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An assessment of the applicability of cold air and oil mist in surface grinding

T. Nguyen, L.C. Zhang*

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia

Abstract

This paper discusses the application of an eco-grinding system using a mixture of compressed cold air and vegetable oil. The feasibility of the system was assessed using the surface grinding of plain carbon steel 1045 with a BWA60MVA1 wheel. The investigation showed that cold air can be used to suppress surface burning under certain material removal rates and has an advantage of reduced grinding forces. With the addition of very small amount of vegetable oil, a larger depth of cut can be performed without burning while keeping a good grinding quality. Grinding chips were of lamellar and leafy shapes, indicating a shearing mechanism of chip formation. There was no significant difference in subsurface hardness of the components ground with coolant or with cold air and oil mist (CAOM), although the latter showed a stronger dependence of surface residual stresses on the depth of cut due to the limited cooling capacity of CAOM.

Keywords: Cold air; Vegetable oil; Lubrication; Grinding force; Hardness; Residual stress

1. Introduction

The main tasks of cooling fluids in a precise grinding operation are cooling, lubrication and cleaning of crammed chips. In the current technology, soluble coolants those contain chemical additives with synthetic formulations are often used. However, due to very stable nature of the solution, these fluids are environmentally hazardous. Disposing of the waste is considerably high cost. Furthermore, prolonged workers contact with the fluids may cause severe dermatitis.

Substantially, environmental and resource problems have urged the search for alternative cooling agents without or with less chemical additives becoming an active study in recently. Paul et al. [1] reported an application of liquid nitrogen which was found to be more advantages in grinding harder materials with higher infeeds. Suzuki et al. [2] investigated the use of a mixture of dry ice grain liquid (CO_2) together with a minimal quantity of lubricant in the grinding of a high speed steel. They found that the normal grinding force could be lower. The ground workpiece quality, however, was not reported. Moreover, these methods have not been widely applied in industry because of the associated high cost of refrigerants and oxygen starvation in the working environment.

On the other hand, impinged air jets have also been tried in grinding. Choi et al. [3] studied the cooling effects of compressed cold air in cylindrical grinding of harden steels with a CBN wheel. It was reported that the effectiveness of the cold air in reducing thermal defects was nearly comparable with the conventional coolant, when the depth of cut was small. However, surface tensile stresses tended to appear and surface roughness would rise when the depth of cut increased. It was concluded that the lack of lubrication in using dry cold air was probably the cause of the problems. Hence, the application of vegetable oil in grinding was studied by Yui and Terashima [4], where a mixture of cold air (−30 °C) and vegetable oil mist (0–8.6 cc/h) was applied to the grinding zone during a surface grinding of a tool steel. However, the critical depth of cut to avoid burning was very low (6 μm). Many important aspects of surface integrity such as surface characterisation and residual stresses have not been carefully addressed.

The present study aims to assess in more detail the feasibility of the application of cold air and vegetable oil in surface grinding. The grindability at different material remove rates is investigated by examining grinding forces and surface integrity.

2. Experiment

Fig. 1 shows the experimental set-up in a surface-grinding machine (Minini Junior 90 CNC-M286) equipped with a cold air and oil mist (CAOM) system (Table 1). Compressed air at 600 kPa with a flow rate of 150SCFM (4095SLPM)

* Corresponding author. Tel.: +61-2-9351-2835; fax: +61-2-9351-7060.
E-mail address: zhang@aeromech.usyd.edu.au (L.C. Zhang).

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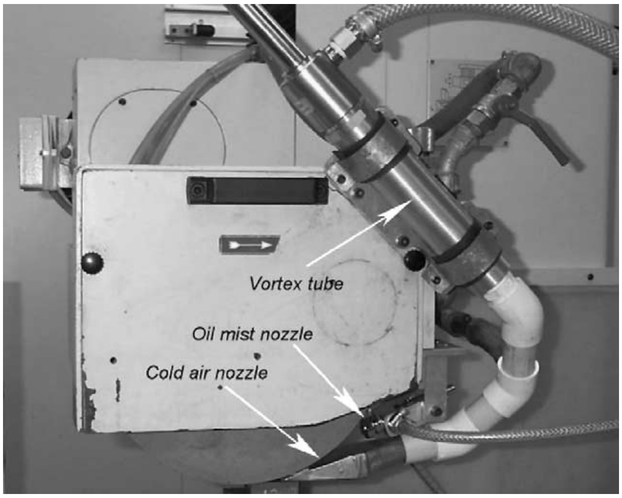

