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# A review of cutting fluid application in the grinding process

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**Abstract**

It is generally accepted that heat generation is the limiting factor in the grinding process due to the thermal damage associated with it. To combat this energy transfer, a cutting fluid is often applied to the operation. These cutting fluids remove or limit the amount of energy transferred to the workpiece through debris flushing, lubrication and the cooling effects of the liquid. There have been many new and exciting systems developed for cutting fluid application in the grinding process. This paper reviews some of the common as well as some of the more obscure cutting fluid systems that have been employed in recent years with an emphasis on creep-feed applications. The review also suggests possible avenues of future research in cutting fluid application for the grinding process.


*Keywords:* Creep feed grinding; Cutting fluid application

## 1. Introduction

Grinding is one of the oldest machining processes. Ancient humans became the first grinding engineers when they discovered one could take two rocks and rub them together in order to form tools and weapons. Grinding engineers now employ the most modern techniques to remove material to form their products. In today's global market, there is the ever-daunting task to make the machining process more efficient. One of the major limiting factors in grinding production rates is thermal damage. This damage can be reduced by the application of a cutting fluid that removes the heat created by the workpiece interaction and lubricates the two surfaces in order to decrease the amount of friction.

This paper reviews some of the common as well as some of the more obscure cutting fluids and systems that have been employed in recent years with a focus on creep-feed applications. Fig. 1 shows the development of the discussion and how this paper is organized. The review concludes by showing the prevailing trends in cutting fluid applications.

## 2. Workpiece damage in grinding

The most notable and severe type of workpiece damage is known as workpiece burn. Burn occurs when enough heat and energy is created by the grinding process to produce discolouration and blemishes which can be seen on the workpiece [1–3]. Workpiece burn, however, can occur even when no physical flaw is observed [1,2]. As the surface temperature increases the microstructure of the material can change. As the microstructure changes, the hardness will vary. Moreover, these variations in the structure can result in detrimental internal stresses [1,3,4]. Often, the resulting internal stresses of a microstructure change leave a tensile stress on the surface of the work which leads to a reduced fatigue life [1,2,4]. If the material is sensitive enough, the workpiece can even crack due to the residual stress or the localized thermal expansion from the grinding process, which is more common in ceramics [5].

### 2.1. Cooling mechanisms

Cutting fluid is applied to the grinding zone to limit the heat generation. The fluid accomplishes this by reducing the amount of friction in the grinding zone through its

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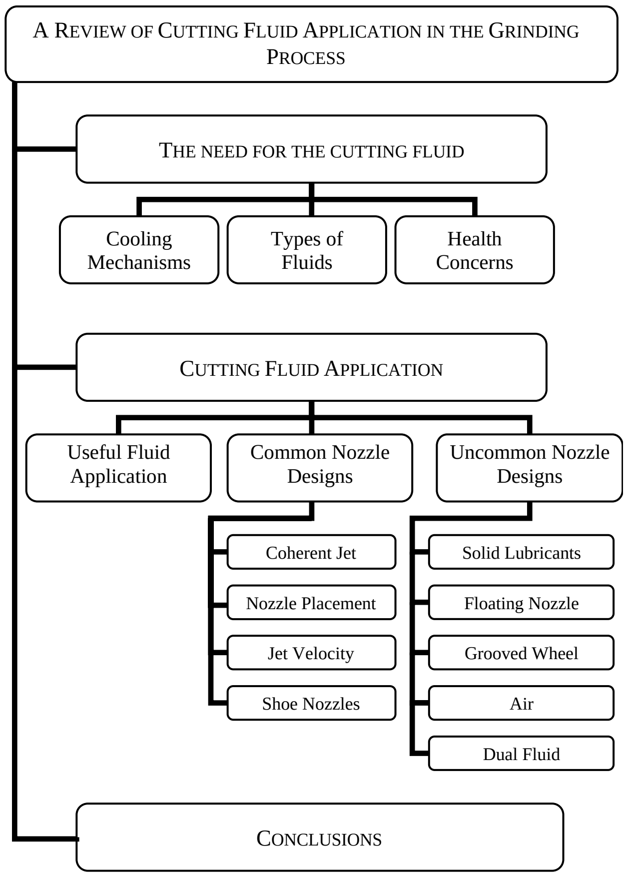


Fig. 1. Outline of discussion.

lubrication properties. It also reduces heat by conducting some of the energy into the fluid instead of the workpiece. Thus, the colder the fluid, the more effective the heat transfer [6]. The third and final purpose of the fluid is to flush away chips from the grinding process [7–9]. If the chips are not removed, they could clog the wheel and essentially dull the wheel so that the only cutting operations occurring would be plowing and rubbing. If this clogging were to happen, the forces and energy input would greatly increase as would the heat input to the workpiece [10].

When the cutting fluid is applied to the grinding zone, it will initially undergo nucleate boiling. This process enhances the rate of heat transfer between the workpiece and the fluid. As the temperature increases further, however, the boiling mechanism will turn to film boiling where a vapour film is developed between the workpiece and the fluid. The vapour acts as an insulator and prevents heat transfer to the fluid. As a result, the workpiece temperature quickly rises and burns the surface of the material [11–13]. For cooling to remain effective, it is imperative that the temperature of the workpiece does not reach or exceed the fluid's film boiling temperature. Guo and Malkin [14] refer to the heat flux that causes the fluid to reach the film boiling temperature as the critical burnout limit. They developed and correlated a model for creep-feed grinding and found that it is generally necessary to have the heat flux below the burnout limit in order to prevent burning of metallic workpieces.

### 2.2. Types of cutting fluid

Blenkowski [15] defined four cutting fluid categories based on their composition: synthetics, semi-synthetics, soluble oil and straight oil. The oil that is used in these fluids is either mineral or synthetic oil and each fluid has its own distinct properties. Mineral oils are naphthenic and paraffinic hydrocarbons that are refined from crude oil. The function of these molecules is to provide a base for other additive molecules to attach themselves to refine and hone specific characteristics of the fluid. These oils should be hydrogenated so that most of the carcinogenic polycyclic aromatics can be destroyed or naturalized [16].

A common disadvantage of soluble oils is their poor emulsion stability, meaning they are prone to the oil separating out of the solution. Semi-synthetics possess good lubrication for moderate and heavy-duty grinding. Moreover, they consist of less mineral oil than soluble cutting fluids, but they require high-quality water and tend to foam very easily. Foam can inhibit the heat transfer because it limits the amount of fluid in contact with the wheel and workpiece. Synthetic oils do not contain mineral oil and are often recognized by their water-like appearance.

