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The effect of compressed cold air and vegetable oil on the subsurface residual stress of ground tool steel

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Abstract

This paper investigates experimentally the effect of compressed cold air (CCA) and vegetable oil on the surface integrity and residual stresses of ground tool steel components. It shows that CCA can reduce grinding temperature and produce a compressive residual stress up to the grinding depth of 30 μm. CCA can also improve surface finish while keeping grinding forces low. Oil was found to be more effective in reducing grinding heating and improving surface finish at small grinding depths.

Keywords: Residual stress; Surface grinding; Tool steel; Surface finish; Compressed cold air; Vegetable oil

1. Introduction

To improve grinding efficiency, water-based grinding fluid is widely used for lubrication, cooling and cleaning. Traditional fluid contains chlorine, sulfur and phosphorus, which are harmful and cause environmental pollution. In automotive fabrication, 15–30% of the machining cost for an automobile manufacture is related to the use of grinding fluid [1]. On the other hand, some materials, such as superconducting magnet ceramics, cannot be ground with grinding fluid since the superconducting properties can be deteriorated. Therefore, fluid-less grinding is required for environment protection, cost reduction and material property protection.

A few investigations have been conducted to evaluate the effects of compressed cold air (CCA) and ester oil on the integrity of machined workpieces under different grinding conditions [1–4]. It has been shown that oil provided effective lubrication, reducing specific energy and grinding forces. CCA was found to have no significant effect on the grinding temperatures and therefore cause thermal expansion and difficulties with size control. Choi et al. [5,6] reported that, depending on materials and grinding conditions, CCA could generate much greater surface compressive residual stresses than conventional fluid. However, a large surface compressive residual stress does not necessarily mean a high cooling efficiency since the surface stress status was determined by the coupled effect of mechanical and thermo-plastic deformation of the workpiece. Insufficient cooling causes high grinding temperature and deteriorates the integrity of the ground components by introducing thermal defects and burning [7–9]. Therefore, a further evaluation of the efficiency by CCA and oil should include a detailed analysis of residual stress profiles in the subsurface of a ground workpiece.

In this study, grinding of an annealed 4140 tool steel under various grinding conditions with/without CCA or vegetable oil will be performed to evaluate their effects on the surface integrity and, in particular, on the subsurface residual stresses.

2. Experiment

The experiment was performed in the down-grinding mode on an annealed 4140 tool steel at a series of grinding depths using a wheel surface speed of 25 m/s and a

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feed rate of 200 mm/min. The grinding machine was a CNC Minini M286 and the grinding wheel was 38A46JVBE of Al_2O_3 abrasives. The workpieces with the dimensions of 15 mm × 30 mm × 50 mm were made from a cylindrical bar. The original workpiece surface layer of 160–180 μm was leveled with sufficient grinding fluid at a grinding depth of 10 μm. Then, five passes of fine grinding at the grinding depths of 5, 3, 2, 1 and 1 μm were conducted using sufficient grinding fluid, Syntilo 3 (Castrol Australian Pty. Limited), to reduce the effect of thermal–plastic deformation on the subsurface residual stresses produced by the leveling. Cutting forces in three directions were recorded using a KISTLER 3-component dynamometer (Type 9257B). The wheel was dressed using a single point diamond dresser at a wheel speed of 28m/s and a feed rate of 157 μm/revolution, respectively. Two-pass dressing was performed with a dressing depth of 25 μm each.

Compressed cold air was produced using a vortex tube (Exair 3299). The temperature and flow rate of the compressed cold air near the contacting point between the wheel and workpiece were −20 °C and 150 standard cubic feet per minute (SCFPM), respectively. For a grinding with oil as lubricant, a thin layer of vegetable oil (less than 2 μm) was spread on the workpiece surface.

