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Dry grinding process with workpiece precooling

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A R T I C L E I N F O

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A B S T R A C T

This paper proposes a workpiece cooling prior to grinding in order to allow a dry processing. Tests and simulation showed good potential. The obtained part quality is good, and there is no thermal damage since there is a higher heat flux from the grinding zone to the workpiece due to the much lower temperature of the last. The process design is a key task for good results and should include a precise determination of the cooling conditions that allow the grinding cycle heating to bring the part temperature close to the environment at the end of spark-out.

1. Introduction

In precision grinding, the control of the energy input is a key factor for producing quality parts and matching surface and subsurface requirements. The adoption of higher material removal rates is limited not only by machine constrains, but also due to the occurrence of thermal damage. As virtually most energy input is dissipated as heat to the grinding zone, the maximum temperature rise should be kept below a threshold value, avoiding the occurrence of workpiece thermal damage [1].

Cutting fluids are being used as an in-process cooling media to keep the workpiece surface below that critical value. The effectiveness in the use of cutting fluids for reducing workpiece temperatures at the grinding zone is strongly dependent on several factors, such as: pressure, flow rate, nozzle design and film boiling occurrence [1–4].

Toward sustainability, the reduction or elimination of cutting fluids is being sought [5,6]. Considering the successful application in milling, minimum quantity of lubricant (MQL) arouse as an alternative toward the minimization of fluid usage. However, MQL application in grinding is limited to specific cases [5]. The complete elimination of oil and the use of cryogenic fluids have been more and more supported by the environmental and economic appeals [6,7]. In other machining processes, successful applications of cryogenic fluids are being beneficial to quality, surface integrity, direct surface hardening and improved tool life [8].

The additional cost of the delivery system and safety requirements to the operator are, however, some drawbacks in the use of cryogenic fluids. Special setup arrangements would be required to properly ensure that the required amount of liquid nitrogen, for example, in terms of pressure and flow rate, would reach the grinding zone. Thermal deformation of the parts is frequently an issue due to the uneven heat distribution. The ideal scenario in terms of sustainability and economics would be the use of dry grinding [5,6] in a wider range of applications.

Aiming to avoid the temperature rise at the grinding zone, engineered wheels with reduced contact area [9,10] or soft bond wheels that promotes free-cut were used. However, most of the applications failed, resulting in prohibitive wheel wear or part burning [5]. In this context, the challenge of dry grinding is still to be accomplished.

2. Proposed dry grinding process with precooled parts

Many grinding processes are not critical to grinding burn and could be performed dry if the temperature rise in the workpiece would not be so high. Precooling the material is being researched in the cutting of biological or soft materials and also for the avoidance of dust [11,12].

In the history of the abrasive machining, the very primitive and manual processes were dry and followed by plunging the part into cold water. In this paper, it is proposed a scheme where the heat is removed from the part prior to grinding and the process is performed dry. So, there would be two steps: part cooling and dry grinding, as shown in Fig. 1.

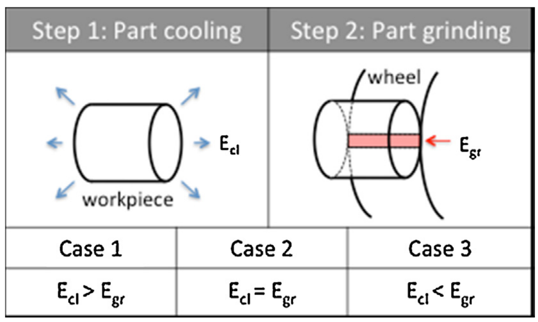

Fig. 1. Part precooling dry grinding approach: two steps and three case studies.

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The process feasibility will depend on how much heat can be drained from the workpiece (E_{cl}) during the cooling phase. This amount should be close to the total heat to be introduced during the grinding phase (E_{gr}) via convection, chip formation, ploughing and sliding of abrasive grains. The values do not have to be exactly the same, since the workpiece can normally accept small temperature variations after processing, depending on its tolerances, expansion coefficient, heat distribution and size.

However, it would be desirable to get the part at the end of the process as close as possible to 20 °C, i.e. the standard metrology temperature.

The available solutions for cooling, shown in Table 1, could be applied depending on the process requirements. The cost of each of these solutions may vary. However, for the cases where the use of ultralow freezers is adequate, they can be actually cheaper than the total expenditure with fluids, including the investment in pumping, filtering, mist removal, fluid cooling and their respective energy consumption.

Table 1
Commercial systems available for part precooling.

System	Temperature (°C)
Immersion in boiling nitrogen	−196
Ultralow freezer	−45 to −85
Dry ice (solid CO_2)	−80
Commercial freezer	−45
Ice bath	0
Commercial refrigerator	1 to 7

3. Heat flow requirements and dimensional analysis

When grinding a workpiece at temperatures significantly lower than ambient, there is a higher heat flux from the process zone to the part in relation to a conventional process. The heat is being generated by the abrasion between wheel and workpiece and at the same time it is transferred from the environment to the part by convection.

