Ultrasonic-assisted grinding of soft steel

Grinding is a manufacturing method that is in widespread use for fine machining. Because of the undefined cutting edges and the many factors involved in the process, grinding is very complex and difficult to control. Optimisation of the chip-forming process is the primary objective of research and development in grinding technology. Paper by **T. Tawakoli, B. Azarhoushang** and **M. Rabiey**.

By optimising the chip-forming process during grinding, energy consumption or energy conversion are reduced and the thermal effect and deformation of the workpiece are also reduced.

Our research shows that ultrasonic-assisted grinding (UAG) can contribute significantly to optimising the chip-forming process in grinding. The principle of this technique consists of adding high-frequency (16-40 kHz) vibrations with amplitudes (2-30 μm) in the feed direction or transverse to the feed direction to the tool or the workpiece. Compared with conventional grinding, UAG is a hybrid process.

By using ultrasonic-assisted machining, a significant reduction in feed force, chip size, tool wear, heat development and also an improvement in surface quality have been achieved. Zhang et al [Zhan01] came to the conclusion, both theoretically and in experiments, that an optimum state of vibration can reduce the feed force and the torque in cutting. Onikura et al [Onik98] found that the use of ultrasonic vibrations reduces the friction between the chip and the tool face of the inserts, which leads to thinner chips and, as a result, a reduction in cutting forces. Azarhoushang and Akbari [Azar07] have achieved significant improvements in terms of roundness, cylindricity and surface roughness in drilling through the use of ultrasonic vibrations. Mult [Mult96] and Uhlmann [Uhlm98] have established that ultrasonic-assisted grinding can be used as an efficient production method for ceramic materials and that ultrasonic-assisted deep grinding offers an enormous reduction in normal forces with slightly greater wheel wear and surface roughness. Tawakoli et al [Tawa07] have shown that with the ultrasonic-assisted dressing of CBN wheels a reduction in grinding forces and dresser wear can be obtained.

For our investigation an ultrasonic-assisted grinding system was developed and used. In the grinding of 100Cr6, both with a coolant and in dry grinding, by superposing ultrasonic vibrations an improvement in surface roughness R_z and also a reduction in normal grinding force was achieved. The effect of vibration amplitudes, feed and depth of cut on surface roughness and normal grinding force was also investigated.

Set-up of the ultrasonic-assisted grinding system

To investigate UAG, a driven workpiece holder device was developed. The ultrasonic vibration chain consists of a piezoelectric converter, a booster, a sonotrode and a special workpiece chucking device.

The ultrasonic generator converts the electric current at about 50 Hz into high-frequency impulses at 21 kHz. These high-frequency electrical impulses reach a piezoelectric converter and by the piezoelectric effect are converted into mechanical vibrations with an ultrasonic frequency (21 kHz). The sound amplitude is amplified first by the booster and then by the sonotrode and is transferred to the workpiece, which is connected to the sonotrode. The resulting vibrations of the workpiece in the tool holder reach an amplitude of 10-30 μm at a frequency of about 21 kHz. The vibrations in the workpiece were tested both transversely to the feed direction and also in the feed direction. Fig 1 shows the test rig for the ultrasonic vibration chain and the workpiece holder.

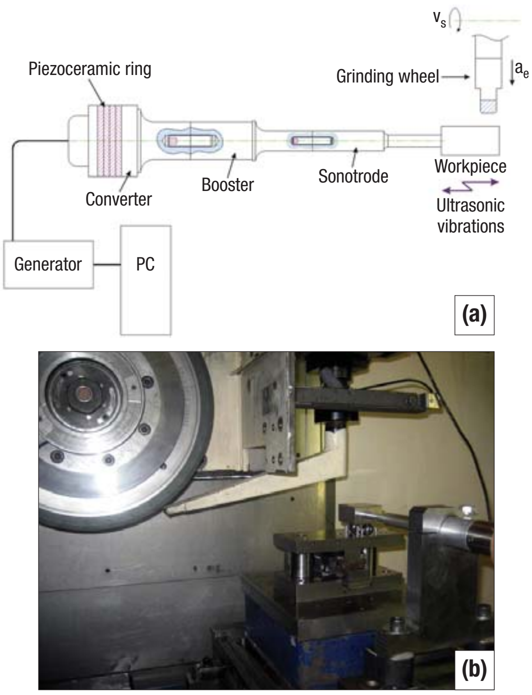

Fig 1 (a) Diagram of the experimental set-up of the vibration chain (b) Test rig for ultrasonic grinding