Residual stress measurements were carried out on an MSF-3M X-ray stress analyzer (Rigaku Co., Japan) using Cr Kα radiation at the maximum load of 30 kV and 10 mA. Since the peaks at high diffraction angles will display a larger shift due to stress, {2 1 1} peak was used for the stress measurement. Counting has undertaken at 2θ angles between 151° and 162° by steps of 0.1° at five fixed ψ angles. To ensure a high measurement precision, data smooth, background subtraction, Lorentz polarization, absorption and stripping of $K\alpha_2$ were performed using program (Instruction Manual, Rigaku) before determining the peak of the diffraction intensity profile. The stress in the measured direction was calculated by linear regression analysis. The elastic modulus and stress constant used in the calculations were 210 GPa and −318 MPa/degree, respectively (from Instruction Manual). To measure residual stress distribution, machined surface of a ground component was removed by an electro-chemical polishing machine, Struers Movipol-3 (Struers, Denmark). The depth of the material removed by the electro-chemical polishing was measured using an optical microscope (Leica). The surface roughness of a machined surface was measured using a profilometer (Mitutoyo, Surftest 402 Series 178) after an ultrasonic and ethanol cleaning.

Specimen preparation would introduce plastic deformation in the workpieces and therefore would bring about residual stresses. To ensure a reliable residual stress characterization with respect to the grinding conditions, all specimens were annealed under a high vacuum at 750 °C for 1 h and 675 °C for 5 h and then were cooled down slowly. Residual stress examination confirmed that the annealed specimens were stress-free.

3. Effect of CCA and oil

3.1. Grinding force and surface roughness

To evaluate the effects of CCA and oil, dry grinding and fluid grinding (Syntilo 3) were also conducted with a fresh wheel for reference. Normal force, F_n, and tangential force, F_t, were calculated from measured force versus time curve [10]. As shown in Fig. 1, forces in dry grinding were high and were reduced by the addition of oil. When CCA is used, forces decrease significantly compared with drying grinding. With the application of oil, the forces decrease further, particularly in the grinding direction, indicating that the main role of the oil is lubrication. In addition, the difference in grinding forces between CCA and grinding fluid is small. The ratio of F_n/F_t as a function of grinding depth is plotted in Fig. 2 and is between 1.4 and 2.1 under any grinding conditions used in this study. This shows that grinding force under these conditions is not so different from each other. Oil also improves surface finish (Fig. 3), especially in dry grinding.

3.2. Surface residual stress

The surface residual stress as a function of grinding depth under various grinding conditions is shown in Fig. 4. Under

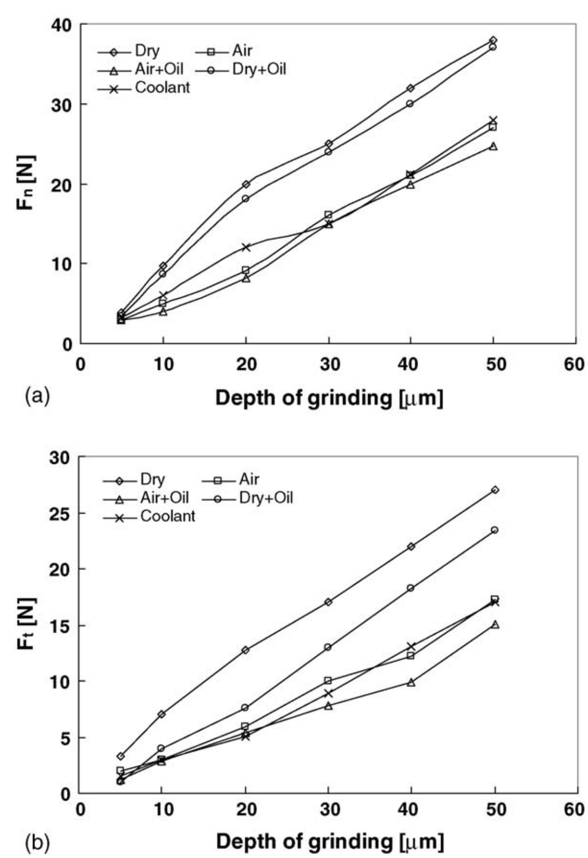

Fig. 1. Grinding force under various grinding conditions: (a) normal force and (b) tangential force.