A major issue is the part size variation during grinding. Its thermal expansion can be a significant fraction of the grinding stock to be removed. The grinding wheel expansion for conventional grinding is not relevant due to the following reasons:

The fraction of heat transferred to the grinding wheel is as low as 15% of the total grinding heat and this may be even lower when the part is precooled,

The nature of the wheel is ceramic with much smaller thermal expansion coefficient,

Its continuous contact with the air at high speed and its porosity allow high heat transfer to the environment by convection and

The in-process measurement systems can compensate for any still small wheel thermal expansion.

To avoid high part temperature and its consequent thermal damage, the amount of heat, which flows into the workpiece, has to be controlled. The analysis can start from the amount of energy needed to remove a certain stock from the workpiece. The grinding stock is a process input. The energy consumed (E_{Gr}) can be measured or theoretically calculated and one can assume that most of that energy is absorbed by the workpiece, which is reasonable if there is no cooling fluid involved. Therefore:

$$E_{Gr} = E_{Cl} \tag{1}$$

In practical cases, however, the temperature variation required might not be promptly available by using the available cooling apparatus described in Table 1. Therefore, three cases may occur:

$$\begin{aligned}&(I) E_{Cl} > E_{Gr}\\&(II) E_{Cl} = E_{Gr}\\&(III) E_{Cl} < E_{Gr}\end{aligned} \tag{2}$$

As the workpiece reaches and stabilizes itself at a desired low temperature, it goes into the machine and starts spinning. The grinding wheel has to start the plunge cycle and should maintaining, at minimum, the same cycle time as in the conventional grinding. Because the part is cold and its diameter is now contracted, the initial wheel head position should be closer to final dimension. As soon as the wheel touches the workpiece, which is continuously expanding due to the gain of energy from ambient, an additional amount of grinding energy starts flowing, accelerating the expansion. At the same time, the grinding wheel is cutting this total expansion in addition to its programed infeed rate. In such situation, the diameter reduction by grinding can be written as

$$\Delta D_{Gr} = \Delta D_{Cv} + \Delta D_{Gh} + \Delta D_{fe} \tag{3}$$

where ΔD_{Gr} is the diameter reduction needed (grinding stock), ΔD_{Cv} is the diameter expansion due to part heat absorption by convection, ΔD_{Gh} is the diameter expansion due to the heating from the abrasive process and ΔD_{fe} is the diameter reduction executed by the machine feed system. The first part of Eq. (3), ΔD_{Cv} can be calculated by

$$\Delta D_{Cv} = D_i \alpha \Delta\theta_{Cv} \tag{4}$$

where D_i is the initial workpiece diameter after removing it from the cooling device, α is the thermal expansion coefficient and $\Delta\theta_{Cv} = \theta - \theta_i$, given by [13]:

$$e^{-t/C} = \frac{\theta - \theta_\infty}{\theta_i - \theta_\infty} \tag{5}$$

where θ_∞ is the room temperature, θ_i is the initial temperature of the workpiece after precooling, θ is the part temperature after grinding and C is a constant given by

$$C = \frac{\rho c V}{hA} \tag{6}$$

where ρ is the part density, c is the specific heat capacity, V is the part volume, h is the convection coefficient and A is the area of the workpiece in contact with the environment. Substitution of Eq. (5) in Eq. (4) results in

$$\Delta D_{Cv} = D_i \alpha [(\theta_\infty - \theta_i) + (\theta_i - \theta_\infty) e^{-t/C}] \tag{7}$$

The second part of Eq. (3), ΔD_{Gh} can be calculated using the specific energy for chip formation in grinding, given by [1], u_G, in this case measured using a power transducer, and knowing the volume to be removed. Considering that almost all the energy is converted into heat and that goes into the workpiece during the plunge dry grinding operation, one has:

$$\Delta D_{Gh} = D_i \alpha \frac{u_G V_w}{\rho V c} \tag{8}$$

where V_w is the volume of material to be ground. Therefore, the last part of Eq. (3), ΔD_{fe} can be calculated by difference, once the total stock at room temperature, ΔD_{Gr} is previously defined.

In each of the cases of Eq. (2), the machine will need to be adjusted to perform a feed movement compatible to the part expansion in order to get the desired final size. In a specific case, grinding could even be performed with no grinding wheel movement at all. This would be the situation where the part thermal expansion along the time matches exactly with the desired grinding feed rate and the total heat removed at the precooling phase is equal to the value absorbed by the piece via convection and abrasion.

4. Simulation and tests

Table 2 shows the parameters used for simulating the plunging grinding operation with precooled parts and respective tests.

The workpiece made of AISI 1045 was soaked into liquid nitrogen for 100 s. The initial diameter, D_i, when the workpiece leaves the liquid nitrogen was calculated. Then, calculating the diameter expansion due to heat convection using Eq. (7) and the expansion due to the plunge grinding using Eq. (8) for a desired