Table 1 highlights and ranks the properties of these four major kinds of grinding fluids [16]. This table reiterates the work of Gong et al. [17] and confirms that there is no clear fluid that is perfect in all aspects. It would be ideal to combine the heat removal, filterability, cost and environmental properties of the synthetic fluids with the lubricity, maintenance and wheel life of the straight oils. There is a possible way to aspire to this goal since most cutting fluids are made from a concentrate mixed with water. Klocke [18] showed that if the oil additive concentration increases the process forces, the grinding energy and temperatures decrease while the wheel life increases. This observation was also confirmed by Yoon and Krueger [19]. It was found that the diluted synthetics had a grinding ratio ($G$-ratio) of 2.5 and 7.5, semi-synthetics had $G$-ratios between 2.5 and 6.5, and soluble oils had $G$-ratios between 4 and 12. Undiluted cutting fluids had $G$-ratios between 60 and 120.

Table 1
Grinding fluid characteristics [16]

| | Synthetics | Semi-synthetics | Soluble oil | Straight oil |
|---|---|---|---|---|
| Heat removal | 4 | 3 | 2 | 1 |
| Lubricity | 1 | 2 | 3 | 4 |
| Maintenance | 3 | 2 | 1 | 4 |
| Filterability | 4 | 3 | 2 | 1 |
| Environmental | 4 | 3 | 2 | 1 |
| Cost | 4 | 3 | 2 | 1 |
| Wheel life | 1 | 2 | 3 | 4 |

1, worst; 4, best.

Table 2
Composition of grinding swarf [5]

| Material | Weight percentage (%) |
|---|---|
| Iron | 50–80 |
| Wheel material (SiC, CBN, $Al_2O_3$) | 4–20 |
| Oil | 0.5–40 |
| Water | 0–30 |
| Alloys | 0–15 |

All aqueous cutting fluids had similar *G*-ratios except for synthetic emulsions containing Extreme Pressure additives, which had a *G*-ratio of 20 at 5% and 50 at 10%. In certain conditions, synthetic emulsion approached the *G*-ratio of undiluted cutting oils.

In 1999, Minke [20] compared oil and water based cutting fluids for different grinding situations. The research suggests that if surface integrity is most important, the ranking sequence for cutting fluids from best to worst would be: ester oil, oil-based coolant and finally water-based emulsions. The report also shows that water-based emulsions have better cooling, but generally lead to higher grinding forces and cannot prevent thermal damage to the workpiece.

### 2.3. Health concerns with cutting fluids

Most cutting fluids provide a breading ground for bacteria which is hazardous to the machine operator [21,22]. Cutting fluids are also known to cause skin disorders such as dermatitis. Moreover, there is the potentially fatal effect of leached heavy metals in the fluid affecting the human respiratory and dietary system [23].

Once the fluid has been used, it contains small amounts of wheel debris and workpiece material [24]. Dahmen et al. [25] developed a process using supercritical carbon dioxide to separate the debris and it was originally implemented for glass grinding with high oil and lead content. The researchers have since modified the system to accommodate metal grinding.

In the early 1990s, it was estimated that 130,000–250,000 tons per year of cutting fluid was used in Germany. After a certain amount of time, all this fluid must be replaced and disposed of in order to maintain a consistent production level. From Table 2, one can understand why there is a need to properly dispose of cutting fluids in the most ecologically friendly manner. The proper disposal of the oil, alloys and iron is the most critical because they pose the greatest environmental hazard [24].

## 3. Conventional cutting fluid application

### 3.1. Useful fluid application

Powell [26] devised a model for determining the depth of fluid penetration into a porous wheel from a shoe nozzle. The same model could be applied for calculating the flow rate through the grinding zone, often referred to as the 'useful flow rate'. Radial pressure inside the shoe was the main parameter assumed to influence the depth of penetration since pressure forces the fluid into the pores of the wheel. The significant parameters of the model are the wheel speed, radius, porosity and permeability. Compared to the grain size of the wheel, the depth of penetration is usually small. This result implies that the cutting fluid remains mainly on the surface of the wheel and does not flow deep into the pores of the wheel [27,28].

Metzger [29] advanced an empirical flow rate model. The model related the required flow rate for acceptable grinding results to the power used by the spindle. Since it was known that power is related to the temperature rise in the cutting zone, it was assumed that the flow rate of the cutting fluid should be dependent on the grinding power. In this model, consideration was given to the nozzle efficiency, fluid type and fluid properties including density and heat capacity.

Using a smooth rotating wheel and workpiece with a small gap between them to represent the grinding zone, Schumack et al. [30] were able to predict the flow rate through the grinding zone. This calculation was done by using Reynolds' equation and claimed to have reasonable correlation with experimental work for laminar flow. Klocke [31] also modelled flow through the grinding zone based on Reynolds' equation for laminar flow. The flow rate was calculated as a function of the space between the wheel and the workpiece, and fluid velocity within the gap. However, in turbulent flow situations the models failed, thus limiting the application of these models. Using a comparable strategy, Hryniewicz [32] modelled flow for a rough non-porous wheel. A modified Reynolds' equation was used to accommodate the fluid turbulence between the wheel and the workpiece. It was reported that satisfactory results were found for low Reynolds numbers, but significant error was observed for high Reynolds numbers.

Guo and Malkin [28] used the momentum and mass continuity equations to analyse the flow through the grinding zone with porous grinding wheels. The resulting differential equations were solved numerically. It was concluded that the useful flow rate could be calculated in terms of the depth of penetration, wheel width, wheel porosity and wheel peripheral velocity. This model claims to predict the useful flow rate accurately if the depth of penetration is known.

Engineer et al. [33] experimentally examined the fluid flow through the grinding zone. A test rig was used to measure the amount of fluid passing through the grinding zone for straight surface grinding. A few years later this setup was refined by Krishnan et al. [34]. The researchers collected measurements for the useful flow rate and supplied flow rate while the work speed, depth of cut, nozzle distance, wheel porosity, dressing depth and dressing leads were varied. The results show that bulk porosity and nozzle position were the main parameters influencing the flow rate through the grinding zone [33,34].