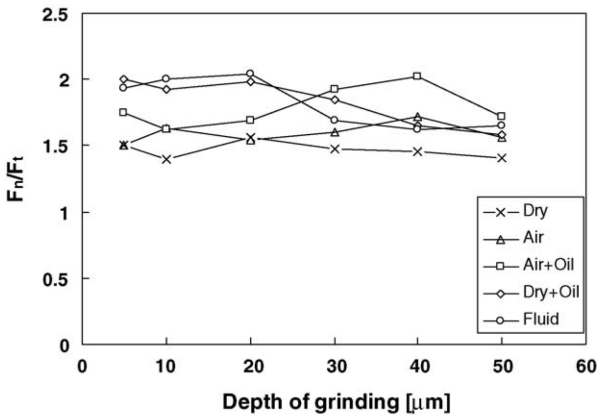

Fig. 2. F_n/F_t as a function of grinding depth under various grinding conditions.

all grinding conditions, the surface residual stress in the grinding direction (longitudinal) is larger than that in the transverse direction. Dry grinding produces a large tensile stress in the grinding direction except the case of small grinding depth (5 μm). Because the amount of grinding heat and mechanical deformation generated in dry grinding is similar to those in CCA, it is seen that CCA is indeed capable of removing grinding heat, resulting in a lower surface residual stresses.

Oil has a clear influence on the surface residual stress. Compared with either dry or CCA grinding, adding oil decreases residual stress in both directions. This improvement is more pronounced at smaller grinding depths. When grinding depth is less than 30 μm, residual stress in both directions using oil is even much lower than that using fluid. The result demonstrates that the effect of grinding heat on the surface stress is mainly caused by wheel–workpiece friction. Oil is more effective in reducing the friction than normal water-based fluid. With further increasing grinding depth, oil starts to lose its lubricability because of the high temperature in the grinding zone. This ineffectiveness of oil seems to occur at a grinding depth between 20 and 30 μm where the residual stress due to grinding increases sharply.

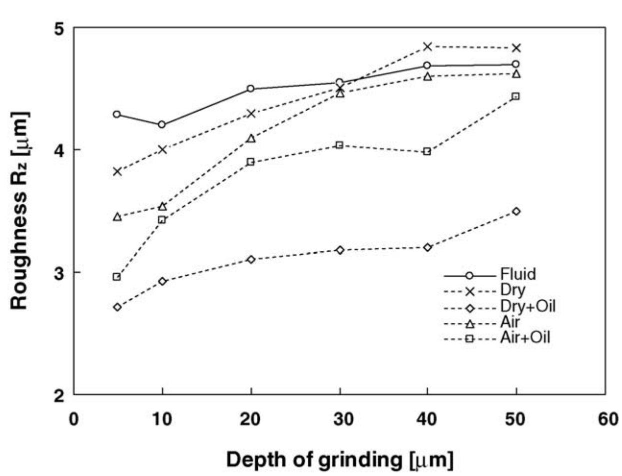

Fig. 3. Surface roughness in transverse direction under various grinding conditions.