Grinding tests with ultrasonic-assisted grinding (UAG) using coolant

The following machines, apparatus and measuring systems were used for the tests:

- Machine tool:
  Elb Micro-Cut AC8 Universal CNC surface grinder
- Ultrasonic generator:
  Mastersonic MMM Generator-MSG.1200.IX,
  1200 W power, frequency steps from 17 to 47 kHz.
- Eddy current for measuring amplitude:
  Micro epsilon eddy NCDT 3300, measuring range from 0 - 0.5 mm, linearity 0.2%, resolution 0.005%, scan rate 100 kHz
- Roughness and profile measuring apparatus:
  Hommel-Etamic, model T-8000
- Force measuring plate:
  Kistler piezoelectric force measuring plate, model 9255B

The settings for the main machining parameters for the tests are summarised in Table 1.

Results of ultrasonic-assisted grinding (UAG) using coolant

Tests were carried out with conventional grinding and, by way of comparison, with ultrasonic-assisted grinding. A typical example is shown in Fig 2. The burn marks with conventional grinding can be seen clearly (Fig 2a). By contrast, a workpiece ground under the same conditions, but with ultrasound, does not display any thermal damage (Fig 2b). With conventional grinding, from a depth of cut of a_e = 0.1 mm thermal damage continued to occur. With UAG the depth of cut could be increased to as much as 0.2 mm without this occurring.

All the tests were repeated four times in order to document the reproducibility of the results. Figs 3 - 7 show the results for the normal grinding forces and surface roughness as a function of vibration amplitude, feed and depth of cut for UAG compared with conventional grinding using coolant.

Fig 3 shows the dependence of normal grinding force on the change in amplitude A. In this illustration amplitude zero shows the results of conventional grinding. The test results show the reduction in grinding force with an increasing vibration amplitude for UAG at feed rates of v_{ft} = 1000 and 2000 mm/min. The fall in grinding force when using ultrasonic assistance is evidence of the optimisation of the chip-forming process compared with conventional grinding without UAG.

The differences in specific normal grinding forces as a function of depth of cut a_e and the specific material removal rate Q'_w, between UAG and conventional grinding are shown in Figs 4 and 5. The tests were carried out at v_c = 60 m/s, f = 21 kHz and A = 10 μm (with UAG). The fire symbols represent the burn marks, or thermal damage, on the ground surface.

Grinding wheel	Vitrified-bond CBN wheel, B126 C125, Ø400 mm
Workpiece	100Cr6, 82 HRB, (60*47*29 mm*mm*mm), soft
Grinding conditions	Feed rate v_{ft} = 1000 - 2000 mm/min, Cutting speed v_c = 60 m/s, Depth of cut a_e = 0.050 - 0.300 mm
Grinding process	Surface grinding
Coolant	120 l/min, emulsion (Castrol Syntilo 2000)
Dressing conditions	Dressing speed quotient q_d = 0.8, Dressing cutting speed v_{cd} = 60m/s, Dressing infeed a_{ed} = 5 μm, contact ratio U_d = 4, Dressing amount $a_{ed\text{-}total}$ = 10 μm
Dresser	Diamond form roller: R_{sp} = 0.2 mm
Direction of sound propagation	Transverse to feed direction (perpendicular to feed)
Conditions of the ultrasonic vibration	Frequency f = 21 kHz, amplitude A = 10μm