Most of these mathematical models and experimental work used laminar flow; however, in reality the flow through the grinding zone is turbulent. Gviniashvili et al. [27] decided to combat this issue using simple flow rate and power equations to develop a useful flow rate model with two loss coefficients. The model's important parameters were power, wheel speed, nozzle flow rate, jet velocity, jet power and the required nozzle outlet gap. Acceptable agreement was found between a high porosity grinding wheel, a knurled aluminium disk and the model. It was said that this model is appropriate for electroplated wheels and lower porosity wheels.

### 3.2. Nozzle design

One of the more popular research topics has been jet coherency. Some of the advantages of these nozzles are the reduction of air entrainment in the cutting fluid, more accurate velocity matching to the wheel periphery, and accurate focussing into the cutting zone [13]. Webster et al. [9,13,16,36,37] brought coherent jet design to the forefront of nozzle design in the grinding field. Their work was pooled from non-grinding operations to develop the coherent jet for grinding operations [38–40]. Using this information base, Webster et al. developed a new nozzle for grinding applications as shown in Fig. 2. The popularity of these jets has grown considerably over the years due to their high performance in a variety of conditions. Silva et al. [41] have used them to compare different cutting fluids when grinding martensitic steel. Steffen [42] studied the improvement when creep-feed grinding Inconel 718 and found over a 40% increase in the material removal rate.

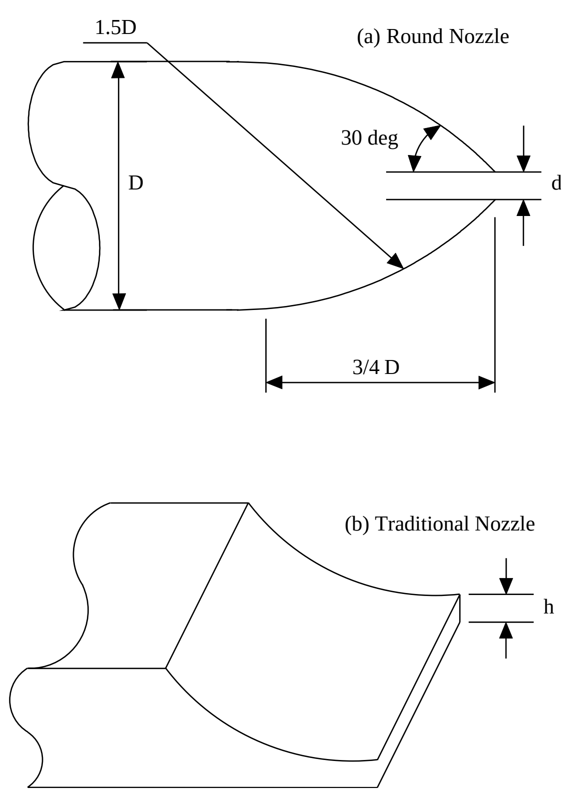


Fig. 2. Nozzle designs [9].

From this work on coherent jets [16,35,36,42], several guidelines for their construction and use have been put forth:

- The nozzle surface finish should be smooth and concave
- The nozzle should have sharp exit edges
- The nozzle should have a high contraction ratio from inlet to exit
- Elbows and changes in the pluming diameter should be avoided
- Performance is not very sensitive to the nozzle angle as long as the flow is directed into the grinding zone
- There may be no need for profiled nozzles since a large single round coherent nozzle or several smaller round coherent jets can be utilized. If expensive rectangular nozzles must be used, an aspect ratio of 5–8 is recommended
- There should be low-pressure fluid flow on the back edge of the workpiece to prevent burn
- A straight pipe placed between a flow conditioner and nozzle is needed to encourage a uniform-velocity flow condition
- The lower the Reynolds number, the more coherent the jet
- With high porosity wheels, water-based fluids can have higher removal rates when compared to straight oils; however, for dense wheels, the opposite appears to be true. Bo-Yi [43] has also confirmed this last point for creep-feed grinding of metal with a shoe nozzle.

### 3.3. Nozzle placement

There has been some work done in the placement of traditional cutting fluid nozzles. Most people aim the nozzles directly at the grinding zone, in plane with the movement of the table, and often as close as possible to the wheel. This placement was confirmed as an ideal location by Engineer et al. [33], where in their study, the distance from the grinding zone was changed and the results showed an improvement in the grinding performance when the nozzle was closer (see Fig. 3). However, the works of Webster et al. and Steffen show when coherent jets are utilized the positioning of the nozzle does not greatly affect the results of the workpiece [16,35,36,42].

Recent work by Zhong et al. [44] has examined the application of fluid by directing it from the sides. In this work, it was said that the new cutting fluid system contributed significantly to the improved surface finish of the samples. It also appeared that the decreased nozzle distance from the wheel and the use of flexible hoses to aid

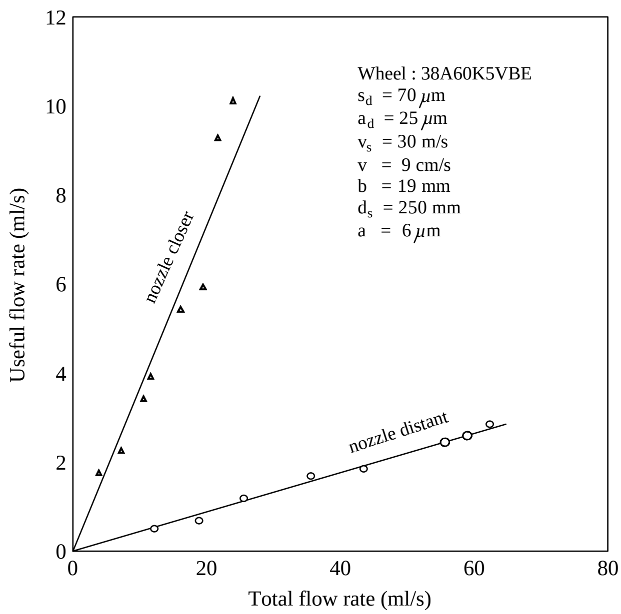


Fig. 3. Effect of nozzle distance on useful flow rate [33].

in the positioning of the nozzles improved the cooling performance at the grinding zone (see Fig. 4). A similar setup was used by Liu et al. [45]; however, here there were three nozzles all delivering oil. The design of the cutting fluid system was not the focus of the study and so a comparison of how the system performed was not mentioned.

