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Creep feed—an effective method to reduce work-surface temperature in high-efficiency grinding processes

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ABSTRACT

Compared with conventional grinding processes, creep-feed grinding has frequently been suspected as the reason for inferior work quality regarding thermal effects in the work-surface layer. Analytical investigations, temperature measurements and practical observations, however, demonstrate clearly that in contrast to this common opinion the work-surface temperature in creep-feed grinding does indeed decrease significantly with increasing depth of cut.

Beginning with a survey on the practical state-of-the-art of creep-feed grinding, the grinding forces and their relation to the grinding energy and the resulting work-surface temperatures are then described analytically. Finally, temperature measurements obtained by means of an improved microthermocouple are presented, proving the established analytical results.

INTRODUCTION

The technique of creep-feed grinding as a radical alternative to conventional surface and cylindrical grinding was developed and introduced into manufacturing industry about 20 years ago in Europe. At first little was known about the specifics of the creep-feed grinding technology, and, as a consequence, rather contradictory opinions on the applicability of the creep-feed concept emerged both in industry and in manufacturing research institutions. One of the least understood phenomena was and still is the discrepancy between the extremely high temperatures in the contact zone between wheel and workpiece and, on the other hand, the comparably low level of thermal effects in the newly generated work surface.

In this paper, the technological fundamentals of forces and temperatures in creep-feed grinding will be analysed and pertinent experiences and test results discussed. It is hoped that this will contribute to clearing away the existing confusion and prove that creep-feed grinding is indeed especially suitable if high demands for work-surface integrity are to be met.

APPLICATION CHARACTERISTICS

Generally, the creep-feed grinding process is marked by a special mode of operation. In contrast to the conventional technique, the depth of cut (a) per pass or revolution is increased a thousand to ten-thousand times, and the work speed (v_w) is decreased in the same proportion. Thus, it is possible to grind profiles with a depth of 1·0–30·0 mm (0·04–1·2 in) in one pass using work speeds from 1·0 to 0·025 m/min (40 to 1 in/min). Fig. 1 illustrates the difference between the two modes of operation in surface grinding. Creep-feed grinding avoids the multiple initial wheel-work contacts which are typical of conventional surface grinding operations. As a consequence, the profile stability of the grinding wheel is improved considerably. On the other hand, in creep-feed grinding the stroke length is increased due to the extended wheel workpiece contact length.

In order to take advantage of the economic and technological benefits of this high-efficiency/high-precision manufacturing process, the application of specially designed machine tools, integrated dressing devices and specially tailored grinding wheels is required (Werner 1973; Kinderjoe 1976; Werner 1978). Conventional surface grinders cannot provide these advanced features, and even modified conventional machines cannot satisfy most of these requirements. This is why in practice many attempts to apply creep-feed technology through machine modifications were bound to fail and in the end often led to incorrect evaluations of the possible process capacity.

Today, two main areas of creep-feed application in surface grinding can be differentiated. The first is the grinding of deep slots with straight parallel slides, and the second is the grinding of all kinds of profiles, especially those with a high depth to width aspect ratio and those which have to be machined in difficult-to-grind materials.

An example pertaining to the first domain of application is a pressure air rotor with 12·7 mm (0·5 in) deep and 3·2 mm (0·125 in) wide slots ground into 20 Mn Cr 5 steel (HR 62) in one pass at a table speed of 75 mm/min (3 in/min).

An important example of the second class of creep-feed application are turbine blades made of superalloys. These workpieces require extreme precision with regard to the root dimensions and the surface integrity and are very difficult to machine. Creep-feed grinding meets all technological and economic requirements, the foremost advantage being that it guarantees low work-surface temperatures at relatively high removal rates (Shafto 1975). An example of this second class of creep-feed application is a turbine blade made from nickel-base superalloy held in a special grinding fixture. Both sides of the symmetrical root profile are ground simultaneously by a twin-wheel creep-feed automate employing two roughing and one finishing passes. The grinding wheels are a relatively soft aluminium oxide type, the grinding wheel profiles being generated by diamond dressing rollers, and as a coolant a 2% emulsion is used that is applied at a pressure of 4 bar (48 psi).