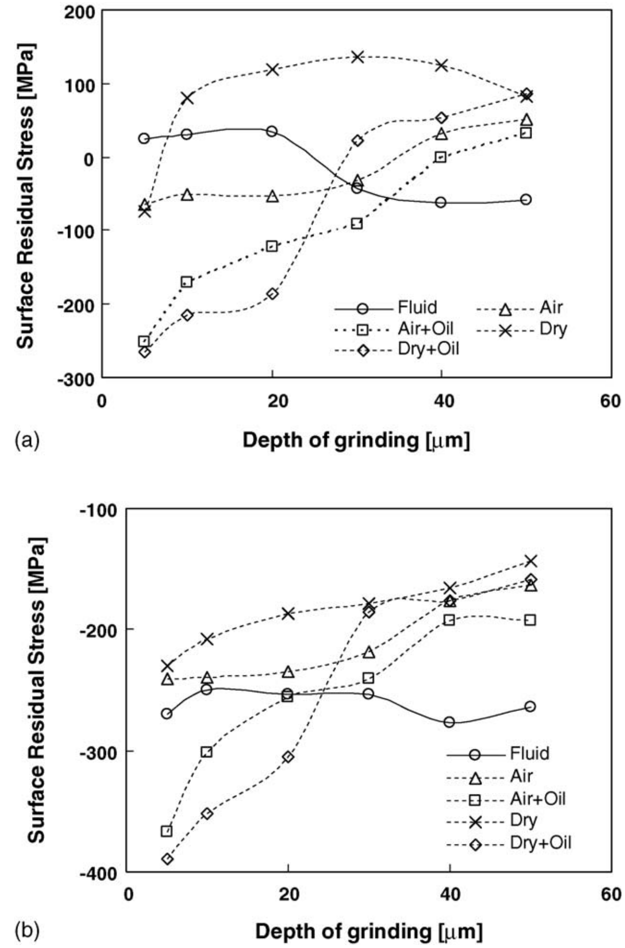

Fig. 4. Surface residual stress under various grinding conditions: (a) in longitudinal direction and (b) in transverse direction.

3.3. Subsurface residual stress

Grinding with fluid at 5 μm produces a small surface tensile stress (Figs. 4 and 5), which is believed to be caused by a high cooling rate at surface. Heating and cooling during grinding generates a surface tensile stress, which decreases with the distance from the surface. Surface compressive stress induced by mechanical deformation also decreases with the distance. A maximum compressive stress occurring at 10 μm (fluid and air curves in Fig. 5) seems to be an indication of the interaction between tensile and compressive stresses. The difference between surface stress and this subsurface maximum compressive stress decreases with grinding depth (see Figs. 6 and 7), demonstrating an increased contribution from tensile stress or penetration of grinding heat at large grinding depth. A comparison of subsurface and surface residual stresses (Figs. 5–7 and 4) shows that the former varies monotonously with increasing grinding depth (or grinding heat) while the latter is insensitive to the grinding

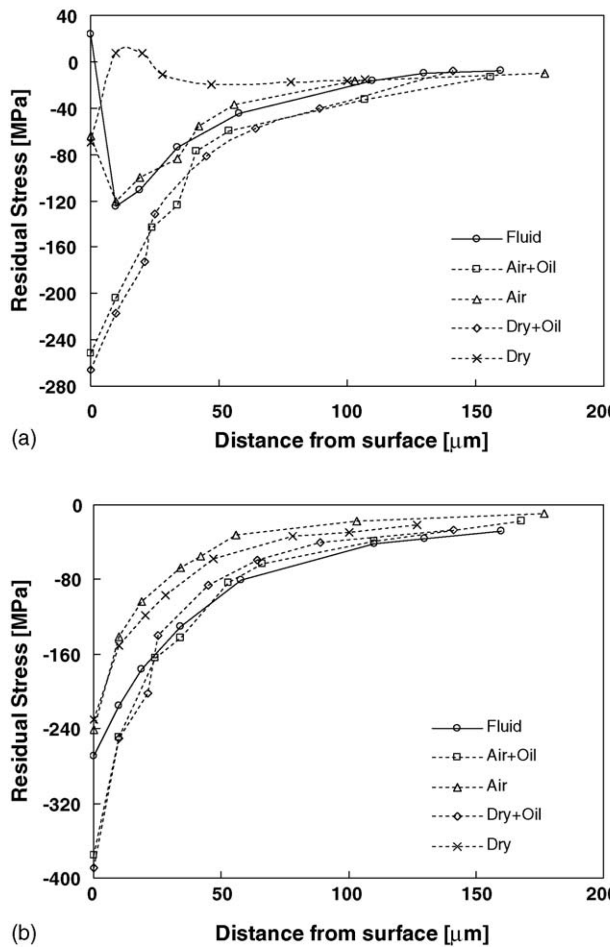

Fig. 5. Residual stress beneath the machined surface at grinding depth of 5 μm: (a) in longitudinal direction and (b) in transverse direction.