Fig. 1. Experimental set-up.

was dried and ejected through a vortex tube, Exair 3299, to generate cold air. A special nozzle was manufactured and assembled to the vortex tube to deliver the cold air stream to the grinding zone. The temperature at the outlet of the nozzle was −20 °C. A jet containing a small amount of olive oil impinged onto the grinding point at a rate of 0.16 cc/min from a distance of 80 mm and an angle of 30° tangential to the workpiece surface. The air pressure of generating the jet was 300 kPa.

Experiments were conducted on plain carbon steel 1045 ($\sigma_Y = 310$ MPa, C = 0.42–0.45%, Mn = 0.60–0.90%) with an aluminium oxide BWA60MVA1 wheel ground at different depths of cut of 5, 10, 15 and 20 μm. The workpiece dimension was 45 mm in length and 19.5 mm in width. To relieve the initial stresses, the specimens were pre-annealed at above 600 °C in vacuum. This guaranteed that the initial stresses in a specimen before grinding were nearly zero (-10.39 ± 8.00 MPa). The wheel speed was 23 m/s and the work speed was 400 mm/min in down grinding. To compare the grindability using the CAOM, grinding tests under other cooling conditions were also applied which were: (a) soluble coolant Noritake SA-02 (1:60) at 20 °C with the flow rate of 14.5 l/min and velocity of 1.95 m/s; (b) atmospheric dry air at the ambient temperature, 20 °C; and (c) cold air of −20 °C. In all these conditions except Case (a), a 1400 W powered vacuum machine was used to remove the dusts contained worn wheel particles and ground chips.

Prior to each test, the wheel was dressed using a single point diamond dresser with two passes at a transverse rate of 157 μm rev^{-1} and a total dressing depth of 50 μm. The workpiece mounted on the vice was then levelled prior to the actual grinding experiment. The levelling was performed under flooding coolant at very small depths of cut to minimise the induced residual stresses. The grinding system was then dried by compressed air to avoid the influence from the above preparation process. Measurement techniques and the accuracies are shown in Table 1.

Table 1
Measurement techniques and the accuracies

Grinding forces	Kistler piezo-electric dynamometer (9257B)
Surface roughness	Surftest 402 machine S.D. = 0.017 μm within 0.22–0.40 μm range
Vickers hardness (HV)	Indenter machine (Shimadzu Seisakusho, NT-M001) with loads were selected by following DIN 51 225 standard: 300, 500 and 1000 g S.D. = 17.24 HV within 198–252 HV range
Residual stresses	X-ray diffraction machine, Rigaku MSF-3M Electrolyte polishing to remove thin surface layer of ground components Method of Moore and Evan [5] to correct the stress relief perturbed by material removal Maximum tolerance (Tol_{max}): 17.6% within −400 to −100 MPa range; 24.0% within −100 to 0 MPa range; 41.5% within 0–35 MPa range

3. Results and discussions

3.1. Effects of compressed cold air

3.1.1. Burning

Fig. 2 shows the surface roughness in transverse grinding direction and degrees of burning varying with depth of cut (*d*) under different cooling conditions. The application of cold air showed some improvements compared with dry grinding. At a small depth of cut, the grinding with cold air generated good surface quality, comparable to that with soluble coolant, Noritake SA-02 (Fig. 3b and d). The surface hardness was not altered (Fig. 4), indicating that thermally induced hardening, which often takes place in dry grinding, did not happen. When the depth of cut became higher, 15 μm say, dry grinding immediately led to severe burning, but with the cold air burning occurred only at the second grinding pass after a certain grinding distance as shown in Fig. 5. This can be explained by the transient cooling process with the air. Since the experiment was conducted in down grinding using an aluminium oxide wheel, a very large energy portion, 60–75%, was conducted into the workpiece [6]. Because the cooling nozzle was moving with the grinding wheel, heat removal outside the grinding zone became very ineffective. Due to its characterised compressibility, the velocity profile of the air flow and hence the induced temperature field is very non-uniform. In the area slightly behind the grinding zone, the air temperature was close to the ambient temperature. Unlike water at its liquid phase, the heat transfer coefficient of air becomes very low when temperature increases [7]. As a result, heat in the workpiece could easily accumulate to accelerate burning. When grinding with coolant, however, a large portion of the energy partition to the workpiece could be significantly convected away by the massy liquid flow.