Creep-feed grinding is not confined to surface grinding, but is also applied in external cylindrical grinding, where it is also called deep grinding. The most impressive

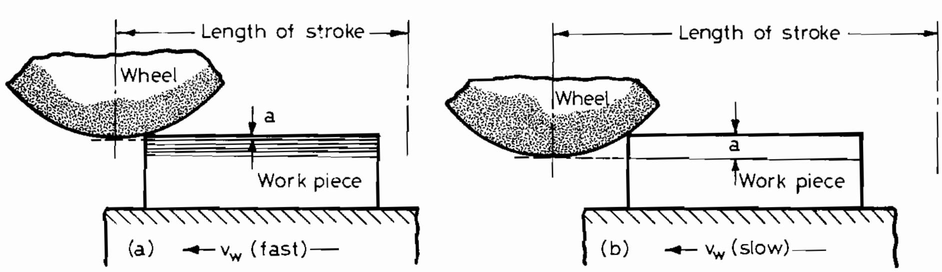

Fig. 1. Principle of (a) conventional and (b) creep-feed surface grinding

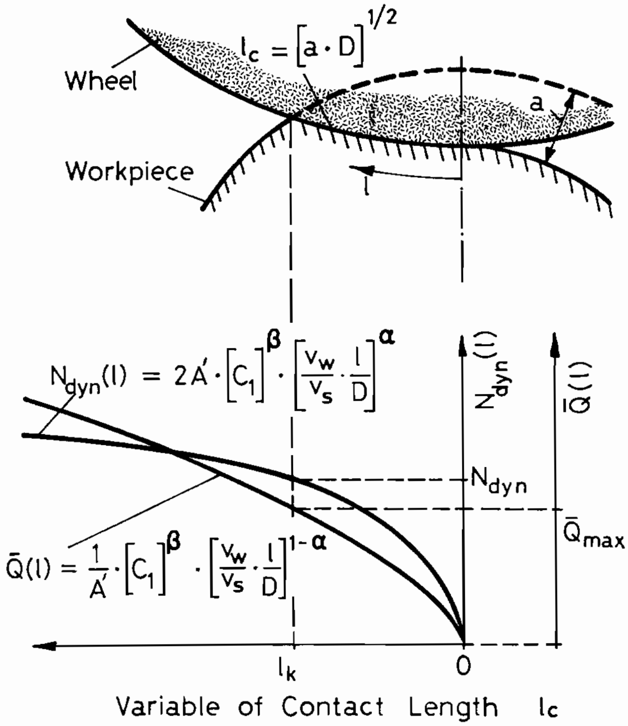

Fig. 2. Dynamic cutting edges and average chip cross-section versus variable of contact length.

example of its potential is the deep grinding of twist drill flutes with a maximum depth of cut of 17·5 mm (0·7 in) and with wheel speeds up to 100 m/sec. The specific removal rates reach values of 600 $mm^3/mm/sec$ (i.e. equivalent to a total removal rate of 1 in^3/sec), which is 50 to 100 times higher than the maximum values in creep-feed surface grinding, and up to 40 times higher than the removal rates attainable by conventional flute profile milling.

ANALYSIS OF FORCES

By means of a recently developed model, the forces generated in grinding can exactly be related to the various process parameters (Werner 1973). The function is derived by superimposing the individual forces $F_e = K \cdot \bar{Q}^n(\ell)$ of all cutting edges instantaneously engaged in the wheel-work contact zone

$$F_n' = K \int_0^{\ell_c} \left[\bar{Q}(\ell) \right]^n \cdot N_{\mathrm{dyn}}(\ell)\, d\ell \,. \tag{1}$$

Knowing the discrete functions of the average chip cross section $\bar{Q}(\ell)$ and the local number of engaged cutting edges $N_{\mathrm{dyn}}(\ell)$ as displayed in Fig. 2, the model equation for the normal grinding force per unit of the grinding width is obtained from (1) as:

$$F_n' = \frac{K}{\varepsilon} \left[C_1 \right]^{\gamma} \left[\frac{v_w}{v_s} \right]^{2\varepsilon - 1} \left[a \right]^{\varepsilon} \left[D \right]^{1-\varepsilon} \tag{2}$$

where

$$D = d_w \cdot d_s/(d_w \pm d_s) \tag{3}$$

= equivalent wheel diameter (plus-sign for external grinding and minus-sign for internal grinding).