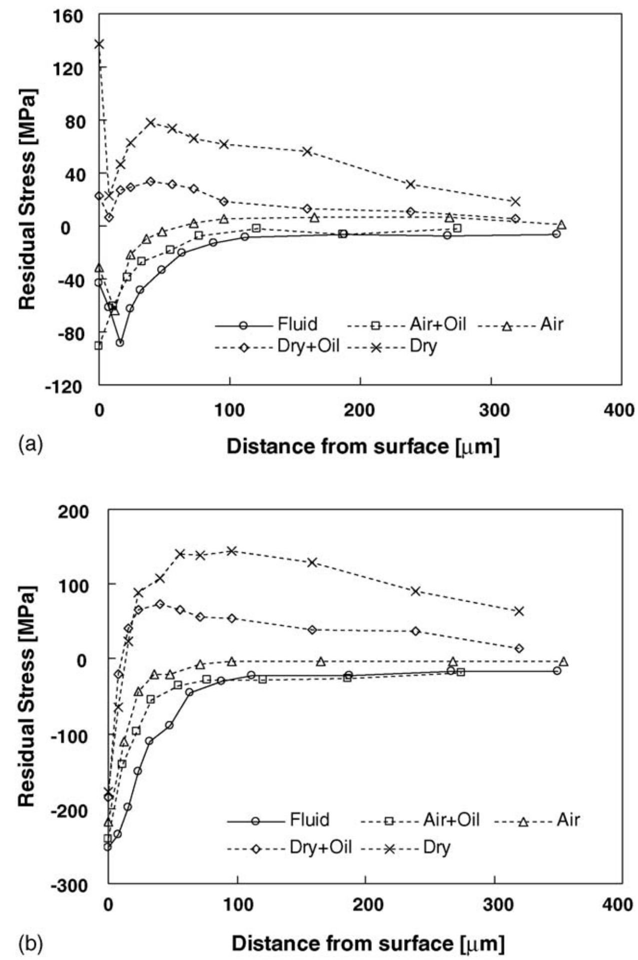

Fig. 6. Residual stress beneath the machined surface at grinding depth of 30 μm: (a) in longitudinal direction and (b) in transverse direction.

depth, indicating a balance at surface between mechanically induced compressive stress and thermally induced tensile stress.

Subsurface residual stress is determined by the grinding heat, which penetrates into the subsurface of the workpiece and can be used to evaluate cooling efficiency under various grinding conditions. Fig. 5 shows that even at a small grinding depth of 5 μm, dry grinding generates a peak in longitudinal tensile stress (7 MPa) located at a depth of 15 μm in the subsurface, which is related to the thickness of the tempered martensite beneath the surface. With further increasing the grinding depth from 30 to 50 μm, maximum tensile stress at the peak increases from 78 to 213 MPa, and the distance of the peak beneath the surface increases greatly from 40 to 128 μm (see Figs. 6 and 7). This indicates an increased strength and penetration depth of the grinding heat with grinding depth, although a linear relationship between grinding force and grinding depth is seen in Fig. 1. Additionally, subsurface stress is highly directional. At 5 μm, transverse stress is compressive while longitudinal one is tensile. When grinding depth increases to 50 μm, transverse stress also becomes tensile and surpasses longitudinal one in magnitude. This is attributed to increased amount of grinding heat and restriction of heat convection in the transverse direction due to a much smaller specimen width than length. Higher compressive stresses in transverse direction were also reported previously [11–13], however, present work shows that it depends largely on the amount of grinding heat generated.

When CCA is used, large subsurface compressive stresses in both directions are obtained at grinding depths up to 30 μm, and the tensile stress peaks induced by dry grinding are eliminated. At the grinding depth of 50 μm, subsurface residual stresses in both directions become tensile but it is still smaller than that in dry grinding. As residual stress at any depth below ground surface is proportional to the temperature increase [14], CCA is indeed able to reduce grinding temperature. Comparing with grinding fluid, CCA shows a similar cooling efficiency to the fluid at grinding depth of 5 μm. By further increasing the grinding depth, the cooling efficiency of CCA becomes worse than that of fluid. This is due to small heat capacity, poor chip cleaning ability and poor penetration of CCA into the grinding zone.