Table 1 Parameters for the grinding tests using coolant

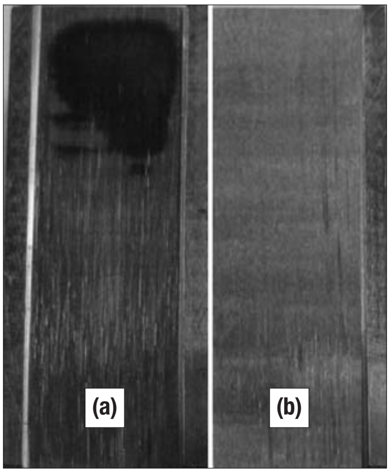

Fig 2 Burn marks with conventional grinding (a), no thermal damage on the surface ground with UAG (b), v_c = 60m/s v_{ft} = 1000 mm/min a_e = 200 μm

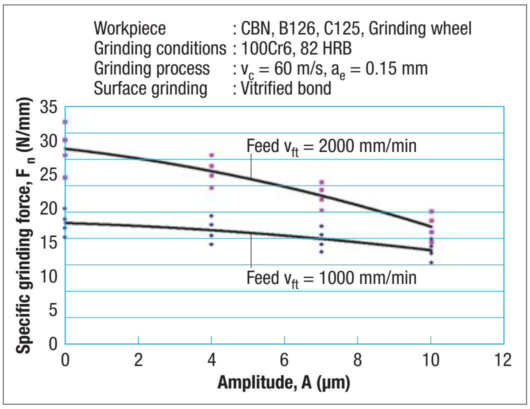

Fig 3 Specific normal grinding forces as a function of vibration amplitude

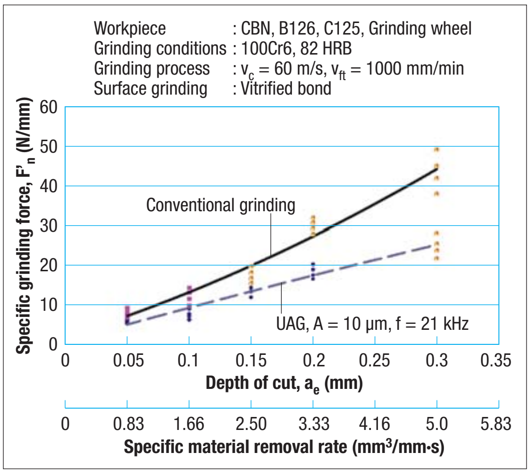

Fig 4 Specific normal grinding forces as a function of depth of cut a_e, v_{ft} = 1000 mm/min (UAG: A = 10μm, f = 21 kHz)

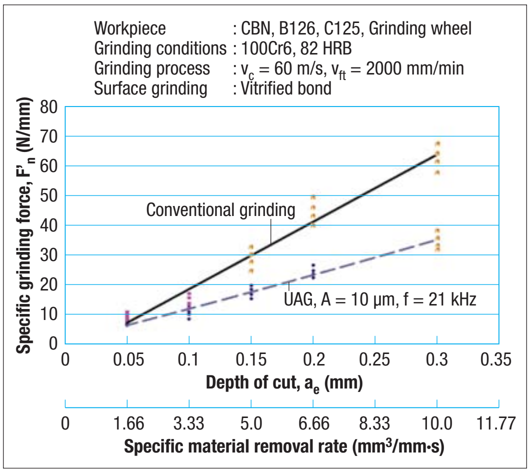

Fig 5 Specific normal grinding forces as a function of depth of cut, v_{ft} = 2000 mm/min (UAG: A = 10 μm, f = 21 kHz)