This model allows grinding forces to be described as a function of the five main process variables (C_1, v_w, v_s, a and D) only using three model parameters (K, γ, ε). Analytic considerations and intensive practical investigations have shown that the exponential coefficients γ and ε vary within bounded ranges (Decneut 1974; Werner 1978; Koenig 1978). The bounds of variation of γ and ε are

$$\begin{array}{ccccc} 0 & \leqslant & \gamma & \leqslant & 1 \\ 0{\cdot}5 & \leqslant & \varepsilon & \leqslant & 1 \end{array} \tag{4}$$

The coefficient ε in particular was found to be an effective measure for the force/temperature related grindability of different work materials. With $\varepsilon \to 1{\cdot}0$ in Equations 2 and 5 the grindability is excellent, because the frictional work in the contact zone is minimised, which causes the grinding forces to drop significantly and the work-surface temperature to remain unchanged with increased wheel speed. Ductile-hard materials such as medium carbon and ball-bearing steels, show this type of behaviour. With $\varepsilon \to 0{\cdot}5$, which occurs for brittle-hard materials and ductile-soft materials with a tendency to load the wheel surface, the grindability becomes unfavourable because the frictional work in the contact zone is at its maximum. As a consequence, grinding forces do not drop and temperatures increase significantly with increased wheel speed. In Table 1, ε-values are listed for different combinations of grinding wheels and work material.

Substituting the specific removal rate $Z' = a \cdot v_w$ and taking $D = d_s$ (because $d_w \to \infty$ in surface grinding) leads to a modified grinding force function

$$F_n' = \frac{K}{\varepsilon}\left[C_1\right]^{\gamma}\left[\frac{Z'}{v_s}\right]^{2\varepsilon-1}\left[a\right]^{1-\varepsilon}\left[d_s\right]^{1-\varepsilon}. \tag{5}$$

Equation 5 is suitable for comparing forces in conventional and creep-feed surface grinding. In Fig. 3a, the normal component of the total grinding force as obtained from

Table 1. Exponential coefficient ε for different combinations of wheel and work material

Work material	Grinding wheel	Exponent
CK 45 Medium carbon steel	EK 60 N 8 Ke	0·81
	EK 80 L 7 VX	0·87
100 CR 6 Ball-bearing steel	EK 60 L 7 VX	0·78
	EK 80 J 7 VX	0·50
AISI 4615 Alloy steel	6A 54 L 5 VX	0·77
AISI 316 Austenitic stainless steel	EK 80 J 7 VX	0·74
X 210 Cr12 Tool steel	EK 60 M 7 Ke	0·63