Ebbrell et al. [7] examined the air boundary and determined the ideal position for a free jet. The study had three jets placed in three different locations. As shown in Fig. 5, there was a nozzle tangential to the cutting arc, a nozzle at an intermediate position and a nozzle at an angular position 15° to the grinding wheel. The useful flow rate was collected and compared for the different positions. It was found that the intermediate position was the most effective when 3.3 lpm passed through the grinding zone compared to 3 lpm and 0.5 l/min for the tangential and angular positions, respectively.

### 3.4. Jet velocity

Kovacevic and Mohan [30] ran experiments at extremely high jet velocities in order to overcome the air barrier surrounding the wheel and compared the results to traditional flooding techniques. The setup was able to produce a coolant exit flow velocity of 365 m/s and a flow rate of 3.64 lpm. Acoustic emission signals, forces and surface roughness were compared in this study. The aluminium oxide wheel was operated at 30 sm/s in a creep-feed grinding mode. The outcome of the tests show that the higher the jet speed the better the overall grinding results become with lower forces and acoustic emissions along with an improvement in the surface finish.

### 3.5. Shoe nozzles

The shoe nozzle is a low-pressure method of applying cutting fluid to the grinding process. According to Salmon, the shoe nozzle is the best method for applying the cutting fluid to the wheel periphery [46]. The system works by the fluid entering a manifold and then propelled to the wheel speed in the shoe and carried into the cutting arc. A simple shoe nozzle can be seen in Fig. 6. Non-porous wheels can experience hydrodynamic lift or hydroplaning. This phenomenon occurs when the cutting fluid is compressed

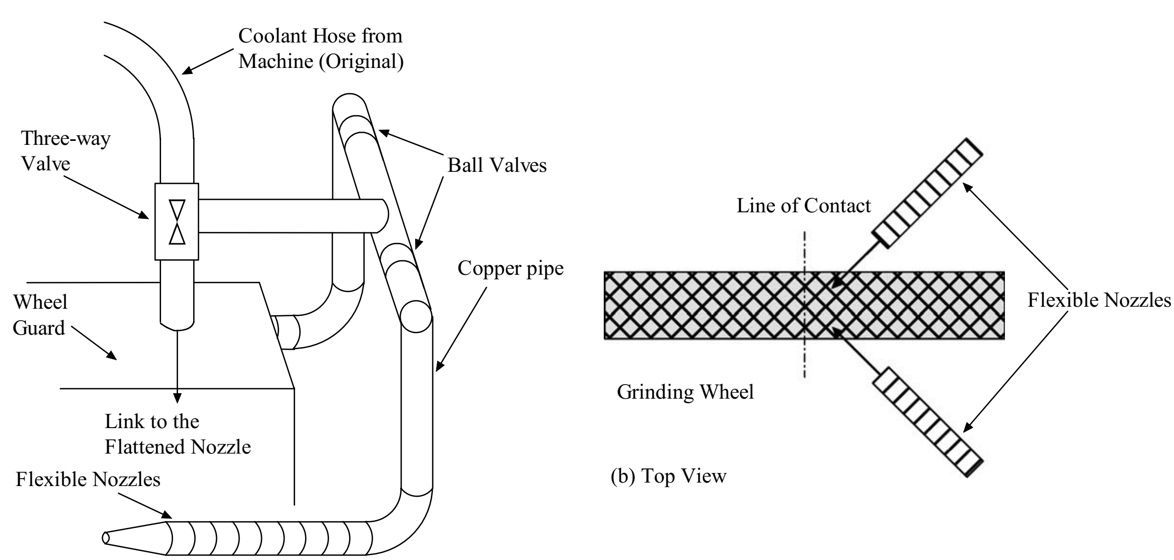


Fig. 4. Zhong's fluid application setup [44].

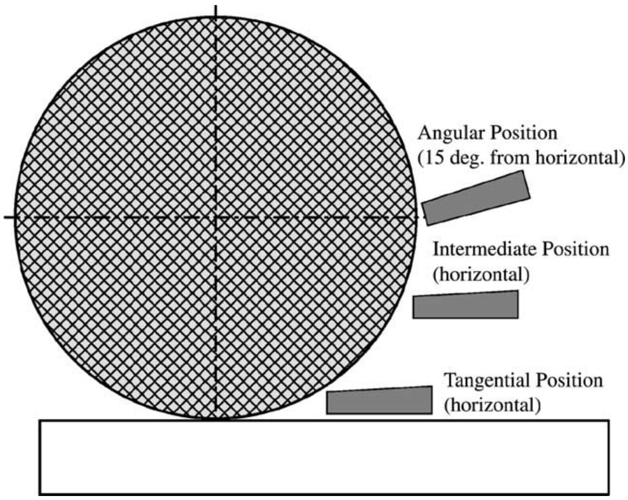


Fig. 5. Nozzle positions [7].

in the gap between the workpiece and grinding wheel. During the grinding process, the material removed, referred to as swarf, fills the gap and increases the gap pressure. If the pressure is too great or the stiffness of the machine is too low, the wheel can actually lift away from the surface of the workpiece [46,47].

One of the major reasons why shoe nozzles are very effective is because they are able to maximize the amount of cutting fluid passing through the cutting zone. If one maximizes the flow through the grinding zone, the normal forces, temperatures and friction will likely be reduced. This result has been confirmed by Klocke et al. [31].

Ramesh et al. [47] developed a shoe nozzle with three adjustable orifice jets to improve the cutting fluid application with a CBN wheel. The first or upper jet disrupts the air curtain and so a vacuum is formed allowing an abrupt flow of coolant into the grinding zone. The second and middle orifice supplies the cutting fluid that leads to the formation of a coolant coating on the grinding wheel. The final and third orifice directly sends the cutting fluid into the grinding zone. With this nozzle the grinding forces were reduced by 40–60% depending on the workpiece, and both the material removal rate and surface finish improved. It was also noticed that as the wheel speed increased, the ratio of tangential to normal forces was reduced. The reduction of this ratio implies a decrease in friction since it is commonly accepted that the friction coefficient is the ratio between the tangential and normal forces [47,48]. It was also said that the cutting fluid shoe application interrupts the formation of a vapour bubble and film boiling and thus the thermal damage zone can be shifted to a higher material removal rate [47].