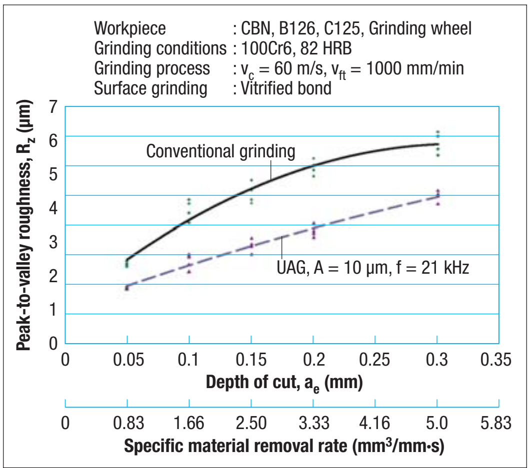

Fig 6 Surface roughness R_z as a function of depth of cut a_e, v_{ft} = 1000 mm/min (UAG: A = 10 μm, f = 21 kHz)

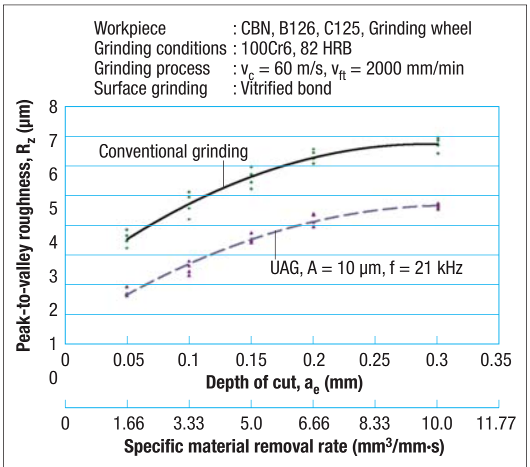

Fig 7 Surface roughness R_z as a function of depth of cut a_e, v_{ft} = 2000 mm/min (UAG: A = 10 μm, f = 21 kHz)

At an amplitude of 10 μm and a frequency of 21 kHz a maximum oscillation acceleration of 174.100 m/s² is generated. The removal process is made easier because of the high-frequency interaction between the active grits and the rapid acceleration of the workpiece. The chips are cut away more easily. Due to the oscillating impacts between the grits and the workpiece the microcracks in the contact zone can spread more quickly and have a positive effect on the next process of chip formation. Consequently, the grinding forces and friction effects are reduced so less plastic deformation occurs in the contact zone.

Figs 6 and 7 show the difference between UAG and conventional grinding as regards average peak-to-valley roughness R_z as a function of depth of cut a_e and specific material removal rate Q'_w. The roughness values with UAG are between 30 and 50% less than with conventional grinding. This shows another important positive characteristic of ultrasonic assistance for the generating of finer surfaces. As a positive factor, not only is a finer surface produced, but also it has a different structure with a greater ratio of contact area. These structure characteristics should be investigated in more detail in further studies.

Grinding tests with ultrasonic-assisted dry grinding (UADG) without the use of coolant

Similar tests as those described above were carried out with ultrasonic-assisted dry grinding. In this case the tests with conventional grinding and ultrasonic-assisted grinding were carried out without the use of coolant.

Fig 1b shows the set-up for the grinding tests. The workpiece is connected to the sonotrode (part of the vibration chain of the ultrasonic system) and is chucked on the force measuring plate.

Grinding tests with ultrasonic-assisted dry grinding (UADG)

The test rig remained unchanged for the tests. The same machines, measuring systems and devices were used. With the conventional tests the ultrasonic unit was switched off, and in the dry grinding tests the coolant delivery pumps were switched off. Unlike in the previous tests the depth of cut was 10 μm to 30 μm.

Results of ultrasonic-assisted dry grinding (UADG)

The grinding tests for conventional grinding without a coolant usually led to thermal damage on the surface of the workpiece. Fig 8 shows two workpieces with three grinding tests in each case. With both workpieces the grinding test in the middle (b) was carried out dry with ultrasonic assistance. It is clear that on both samples there is less thermal damage in the middle section compared with the other areas. Both workpieces (I) and (II) were ground conventionally, dry, in the areas (a) and (c) and display clearly visible thermal damage.