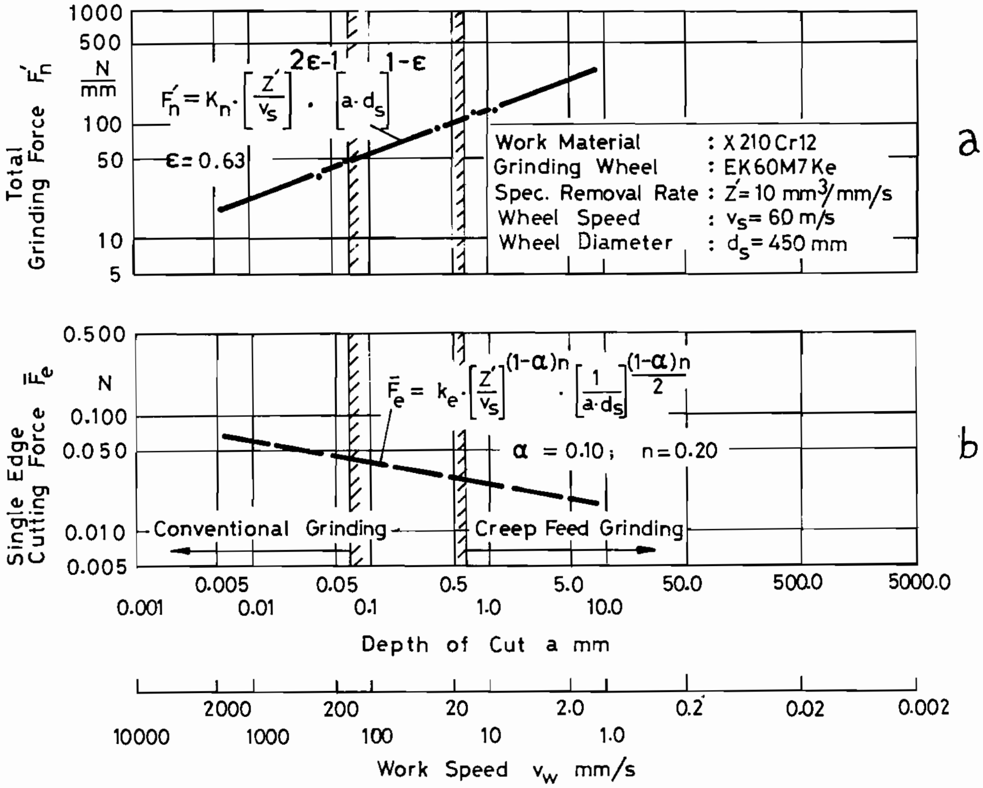

Fig. 3. Grinding forces versus depth of cut at constant removal rates in surface grinding.

practical investigations (Sperling 1970) is plotted versus the depth of cut a. Notice that the work speed v_w is reduced proportionally, such that the specific removal rate Z' remains constant ($Z' = a \cdot v_w = \text{constant}$). The results for the left-hand regime (i.e. small depth of cut and high work speed) correspond to conventional surface grinding and show relative low force magnitudes. In the right-hand regime (i.e. large depth of cut and low work speed), corresponding to conditions in creep-feed surface grinding, the normal forces are about three times as high. The figure shows that the measured forces can be exactly described by means of Equation 5. The exponential coefficient $\varepsilon = 0{\cdot}63$ is related to the high alloy tool steel X 210 Cr 12 and indicates that the grindability of this material is on the more unfavourable side, which is well known from practice.

In contrast to the total grinding force, the average force $\bar{F}_e$ per individual cutting edge decreases versus depth of cut at a constant removal rate Z', as shown in Fig. 3b. The pertinent function can be derived from Equation 5 by dividing it by the number N'_{mom} of all instantaneously engaged edges in the contact zone (Werner 1971).

$$\bar{F}_e = \frac{F_n'}{N'_{\text{mom}}} = k_e \left[\frac{Z'}{v_s}\right]^{\lambda} \left[a \cdot d_s\right]^{\frac{-\lambda}{2}}$$

where (6)

$$N'_{\text{mom}} = A \left[C_1\right]^{\beta} \left[\frac{Z'}{v_s}\right]^{\alpha} \left[a \cdot d_s\right]^{\frac{1-\alpha}{2}}$$

with $\lambda=(1-\alpha)n$, where α and n have the same meaning as defined in the context of Equation 2. With increasing depth of cut, N'_{mom} is increasing faster than F'_n, mainly because of the increasing wheel-workpiece contact zone. As a consequence, the average contact force per single cutting edge is significantly smaller in creep-feed grinding as compared to the conventional surface grinding process.

As an important practical consequence, the reduced average load per individual cutting edge in creep-feed grinding requires the application of softer grinding wheels. If a relatively hard grinding wheel, for example grade R or P as used in conventional processes, would be applied at creep-feed conditions, the cutting edges could not break loose from the wheel surface early enough and would form larger areas of flattened wear land. This in turn would lead to an unstable wear behaviour of the grinding wheel and to occasionally increasing temperatures. This can easily be avoided by using an appropriate tool with a softer grade in the range of E–H. In practice, this phenomenon is well recognised empirically. However, by means of the presented analysis it can, for the first time, be explained in the light of the technological fundamentals of the process. Frequently the favourable performance of softer wheels in creep-feed grinding is explained as an indirect result of a coarse wheel structure, assumed to be necessary for transporting the generated chips through the contact zone. This interpretation is incorrect, because the individual chip volumes in creep-feed grinding are no greater than in conventional grinding, provided that the removal rates are identical. The real reason is that a coarser wheel structure allows the cutting fluid to be more efficiently fed through the contact zone, reducing grinding forces, contact temperatures and wheel wear. Fortunately, the property of a coarser structure goes well along with a softer wheel grade; however, these two characteristics are required for two very different reasons as discussed above.