Oil is found to be more effective at a small grinding depth in producing large subsurface compressive residual stresses.

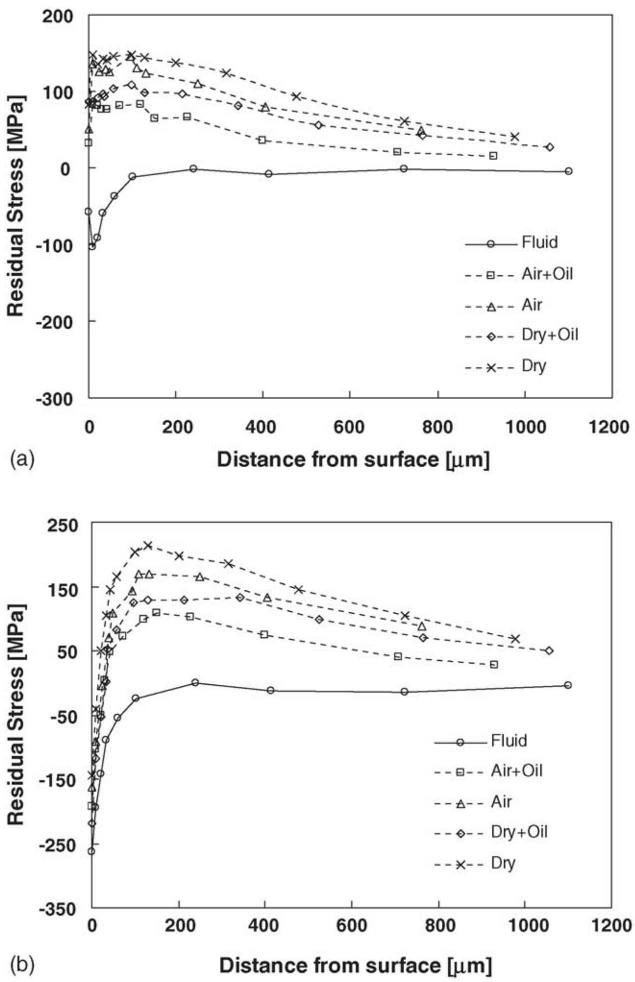

Fig. 7. Residual stress beneath the machined surface at grinding depth of 50 μm: (a) in longitudinal direction and (b) in transverse direction.

Fig. 5 shows that dry grinding with an addition of oil reduces residual stress significantly. Comparing dry grinding with that involving oil or CCA plus oil, it is seen that the subsurface stress is very similar to each other, indicating that reduction of the stress is mainly due to the role of oil in reducing friction heat. An additional cooling by CCA cannot provide any further benefit in terms of producing a large compressive stress. This is further demonstrated if considering the fact that residual stress using oil is even much lower than that using fluid. When grinding depth is increased, additional cooling is required due to the increased heat and ineffectiveness of oil at a higher temperature. Consequently, the stress induced by grinding with both CCA and oil becomes lower than that using oil alone (Figs. 6 and 7).

4. Conclusions

(1) CCA shows a good cooling efficiency at small grinding depths and is able to generate a compressive residual stress beneath the surface up to the grinding depth of 30 μm. With an increase of grinding depth, the cooling efficiency of CCA becomes worse than that of traditional grinding fluid. Compared with fluid and dry grinding, CCA improves surface finish.

(2) Oil is more effective than either fluid or CCA in reducing wheel–workpiece friction. As a result, grinding using oil produces a good surface finish, reduces grinding forces and increases subsurface compressive residual stresses. In this case, additional cooling by CCA does not further increase compressive residual stress. Hence, at small depths of grinding oil can replace grinding fluid or CCA in finish grinding to improve surface integrity and reduce cost and environmental deterioration.

Acknowledgement

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