Zitt and Schäfer [3] compared four different shoe nozzles. The first nozzle is a modified free jet. This nozzle has a de-turbulence zone where the flow is able to become laminar. Also, the exit of the nozzle has very sharp edges allowing the flow to be directed precisely. The second nozzle has a flat section on the top to disrupt the air boundary. The resulting negative pressure caused by the air flow disruption drags the cutting fluid through a de-turbulence zone so that the fluid is laminar as it makes contact with the grinding wheel. The third nozzle is very similar to the design of Ramesh et al. [47]. The fourth and final nozzle has a large opening that wets the grinding wheel over a large area at low pressure resulting in a contact zone which is heavily flooded. The nozzles were designed for surface grinding with large depths of cut.

All of these studies confirmed that a shoe nozzle is a very efficient method of applying cutting fluid in the grinding process. The one major setback is that they must always be

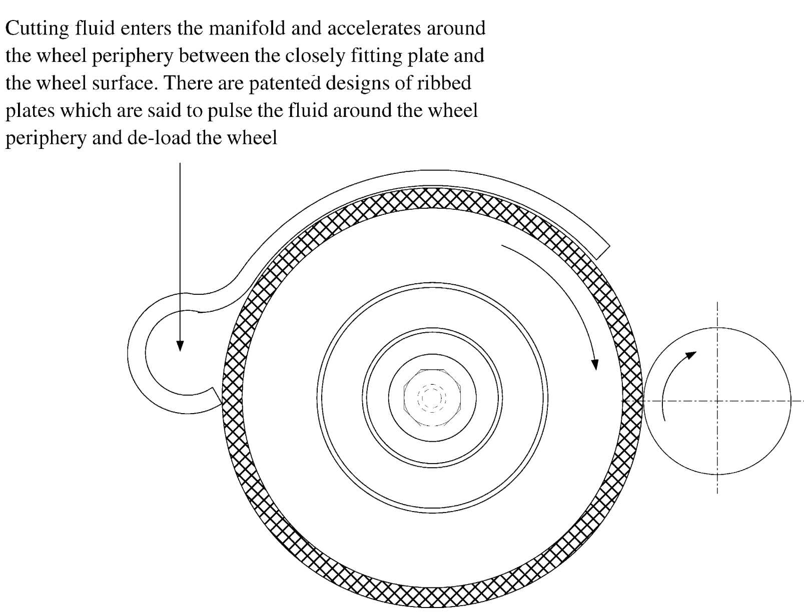


Fig. 6. Basic shoe nozzle [45].

in close contact with the periphery of the wheel. This constraint implies that as the wheel wears or is dressed, the nozzle must be adjusted to maintain consistent or acceptable results. The distance to the wheel can be maintained via a mechanical servo device; however, such a device only adds to the complexity of the system and exposes delicate mechanisms to a very harsh environment [13,18].

## 4. Unconventional cutting fluid application

### *4.1. Solid lubricants*

There have been several different researchers that have studied solid lubricants. Typically, graphite is used because of its weakly bonded hexagonal plate structure [49]; however, more recently molybdenum disulfide ($MoS_2$) has been used. Salmon [50] uses $MoS_2$ as a 'hard lubricant' and titanium aluminum nitride (TiAlN) to resist wear on CBN wheels. The coated wheels do not require the added lubricity of the oil that CBN wheels typically operate in because they perform adequately with water-based fluids. Salmon believes that the coated wheels will surpass the traditional wheels and has the added bonus of operating with the environmentally-friendly water-based coolant.

Shaji and Radhakrishnan [51] describe a grinding process that uses a graphite paste as a lubricant. A comparison of the performance of graphite-assisted grinding with dry grinding and conventional wet grinding was made. In the comparison workpiece material, dressing conditions and cutting fluid application were varied. The graphite lubricant was made with a water-soluble oil in the weight ratio of 1:1 (powder graphite to oil). The paper makes no reference to exactly what kind of oil was used and how it played a role in the lubrication of the grinding zone. The study shows that the tangential forces, grinding zone temperatures and specific energies are lower with the graphite paste when compared to dry or coolant grinding. With the graphite-assisted grinding, the ratio of tangential to normal forces was lower, indicating less friction; however, the system had problems with wheel clogging and grinding ductile materials.

Shaji and Radhakrishnan [52] have also used slotted wheels with graphite impregnated into the slots. There were three different wheels with varying numbers of slots: 10, 15 and 20. Compared to conventional dry- and wet-grinding, the normal forces with the graphite slotted wheels were found to be more or less the same or even slightly higher at low infeed rates, but at increased infeed rates, these forces were higher in most cases. The surface roughness, residual stresses and hardness profiles were improved with the graphite wheels. The results of these experiments are promising; however, these experiments were done with small depths of cut and do not represent a conclusive improvement over more traditional cutting fluid application.

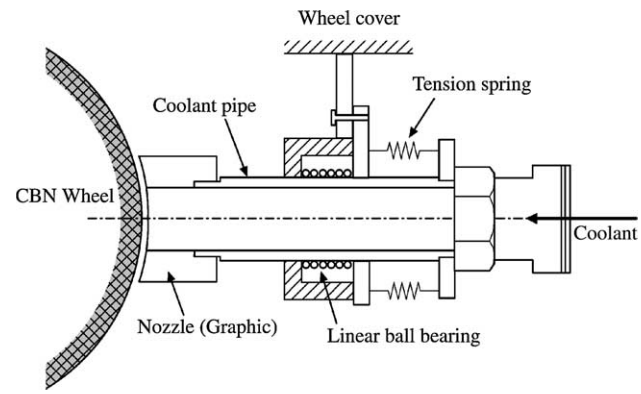


Fig. 7. Schematic illustration of a floating nozzle [53].

### *4.2. Floating nozzle*

As shown in Fig. 7, a floating nozzle is made from a nozzle with an exit facing the grinding wheel, a coolant delivery tube, a holder connected to the wheel cover for the delivery tube to smoothly move laterally and a spring mechanism on the end to ensure contact with the wheel. The front of the nozzle is made of a rather soft material such as graphite so that it can be easily ground by the wheel.

Ninomiya et al. [53] found that by using a floating nozzle on a CBN wheel, the wheel wear was reduced in half for shallow depths of cut and low workpiece speeds. It was also found that the surface finish was enhanced under these conditions. When compared with traditional coolant application, the floating nozzle improves the grinding performance with an impressive one twelfth of the cutting fluid. The reason for this reduction is that the necessary amount of coolant reaches the grinding zone through the floating nozzle. It was discovered, however, that when the work speeds were increased beyond 20 m/min there was significant wheel wear.