ANALYSIS OF TEMPERATURES

The tangential component of the total grinding force is in close relation to the thermal load in the wheel-workpiece contact area. The total energy input per unit of time is equivalent to the grinding power L_s, which in turn is formed by multiplying the tangential grinding force F_t and the grinding wheel speed v_s

$$L_s = F_t \cdot v_s \,. \tag{7}$$

In this equation energy per unit of time is related to the work surface A_s covered by the grinding wheel in the same time unit

$$A_s = b_s \cdot v_w \tag{8}$$

where b_s = grinding width and v_w = work speed, the energy q per unit of ground surface can be expressed as

$$q = \frac{L_s}{A_s} = F_t' \cdot \frac{v_s}{v_w} \,. \tag{9}$$

By using Equation 5, which is related to the tangential force component through $F_t' = \mu \cdot F_n'$, μ = constant, Equation 9 leads to

$$q = \frac{\mu K}{\varepsilon} \left[C_1 \right]^{\gamma} \left[\frac{v_s}{Z'} \right]^{2-2\varepsilon} \left[a \right]^{2-\varepsilon} \left[d_s \right]^{1-\varepsilon} \tag{10}$$

For large work speeds ($v_w > 10$ m/min) and extensions of the wheel-workpiece contact zone below 1·5 mm, the heat impact on the work surface is a quasi-instantaneous one, because the heat-generating contact area passes over any point of the work surface within less than 0·01 sec. At these conditions, the maximum temperature generated in a certain depth (for example 0·1 mm) below the newly generated work surface, can be assumed to be proportional to the energy q induced per unit area of the work surface

$$T_{\max(\gg a)} \simeq q = \frac{K_1}{\varepsilon}\left[\frac{v_s}{Z'}\right]^{2-2\varepsilon}\left[a\right]^{2-\varepsilon}\left[d_s\right]^{1-\varepsilon}$$

with (11)

$$K_1 = \mu K [C_1]^{\gamma}.$$

This rather simplified temperature model assumes that the entire energy generated during the grinding process actually flows into the work surface. This is not true because a certain fraction of the energy is retained in the chips in the form of heat and is removed together with them. In essence, the grinding wheel continuously penetrates into the work piece material which has been preheated by its own action. Thus, the purpose of the above derivation can only be to demonstrate that the work-surface temperature tends to rise if the depth of cut is increased and the work speed proportionally decreased in the regime of conventional grinding. As shown in Fig. 4, Equation 11 provides asymptotic limits for the surface temperature curve t_1, established on the assumption that the total grinding energy flows into the work surface.