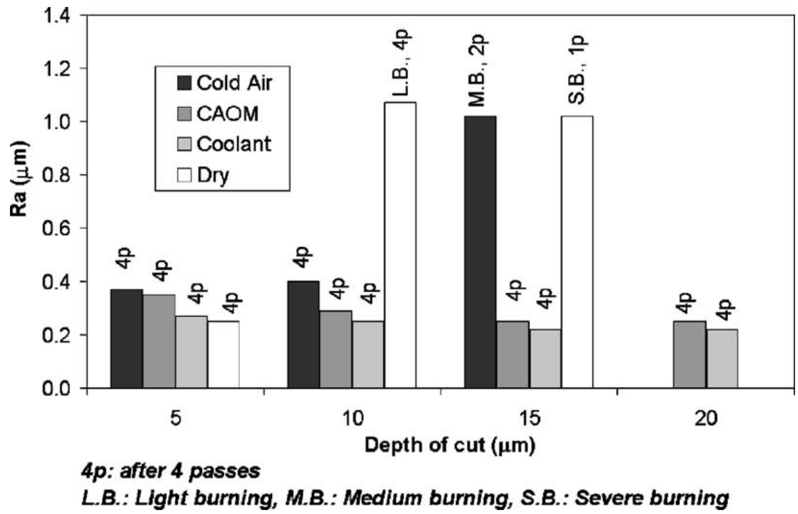

Fig. 2. Surface roughness in transverse grinding direction with degrees of burning.

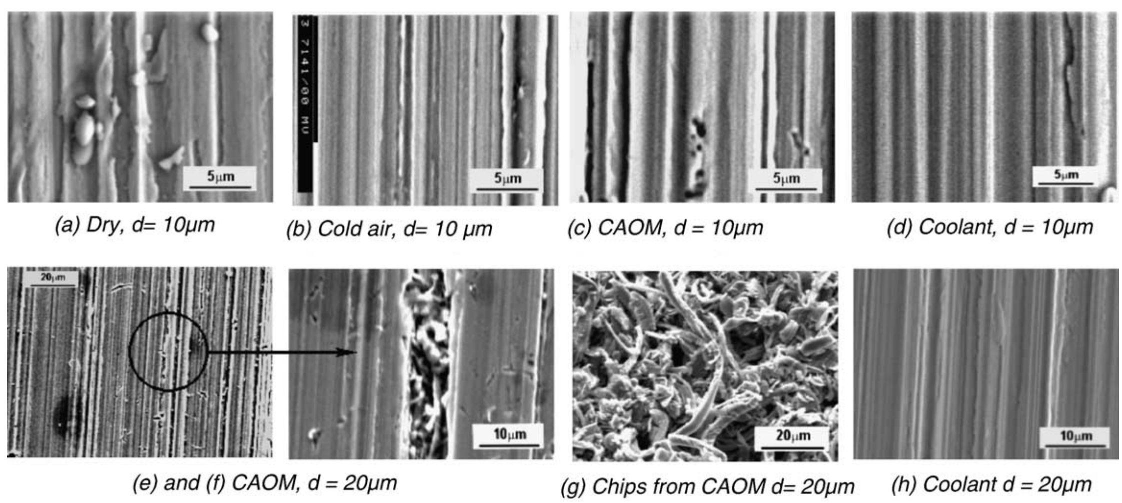

Fig. 3. Surface morphology and chips under different cooling conditions.

3.1.2. Grinding forces and specific energy

It is interesting to note that when grinding with cold air at a depth of cut below the critical burning depth, 10 μm in the present case, the grinding forces and specific energy are lower than those associated with the grinding using coolant as shown in Figs. 6–8. This may be due to the bonding effect, or in other words, the re-welding between the chip particles together and to the work material. When steel is ground in dry air, this bonding is weak since the freshly ground steel is coated with a thin layer of oxide from 10 to 20 Å in thickness [8]. With sufficient coolant, however, atmospheric oxygen is greatly excluded from the grinding zone thus the oxidation process is slowed down. Hence, in this sense, the application of cold air is advantageous at small depths of cut.

