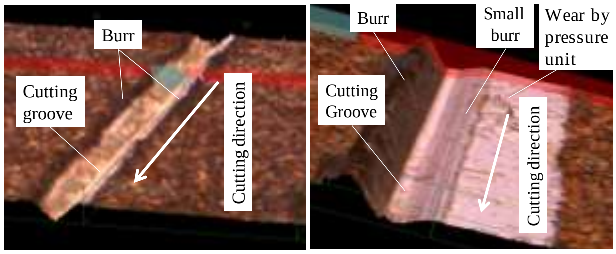


Figure 5. External view of microcutting equipment

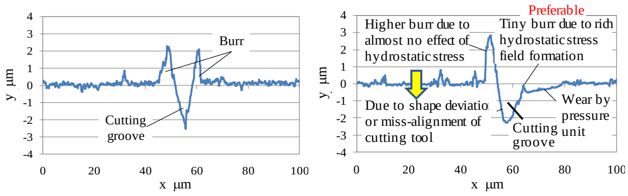
3.2. Experimental results and discussion

Figures 6 and 7 show 3D images and cross-sectional shapes of cutting grooves, respectively. In both figures, (a) and (b) indicate normal and developed cutting tools, respectively.



(a) Normal tool (b) Developed tool

Figure 6. 3D image of cutting groove



(a) Normal tool (b) Developed tool

Figure 7. Cross-section of cutting groove

In Figures 6(a) and 7(a), relatively large burrs are generated around both cutting groove shoulders. In Figures 6(b) and 7(b), the burr generated on the right side of cutting groove is remarkably small due to relatively high-hydrostatic pressure, while such a preferable phenomenon is hardly recognized on the left side where insufficient hydrostatic pressure might be given due to the shape deviation of tool pressure unit or the miss-alignment of cutting tool in the microcutting.

4. Conclusion

In order to develop a cutting method assisted by a localized compressive hydrostatic stress for reducing unnecessary plastic deformations, a molecular dynamics simulation and a microcutting experiment were performed by using developed cutting tools. As a result, it is clarified that the developed method has an advantage to reduce the burr formation.

Acknowledgement

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