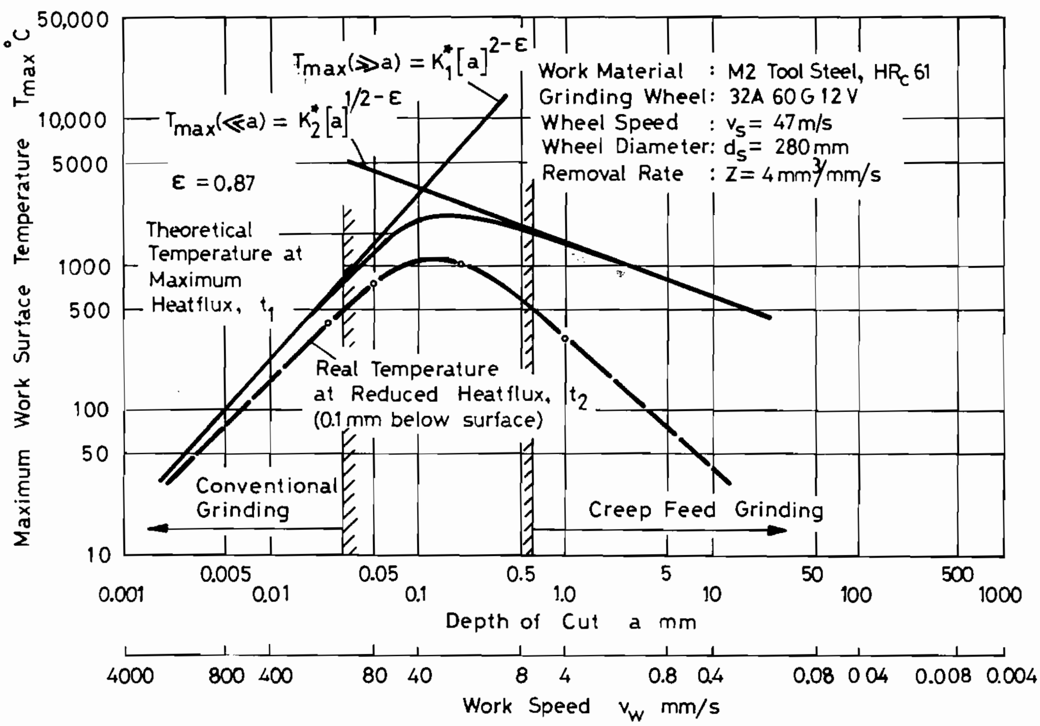

Fig. 4. Maximum work-surface temperature in conventional and creep-feed surface grinding.

If this initial trend of steeply increased surface temperature versus depth of cut would continue in the regime of creep-feed operation, creep-feed grinding would not be possible at all because of extremely high temperature values in the range of the vaporisation temperature of the work material. Practice, however, shows that the real temperatures in the surface layer of workpieces ground at creep-feed condition often fall below those achieved at conventional grinding conditions. This can be explained in the following paragraphs.

For very small work speeds ($v_w < 0{\cdot}25$ m/min) and large extensions of the contact zone in excess of 15 mm, there is no longer an impulse-type heat input into the work surface, but rather a steady heatflux over a period of time lasting for several seconds. Under these conditions, the maximum temperature generated in a certain depth (for example 0·1 mm) below the new work surface, can be assumed to be proportional to the ratio of the total energy q induced per unit area and the time t_s the wheel needs to pass over any point of the work surface

$$T_{\max(\ll a)} \simeq \frac{q}{t_s}, \quad \text{where} \quad t_s = \frac{\ell_c}{v_w} = \frac{\sqrt{(a \cdot d_s)}}{v_w} \tag{12}$$

here ℓ_c = contact length between wheel and workpiece. With Equation 10 it follows from Equation 12 that

$$T_{\max(\ll a)} = \frac{K_2}{\varepsilon}\left[v_s\right]^{2-2\varepsilon}\left[Z'\right]^{2\varepsilon-1}\left[a \cdot d_s\right]^{\frac{1}{2}-\varepsilon} \tag{13}$$

Examination of Equation 13 shows that for creep-feed grinding the work-surface temperature tends to decrease with increasing depth of cut and proportionally decreasing work speed. This behaviour occurs in spite of the steadily increasing total grinding force (Equation 5 and Fig. 3a) and the energy generated per unit work surface. The obvious reason for this fortunate characteristic is derived from the fact that the ever-increasing amount of heat flows into the workpiece at a steadily decreasing rate (i.e. energy per unit time) and throughout a permanently increasing period of time. Actually, more heat energy flows at a lower rate for a longer time, thereby heating a deeper surface layer to lower average and maximum temperatures. In Fig. 4, Equation 13 provides the asymptotic limits for the maximum surface temperature in the creep-feed regime, assuming that the total energy generated flows into the work surface.

This assumption, however, becomes more and more incorrect as the depth of cut increases at constant removal rate: at a depth of cut of $a = 0{\cdot}025$ mm and a corresponding work speed of $v_w = 160$ mm/sec about 25% of the energy is removed with the chips as estimated from the temperature difference of curves t_1 and t_2 in Fig. 4. At $a = 1{\cdot}0$ mm and $v_w = 4$ mm/sec, this percentage is increased to over 75%. This elimination of energy leads, as the practical measurements in Fig. 4 show, to an even faster decline of the overall work-surface temperature level in the regime of creep-feed grinding. The procedure and technique of these temperature measurements are described in the following paragraphs.