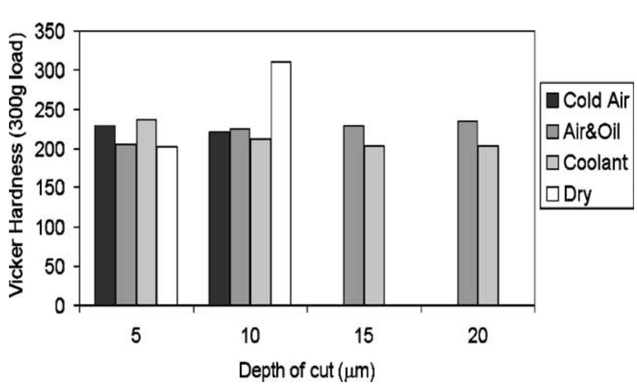

Fig. 4. Surface hardness.

Nevertheless, the use of cold air accelerated the wheel wear. The grinding force increased linearly with the number of the grinding passes, as illustrated in Fig. 9. This is similar to the linear relationship between the grinding force and the wheel flat area of wear [9]. That was partly the reason that a wheel with the cold air did not perform well at the second grinding pass when the depth of cut was 15 μm. The worn wheel also prevented the penetration of the cold air into the grinding zone.

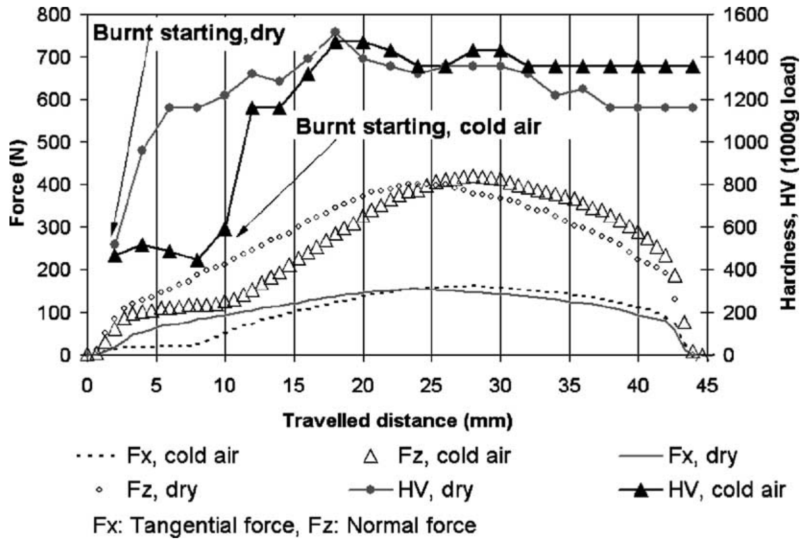

Fig. 5. Burning occurrence ($d = 15\,\mu$m) with dry and cold air: distribution of ground surface hardness and variation of grinding forces along burnt workpiece.

3.2. The application of CAOM

3.2.1. Surface morphology

With the addition of a very small amount of vegetable oil in the cold air stream, higher depths of cut above 10 μm could be performed without burning. A large number of lamellar and leafy chips collection as shown in Fig. 3g indicate a shearing mechanism in chip formation [1]. This is different from the molten spheres when burning occurred [8] as shown in Fig. 3a.

The surface roughness as shown in Fig. 2, however, was generally higher if compared with the results of grinding with coolant. This may be attributed to the poor cleaning capacity of the air stream. The particles/chips can scratch and even penetrate to the ground surface as shown in Fig. 3e and f, leading to a poorer surface finish.

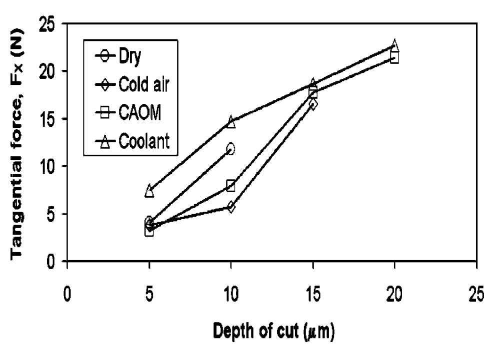

Fig. 6. Tangential grinding forces.