### *4.3. Radial coolant jets*

Researchers have advanced the idea of sending the cutting fluid through the wheel instead of directing the fluid at the grinding zone via a nozzle [54–58]. It was felt that since the coolant would be in direct contact with the grinding zone, the fluid would be used more effectively.

Xu et al. [54] worked with a radial cooling mechanism. It was felt that by using perforated electroplated CBN grinding wheels with radial jets, where the fluid is forced from the cooling holes at high pressure, the fluid would break the boundary layer. Xu et al. were able to increase the critical heat flux, improve the cooling effect in the contact zone and increase overall efficiency. The temperature of the workpiece surface in the grinding zone was steadily kept below the film boiling temperature of 100–120 °C for water-based coolants, even with a high heat flux. This fluid application has great potential to revolutionize the creep-feed grinding field.

### 4.4. Grooved wheel

Shigeki et al. [59] shows that by having 4–36 small grooves, 3 mm wide and 0.5 mm deep, the heat transfer coefficient rises leading to more efficient grinding. A reason for the elevation in the heat transfer coefficient is due to coolant being held and stirred by the grooves. As the number of grooves increases there is also an increase in the heat transfer coefficient. The researchers suggest that the grooves have a possibility of improving the efficiency in heavy grinding with super-abrasive wheels with no porosity.

### 4.5. Air as a coolant

In 1998, Baheti et al. [60] intrigued the grinding field when they experimented with cold air and ester oils. They showed that with straight surface grinding on carbon steels using aluminum oxide wheels with environmentally safe ester oil and air provided acceptable results. Part of the study developed a mathematical model of the process to predict with reasonable accuracy the temperature rise.

Choi et al. [61] reported that the effectiveness of cold air was nearly comparable with conventional wet-grinding for shallow depths of cut; however, tensile surface residual stresses would appear and the surface roughness would increase with larger depths of cut as a result of the lack of lubrication through the grinding zone. Yui and Terashima [62] mixed cold air (−30 °C) and vegetable oil mist (0–8.6 cc/h) in order to improve upon cold air application. The results were that the critical depth of cut was only 6 μm. Nguyen and Zhang [47] separated cold air and oil application. The air was compressed to 600 kPa with a flow rate of 4095 SLPM. It was dried and ejected through a vortex tube to generate the cold air at −20 °C. A jet just above the air nozzle applied small amounts of olive oil to the wheel at a rate of 0.16 cc/min. The results showed that 15 μm was the maximum depth of cut before severe burn occurred.

Inoue and Aoyama [63] used cold air at −33 °C with a flow rate of 320 N l/min at a pressure of 200 kPa. The lubricant was ‘salad oil’ and was supplied at 6 ml/min. The results from this setup were compared with dry grinding and grinding with an oil-based fluid supplied at 400 kPa and 50 l/min. From the results when the depth of cut exceeded 0.1 mm, the oil-based cutting-fluid grinding showed the lowest temperature rise. This result indicates that conventional oil-based cutting-fluid grinding has an advantage over cooling-air and minimum-quantity lubricant application in terms of temperature rise control for large depths of cut. In general, the study showed that when using air and oil for shallow depths of cut, the temperatures, surface roughness and post-grinding surface hardness are comparable to that of more traditional cutting fluid application.

This type of cutting fluid application appears to be useful only for shallow depths of cut. In these studies, it was found that a large portion of the energy was convected away from the work by liquid coolant. The researchers of this area have said that further work needs to be done in this area for higher removal rates.

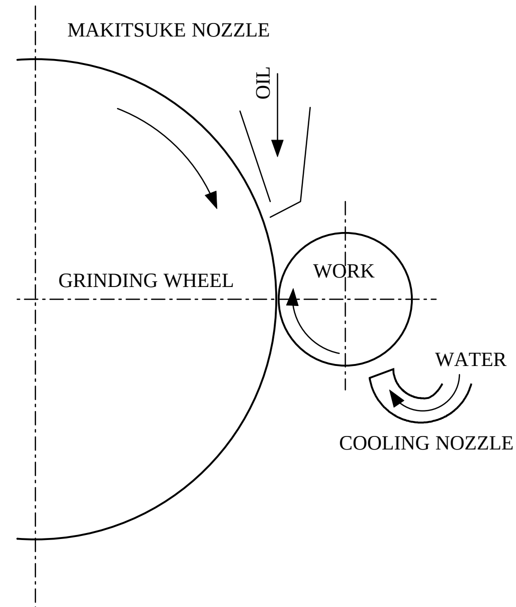


Fig. 8. Dual cutting fluid setup [64].

### 4.6. Dual fluid supply

In the 1980s, Yokogawa et al. [64] used a dual cutting fluid method in a cylindrical grinding operation. Mineral oil was used to lubricate the grinding zone and water was used to cool the workpiece. The experiments were carried out with a removal rate of 1200 mm$^2$/min, a wheel speed of 3600 m/min, and a CBN wheel. The oil was applied via a Makitsuke nozzle which is similar to a shoe nozzle. The coolant water was applied to the underside of the workpiece via a positional nozzle, (Fig. 8). The most challenging portion of this design and setup was to successfully separate the oil and water after grinding. No attempt was made to separate the flows prior to entering the reservoir. The researchers used the different specific gravities to separate the fluids. Any oil would naturally rise to the top and the water would settle to the bottom of the tank. The results of the study were encouraging. The surface roughness of the workpiece was dramatically improved. With conventional cutting fluid application the surface roughness was approximately 3 μmRz but with the dual cutting fluid application the surface roughness dropped to under 1 μmRz for the same removal. Also, grinding zone temperatures dramatically decreased with the dual fluid application.

## 5. Conclusions

Of the methods described in this paper, the coherent jet appears to be the most effective for industry at the present time. Steffen [42] was easily able to implement a coherent jet system on a Blohm Planomat 408 for under $2000CAD and achieved an increase of 30–61% in the Critical Specific Material Removal Rate (CSMRR) depending on the process parameters. While other methods use far less cutting fluid and are thus more environmentally friendly, they do not seem to instantly increase material removal rates to this level for this price.