TEMPERATURE MEASUREMENTS

From the rising grinding force experienced in creep-feed grinding, available literature generally indicates that work-surface temperature tends to rise in the same proportion (Brandin 1975; Geisweid & Gaertner 1978; Koenig & Lauer-Schmaltz 1978).

Practical measurements of the surface temperature have been rarely carried out. Frequently, however, the steadily rising temperature in the wheel–workpiece contact zone has been determined by experiment (Dederichs 1972; Shafto 1975). Unfortunately, these results have often been related to the work-surface temperatures which, as a consequence, have falsely been regarded as rising steeply with increasing depth of cut. The contrary could have easily been confirmed by checking the existence of the thermally influenced surface layers. Micro hardness tests show that there is not the faintest sign of a hardened or tempered layer, provided that the creep-feed process is performed at undisturbed conditions.

This last statement should be regarded with reservation because if the grinding wheel becomes loaded with work material, a metal-to-metal friction process similar to that of friction sawing takes place, which causes the temperature in the contact zone and in the newly generated work surface to surge. This rather common disturbance of creep-feed grinding process is likely if the wheel is too hard and the coolant is not applied effectively. Shafto (1975) tried to explain this unfavourable temperature surge by an obscure film biling effect, speculating that the energy transfer rate becomes too large for the applied coolant. Due to this unrealistic concept, Shafto can hardly explain why the observed surges do last for a few seconds only. A more realistic answer is that because of the sudden and extremely high temperature increase, the wheel surface structure breaks down severely. This leads to an intensive self-dressing effect and results in the total elimination of the loading particles from the wheel surface. As a consequence, the wheel then returns to its normal low temperature state.

In order to clarify this controversial situation and to support the analytical results derived, carefully designed experiments have been carried out recently, aiming to measure the true work-surface temperatures in both the regimes of conventional and creep-feed surface grinding.

For this purpose, a modified micro-thermocouple method was developed. Fig. 5 shows the arrangement of the experiment. Firstly, it is noticed that the workpiece has been parted in the direction parallel to the grinding-wheel motion. This serves for an

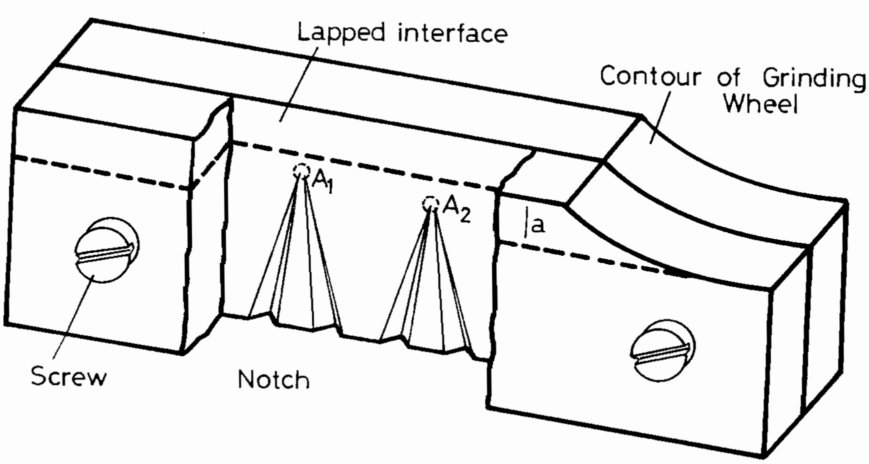

Fig. 5. Arrangement for work-surface temperature measurements.

undisturbed flow of the temperature field through the work material. The interface between the two parts has been lapped to ensure a close contact. Secondly, in one of the two hardened plates wedge-shaped notches are ground as shown in Fig. 5. At the small bridges (A_1, A_2, . . . A_i) between two respective notch points, the welding points of the thermocouples were placed. The advantage of this method is that the heat flux at the measuring point is not disturbed at all by any void within the workpiece. Thirdly, the exact position of the welding points of the thermocouples was determined after grinding by measuring the remaining distance from the newly generated work surface with the use of a microscope.