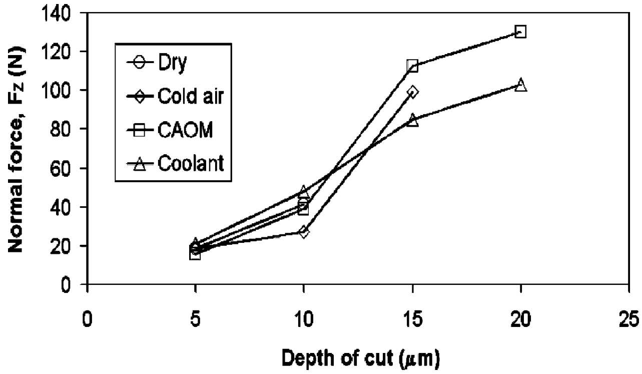

Fig. 7. Normal grinding forces.

3.2.2. Grinding forces

As expected, a significant benefit achieved by the addition of vegetable oil in cold air was to reduce the wheel wear, as shown in Fig. 9. The specific energy, on the other hand, was not higher than the grinding with coolant (Fig. 8). However, the use of CAOM caused an increment of grinding forces if the depth of cut was greater than 10 μm (Figs. 6 and 7). As discussed above, a larger number of chip/particles was produced at higher depth of cut. Because of the poor cleaning capacity of the air stream, a large number of these contaminates might be either loaded onto the wheel or embedded into the ground material, thus produced higher grinding forces.

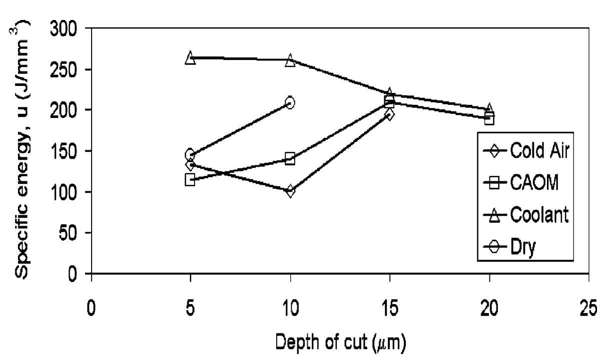

Fig. 8. Specific energy.

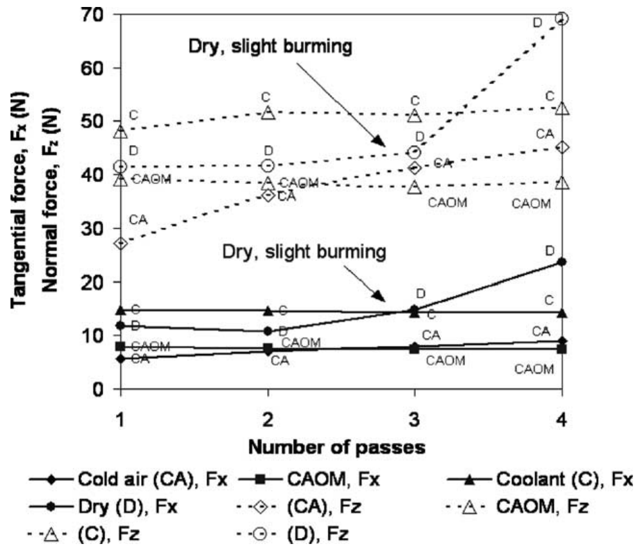

Fig. 9. Variation of grinding forces with the number of grinding passes.

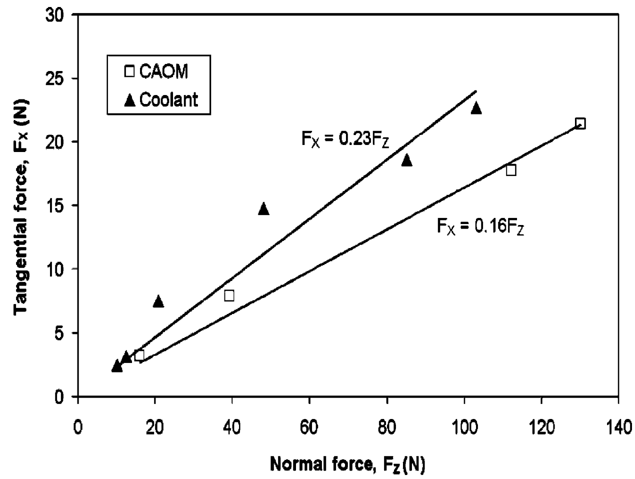

Fig. 10. Tangential and normal force components.