Shoe nozzle and radial jet systems have the capacity to change cutting fluid application; however, they are currently relatively fragile systems when placed in a production environment. They also generally have a higher retrofit cost when compared to the coherent jet. More research needs to be done with these systems. When their cost is lower and their robustness has improved they have the potential to become competitive with the coherent jets in industry where reliability, production rates and costs are a priority.

The quest for the delivery system that encompasses both high production rates and low environmental impact is still ongoing. The systems discussed in this paper that have the highest cutting fluid application generally have the highest material removal rates or largest depths of cut. The more environmentally sound methods such as air or graphite have relatively small depths of cut and significantly lower material removal rates. It will likely take more research and advances to persuade industry to adopt these methods; however, in the long run, these practices have the potential to revolutionize the grinding field. Academic research in cutting fluid application should focus on trying to increase the material removal rates of these environmentally-conscious methods.

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## References

[1] J.A. Badger, A. Torrance, Burn awareness, Cutting Tool Engineering 52 (12) (2000).
[2] W.B. Rowe, D.F. McCormack, T. Jin, Controlling the surface integrity of ground components, Abrasives (DEC/JA) 2001; 24–30.
[3] L. Zhen-Chang, A. Satoshi, N. Masahiro, Influence of grinding oil viscosity on grinding heat and burn damage in creep-feed grinding, Lubrication Engineering 51 (8) (1995) 647–651.
[4] X. Chen, W.B. Rowe, D.F. McCormack, Analysis of the transitional temperature for tensile residual stress in grinding, Journal of Materials Processing Technology 107 (1–3) (2000) 216–221.
[5] O. Desa, S. Bahadur, Material removal and subsurface damage studies in dry and lubricated single-point scratch tests on alumina and silicon nitride, Wear 225–229 (II) (1999) 1264–1275.
[6] S. Malkin, Grinding Technology: Theory and Applications of Machining with Abrasives, Wiley, New York, 1989.
[7] S. Ebbrell, N.H. Woolley, Y.D. Tridimas, D.R. Allanson, W.B. Rowe, Effects of cutting fluid application methods on the grinding process, International Journal of Machine Tools and Manufacture 40 (2) (2000) 209–223.
[8] C.Y. Wang, X. Wei, Z.C. Pan, Y.X. Song, Effects of surfactant in stone machining, Key Engineering Materials 250 (2003) 194–199.
[9] J.A. Webster, C. Cui, Flow rate and jet velocity determination for design of a grinding cooling system, Technical Papers Supplement of the First International Machining and Grinding Conference, Dearborn, Michigan, 12–14 September, 1995.
[10] P.Q. Ge, J.F. Li, C.H. Lu, Z.C. Liu, Performance evaluation and action mechanism analysis of extreme pressure additives used for oil-based cutting fluids, Key Engineering Materials 250 (2003) 281–286.
[11] J.D. Campbell, Tools to measure and improve coolant application effectiveness, in: Proceedings of the Second International Machining and Grinding Conference, Dearborn, Michigan, 8–11 September, 1997.
[12] W.B. Rowe, T. Jin, Temperatures in high efficiency deep grinding (HEDG), CIRP Annals—Manufacturing Technology 50 (1) (2001) 205–208.
[13] J. Webster, E. Brinksmeier, C. Heinzel, M. Wittman, K. Thoens, Assessment of grinding fluid effectiveness in continuous-dress creep feed grinding, CIRP Annals 48 (2) (2002) 581–598.
[14] C. Gou, S. Malkin, Analytical and experimental investigation of burnout in creep-feed grinding, CIRP Annals 43 (1994) 283–286.
[15] K. Blenkowski, Coolants and lubricants: part 1—the truth, Manufacturing Engineering March (1993) 90–96.
[16] J.A. Webster, C. Cui, R.B. Mindek Jr., Grinding fluid application system design, CIRP Annals 44 (1) (1995) 333–338.
[17] P.Q. Ge, L. Wang, Z.Y. Luan, Z.C. Liu, Study on service performance evaluation of grinding coolants, Key Engineering Materials 258–259 (2004) 221–224.
[18] E. Brinksmeir, C. Heinzel, M. Wittman, Friction, cooling and lubrication in grinding, Annals of the CIRP 48 (2) (1999) 581–598.
[19] S.C. Yoon, M. Krueger, Optimizing grinding performance by the use of sol–gel alumina abrasive wheels and a new type of aqueous metalworking fluid, Machining Science and Technology 3 (2) (1999) 287–294.
[20] E. Minke, Contribution to the role of coolants on grinding process and work results. Technical Paper—Society of Manufacturing Engineers. MR (MR99-227), 1999, pp. 1–18.
[21] M.L. Hoff, Cutting fluids: necessary nuisance to productivity tool. Society of Manufacturing Engineers. MR (MR02-302), 2002, pp. 1–6.
[22] C.A. Sluhan, Selecting the right cutting and grinding fluids, Tooling and Production 60 (2) (1994) 7.
[23] H.S.E. Anon, Warnings for grinding coolants, Metalworking Production 147 (5) (2003) 44.
[24] E. Brinksmeier, J. Eckebrecht, Possibilities for the disposal of grinding swarf, CIRP Annals—Manufacturing Technology 43 (2) (1994) 593–597.
[25] N. Dahmen, J. Schon, H. Schmieder, K. Ebert, Supercritical Fluid Extraction of Grinding and Metal Cutting Waste Contaminated with Oils, ACS Symposium Series 670 (1997) 270–279.
[26] J.W. Powell, The application of grinding fluid in creep feed grinding, PhD Thesis, University of Bristol, 1979.
[27] V.K. Gviniashvili, N.H. Woolley, W.B. Rowe, Useful coolant flowrate in grinding, International Journal of Machine Tools and Manufacture 44 (6) (2004) 629–636.
[28] C. Guo, S. Malkin, Analysis of fluid flow through the grinding zone, Journal of Engineering for Industry 114 (1992) 427–434.
[29] J. Meteger, Superabrasive Grinding, Butterworth, Oxford, 1986.
[30] M.R. Schumack, J.B. Chung, W.W. Schultz, E. Kannatey-Asibu, Analyses of fluid flow under a grinding wheel, Transactions of the ASME 113 (1991) 190–197.
[31] F. Klocke, A. Baus, T. Beck, Coolant induced forces in CBN high speed grinding with shoe nozzles, CIRP Annals—Manufacturing Technology 49 (1) (2000) 241–244.