The resulting measurements are more accurate than those achieved before in any other practical investigation on work-surface temperatures in grinding. As Fig. 4 shows, the results are in very close agreement with the analytical findings. For the hardened M2 tool steel ground, the character of the maximum work-surface temperature as generated 0·1 mm below the machined work surface is given by curve t_2. In the regime of conventional grinding, t_2 increases following the predicted trend of Equation 11, which in turn is represented by the curve t_1. With increasing depth of cut and proportionally decreasing work speed, t_2 reaches a maximum at 1100°C and decreases in the regime of creep-feed grinding at nearly the same rate as it increased before. In this area of larger depth of cut, t_2 deviates rather clearly from t_1, as an increasingly higher fraction of the total heat energy is removed by the chips and does not flow into the work surface. However, the temperature measured follows the declining trend predicted by Equation 13, and the order of magnitude is very reasonable.

For practical applications it is important to avoid the transitional area between conventional and creep conditions, where the work-surface temperature is at a maximum. Unfortunately, however, there are some important areas of high-efficiency grinding, e.g. gear-form grinding, thread-deep grinding and external profile grinding, where the applicable combination of depth of cut and work speed is in this unfavourable transient regime. Here all other methods which reduce the energy level must be utilised, e.g. application of oil as a coolant at high pressures, optimum wheel specifications and reduced wheel speed.

CONCLUSIONS

The results of the described temperature measurements prove beyond doubt, for the first time, that creep feed is an effective method to reduce the work-surface temperature in high-efficiency grinding processes. This decreasing influence is effective even for work materials with an unfavourable grindability, i.e. low ε-values. For $\varepsilon \rightarrow 0{\cdot}5$, Equation 13 predicts a rather high surface temperature (curve t_1) which remains constant irrespective of the depth of cut. However, due to the increasing fraction of the energy taken away with the chips, the real work-surface temperature (curve t_2) will neverthless decrease significantly for these materials.

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NOTATION

a = depth of cut
A_s = work surface covered by the grinding wheel
C_1 = cutting-edge density
d_w = workpiece diameter
d_s = wheel diameter
D = equivalent wheel diameter $d_w \cdot d_s/(d_w \pm d_s)$
F'_n = specific normal grinding force
F'_t = specific tangential grinding force
ℓ_c = contact length between wheel and workpiece
L_s = grinding power
$N_{\mathrm{dyn}}(\ell)$ = local number of engaged cutting edges
N_{mom} = number of all instantaneously engaged edges in contact zone
n = exponent of empirical chip cross-section/force function
$\bar{Q}(\ell)$ = average chip cross-section
q = energy per unit of ground surface
T = temperature
v_w = work speed
v_s = wheel speed
Z' = specific removal rate

A = constant
K = proportionality factor
ε = $\frac{1}{2}[(1+n)+\alpha(1-n)]$, exponent
α, β = coefficients of cutting-edge distribution
γ = $\beta\,(1-n)$, exponent
k_e = constant = $\dfrac{K}{A\varepsilon}\left[C_1\right]^{n\beta}$

λ = $(1-\alpha)\,n$, exponent
μ = constant
K_n = constant = $\dfrac{K}{\varepsilon}\left[C_l\right]$
K_1^* = constant
K_2^* = constant

زيادة كفاءة عملية تجليخ المعادن عن طريق زيادة عمق القطع وسرعة التغذية البطيئة

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خلاصة

لم تعد عملية تجليخ المعادن مجرد عملية للحصول على جودة السطح المطلوبة فحسب بل تطورت لتصبح عملية تشغيل أساسية نحصل من خلالها على الشكل النهائي للمنتج وجودة السطح المطلوبة في آن واحد ، مما كان له الأثر في زيادة الانتاج .

يعالج هذا البحث تأثير درجة الحرارة الناتجة والتي تتناسب طرديا مع زيادة معدل المعدن المقطوع من المنتج ، ويستحدث طريقة جديدة للقطع لزيادة كفاءة عملية التجليخ مع استبعاد التأثير الحراري الناتج الذي قد يغير من خواص المنتج .

تتلخص هذه الطريقة في القطع بسرعة تغذية بطيئة جدا مع زيادة عمق القطع حتى يكون معدل حجم المعدن المزال كبيرا . وفي النهاية يعطى البحث الحدود والضوابط بين هذه العملية الحديثة وعملية التجليخ العادية .