The tangential and normal force components were nearly linear in the whole variation range of the depths of cut (Fig. 10). The slopes can be regarded as the coefficients of friction, which were 0.16 and 0.23 under CAOM and coolant, respectively. It must be pointed out that fatty acids in vegetable oils can lubricate well only when the temperature is below 150 °C. It indirectly implies that the grinding temperatures under CAOM had to be low.

3.2.3. Hardness

The hardness profiles of ground components with CAOM and coolant are illustrated in Fig. 11. The result showed that the hardness of the component ground with CAOM was more or less the same as that ground with coolant. It suggests that the improvement of lubrication by a small amount of vegetable oil in the cold air stream could significantly reduce the thermal impact on the workpiece. This, to a certain extent, aligns with the conclusion of Tönshoff et al. [10] in discussing the dressing effect on hardening.

3.2.4. Residual stresses

There are three sources for surface residual stresses in a ground component: the mechanical traction, the thermal flux and the material's phase transformation [11]. The mechanical effect generally induces compressive stresses whose magnitudes depend on the "friction" factor, a ratio between the normal and shearing force components [12]. The strength of grinding heat, however, often produces unfavourable tensile stresses [13]. If the ground component experiences a critical temperature with rapid cooling, the phase transformation may take place and often results in additional tensile stresses [14].

Fig. 12 shows the variation of residual stresses with the depth of cut (d) from the present experiment. The small

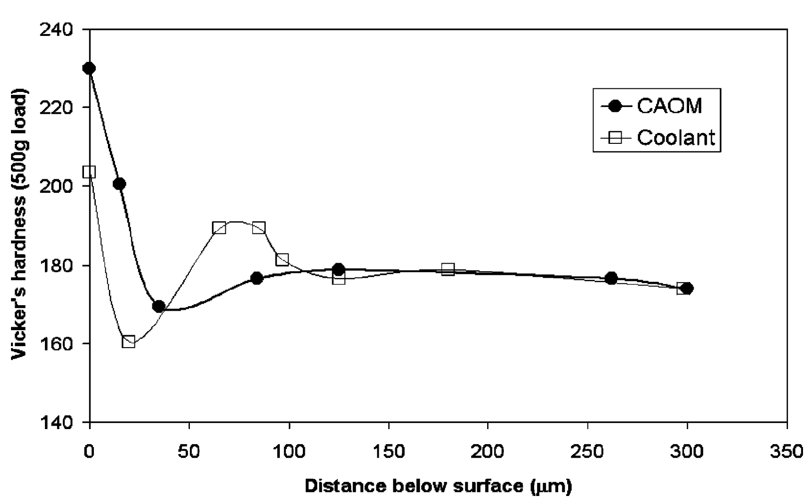

Fig. 11. Sub-surface hardnesses, $d = 15\,\mu m$.