[32] F. Engineer, C. Gou, S. Malkin, Experimental measurement of fluid flow through the grinding zone, ASME Journal of Engineering for Industry 114 (1992) 61–66.

[33] P. Hryniewicz, A.Z. Szeri, S. Jahanmir, Application of lubrication theory to fluid flow in grinding: part I—flow between smooth surfaces, Journal of Tribology 123 (1) (2001) 94–100.

[34] R. Kovacevic, R. Mohan, Effect of high speed grinding fluid on surface grinding performance, Technical Papers of the First International Machining and Grinding Conference. Dearborn, Michigan, 12–14 September, 1995, pp. 917–931.

[35] C. Cui, J.A. Webster, Experimental Investigation of Coolant Jet Design for Creep Feed Grinding of Gas Turbine Airfoils, IGTI, ASME Cogen Turbo Power, 1994. pp. 91–96.

[36] J.A. Webster, Optimizing coolant application systems for high productivity grinding, Abrasives October/November (1999) 34–41.

[37] J. Webster, Grinding fluid effectiveness in CDCF grinding, Grinding and Abrasives June/July (2002) 24–26.

[38] H. Rouse, M. Asle, J.W. Howe, D.E. Metzler, Experimental investigation of fire monitors and nozzles, 117th ASCE Transactions, 1952.

[39] J.A. Owczarek, D.O. Rockwell, An experimental study of flows in planar nozzles, Journal of Basic Engineering 1972; 94.

[40] T.T. Yeh, G.E. Mattingly, Mixing motions produced by pipe elbows, NISTIR 89-4029, 1989.

[41] E.J. Da Silva, E.C. Bianchi, J.F.G. De Oliveira, P.R. De Aguiar, Evaluation of grinding fluids in the grinding of a martensitic valve steel with CBN and alumina abrasives, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 217 (8) (2003) 1047–1055.

[42] J. Steffen, Application of a coherent Jet Coolant system in Creep Feed Grinding of Inconel 718, MASc Thesis, Dalhousie University, 2004.

[43] C. Bo-Yi, Comparative study of creep-feed and shallow-cut grinding on ceramics. TMS Annual Meeting, Processing of Metals and Advanced Materials: Modeling, Design and Properties 1998; 135–148.

[44] U. Zitt, L. Schaefer, Nozzles and grinding wheel concepts for optimization of cooling in high performance grinding, Abrasives October/November (1998) 31–37.

[45] N. Krishnan, S. Malkin, S. Guo, Fluid Flow through the grinding zone in creep feed grinding, in: First International Machining and Grinding Conference, Dearborn, Michigan, 12–14 September, 1995, pp. 905–916.

[46] S.C. Salmon, Modern Grinding Process Technology, McGraw Hill, New York, 1992.

[47] K. Ramesh, S.H. Yeo, Z.W. Zhong, K.C. Sim, Coolant shoe development for high efficiency grinding, Journal of Materials Processing Technology 114 (2001) 240–245.

[48] T. Nguyen, L.C. Zhang, An assessment of the applicability of cold air and oil mist in surface grinding, Journal of Materials Processing Technology 140 (1–3) (2003) 224–230.

[49] W.D. Callister Jr., Materials Science and Engineering an Introduction, Fifth ed., Wiley, New York, 2000.

[50] S.C. Salmon, The effects of hard lubricant coatings on the performance of electro-plated superabrasive grinding wheels, Key Engineering Materials 238–239 (2003) 283–288.

[51] S. Shaji, V. Radhakrishnan, An Investigation on surface grinding using graphite as lubricant, International Journal of Machine Tools and Manufacture 42 (2001) 733–740.

[52] S. Shaji, V. Radhakrishnan, Application of solid lubricants in grinding: investigations on graphite sandwiched grinding wheels, Machining Science and Technology 7 (1) (2003) 137–155.

[53] S. Ninomiya, M. Iwai, T. Uematsu, K. Suzuki, R. Mukai, Effect of the floating nozzle in grinding of mild steels with vitrified CBN wheel, Key Engineering Materials 257–258 (2004) 315–320.

[54] H.J. Xu, Y.C. Fu, F.H. Sun, Research on enhancing heat transfer in grinding contact zone with radial water jet impinging cooling, Key Engineering Materials 202–203 (2001) 53–56.

[55] L. Zhen-Chang, A. Satoshi, N. Masahiro, Influence of grinding oil viscosity on grinding heat and burn damage in creep-feed grinding, Lubrication Engineering 51 (8) (1995) 647–651.

[56] W. Graham, M.G. Whiston, Some observations of through-wheel application in grinding, International Journal of Machine Tool Design and Research 18 (1978) 9–18.

[57] T. Suto, T. Waida, H. Noguchi, H. Inoue, High performance creep feed grinding of difficult to machine materials with new-type wheels, Japan Society of Precision Engineering 24 (1) (1990) 39–44.

[58] S.M. Rezaei, T. Suto, T. Waida, H. Noguchi, Creep feed grinding of advanced ceramics, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 206 (B2) (1992) 93–99.

[59] S. Okuyama, Y. Nakamura, S. Kawamura, Cooling action of grinding fluid in shallow grinding, International Journal of Machine Tools and Manufacture 33 (1) (1993) 13–23.

[60] U. Baheti, C. Gou, S. Malkin, Environmentally Conscious Cooling and Lubrication for Grinding, Proceedings of the International Seminar on Improving Machine Tool Performance, San Sebastian, Spain, 6–8 July, 1998, vol. 2, 1998 pp. 643–654.

[61] H.Z. Choi, S.W. Lee, H.D. Jeong, A comparison of the cooling effects of compressed cold air and coolant for cylindrical grinding with a CBN wheel, Journal of Materials Processing Technology 111 (2001) 265–268.

[62] A. Yui, M. Terashima, in: Proceedings of the Third International Conference on Abrasive Technology, 1999, pp. 394.

[63] S. Inoue, T. Aoyama, Application of air cooling technology and minimum quantity lubrication to relief grinding of cutting tools, Key Engineering Materials 257–258 (2004) 345–350.

[64] M. Yokogawa, K. Yokogawa, Improving grinding performance of CBN wheels by dual-fluid supply method, International Journal of the Japan Society for Precision Engineering 27 (1) (1993).