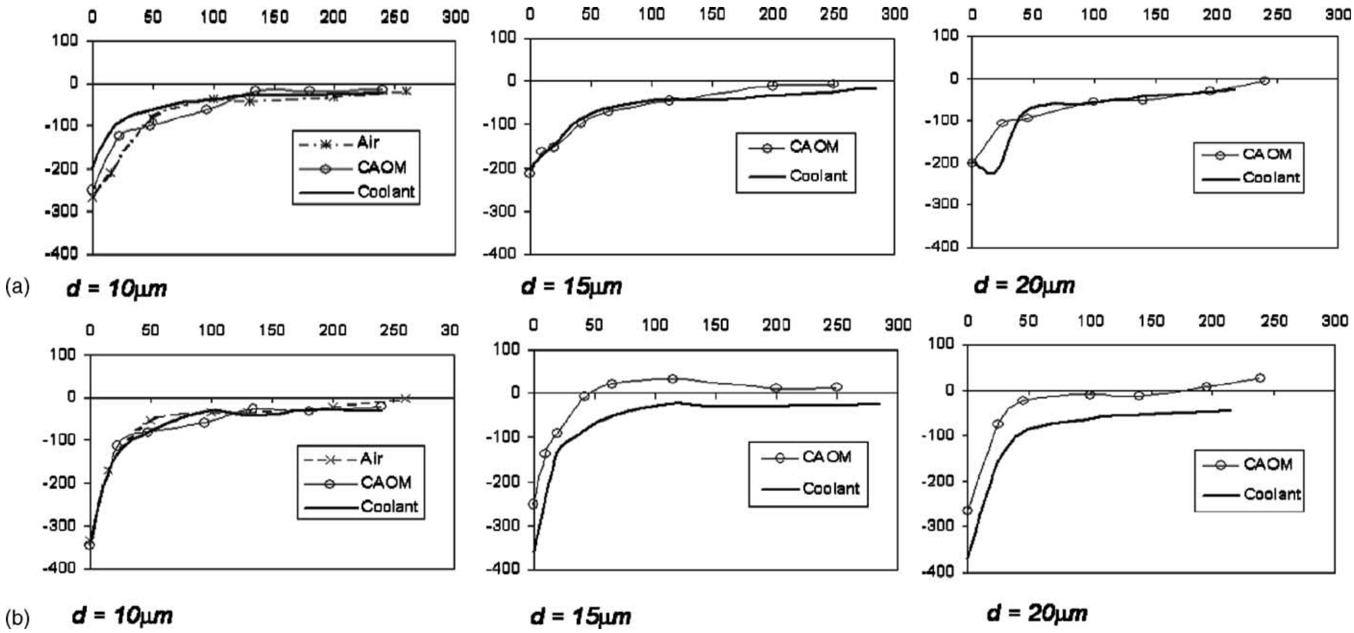

Fig. 12. Surface residual stress profile—residual stress (MPa) versus depth below surface (μm): (a) longitudinal stress; (b) transverse stress.

hardness values of the ground components (Figs. 4 and 11), which are much less than 463 HV [13], excluded the martensitic phase transformation induced by grinding. When the depth of cut was small, similar to the case with coolant, CAOM also provide a sufficient heat removal rate, so that the residual stresses were compressive. This means that the deformation during grinding was predominantly mechanical.

However, when grinding at a high depth of cut with CAOM, e.g. 15 μm, it is interesting to see that the residual stresses in the transverse grinding direction tend to become tensile, although remaining compressive along the grinding direction. This can be explained by the non-uniformity of heat transfer in the vicinity of the grinding zone. In an investigation on the heat and mass transfer between impinging gas jets and solid surfaces, Martin [15] pointed out that the highest local Nusselt number (or convective heat transfer coefficient) is obtained at the jet impingement point and it decreases with the distance to the direction of air expansion. Therefore, in a grinding process, a large portion of the heat convected by cold air, was in the grinding direction aligned with the nozzle, rather than in the direction transverse to it. This effect could become more perceptible with the involvement of the oil mist whose conical flow lubricated more the middle part of the workpiece, creating a severer non-uniform heat flux across the thickness of the workpiece; resulting in thermal residual stresses which are tensile. In the grinding with coolant, however, the transverse grinding heating was much more uniform since the whole grinding zone was normally well cooled by a significant liquid flow. Thus as a result, the transverse residual stresses were also compressive as shown in Fig. 12.

4. Conclusions

(1) Under low material removal rates, cold air can be used to suppress surface burning with an advantage of reducing grinding forces. The surface hardness was not altered, indicating that thermally induced hardening does not happen. However, the lack of lubrication prevented its applicability for higher material removal rates.
(2) With the addition of a small amount of vegetable oil mist in the cold air stream, larger depths of cut can be performed without burning while keeping the grinding quality comparable to the grinding with coolant.
(3) Grinding chips were of lamellar and leafy shapes, revealing a shearing mechanism of chip formation.
(4) The surface cleaning ability of CAOM is worse than that of coolant, thus causing a slight increase of ground surface roughness.
(5) The residual stress profiles in components ground with CAOM are highly directional, compressive in grinding direction and tensile in transverse grinding direction. This was due to the non-uniformity of the heat flux created by the flow of CAOM.

Overall, cold air with oil mist can be used for fine grinding with small depths of cut. For a broader application, the cooling and lubrication capacity needs to be further developed.

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