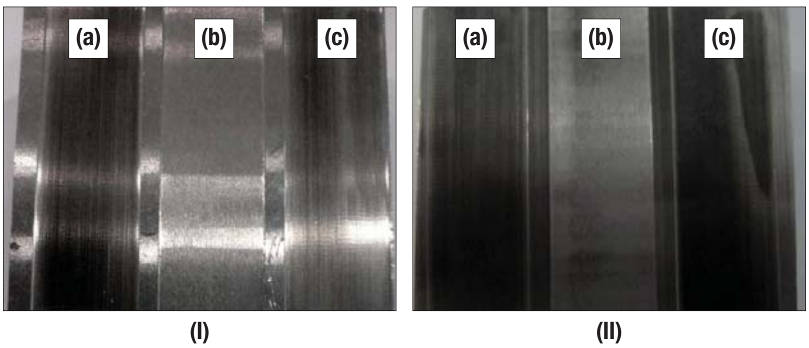

Fig 8
(I) v_{ft}=1000 mm/min v_c=60 m/s,
(a) a_e=15 μm (CDG), (b) a_e=15 μm A=10 μm (UADG), (c) a_e=10 μm (CDG)
(II) v_{ft}=2000 mm/min v_c=60 m/s,
(a) a_e=25 μm (CDG), (b) a_e=30 μm A=10 μm (UADG), (c) a_e=30 μm (CDG)
CDG = conventional dry grinding, UADG = ultrasonic-assisted dry grinding

Fig 9 shows the dependence of specific normal grinding force on the change in amplitude A. In this illustration amplitude zero represents the results of conventional grinding. The test results show the reduction in grinding force with an increasing vibration amplitude for UADG at feed rates of v_{ft} = 1000 and 2000 mm/min. In dry grinding with ultrasonic assistance a similar positive effect of falling specific normal force with increasing amplitude can be seen, as is also the case with the use of coolant (see Fig 3). Here too the optimised chip-forming process with the aid of ultrasonic assistance can be seen.

Figs 10-13 show comparisons of the normal grinding forces and surface roughness with ultrasonic-assisted dry grinding and conventional dry grinding as a function of depth of cut. The tests were carried out at a cutting speed of v_c = 60 m/s, a vibration frequency of f = 21 kHz and an amplitude of A = 10 μm. With dry grinding too, similar results are obtained as with grinding using coolant.

Figs 10 and 11 show comparisons of the specific normal grinding forces and surface roughness as a function of depth of cut a_e and of specific material removal rate Q'_w, between ultrasonic-assisted dry grinding and conventional grinding. The tests were carried out at v_c = 60 m/s, f = 21 kHz and A = 10 μm (with UAG). The fire symbols represent the burn marks and the thermal damage on the ground surface. Ultrasonic-assisted dry grinding is characterised by lower specific grinding forces.

Figs 12 and 13 show the surface roughness values R_a and R_z as a function of depth of cut a_e for dry grinding with conventional grinding and with ultrasonic-assisted grinding. This again shows the great advantage of ultrasonic-assisted grinding using coolant, but also that of dry grinding, which is characterised by 30-50% lower surface roughness values. This finer surface is particularly significant with the R_z values.

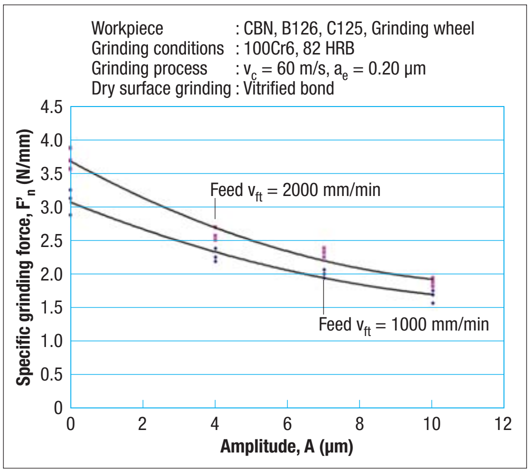

Fig 9 Specific normal grinding forces as a function of vibration amplitude (a_e = 20 μm, f = 21 kHz)

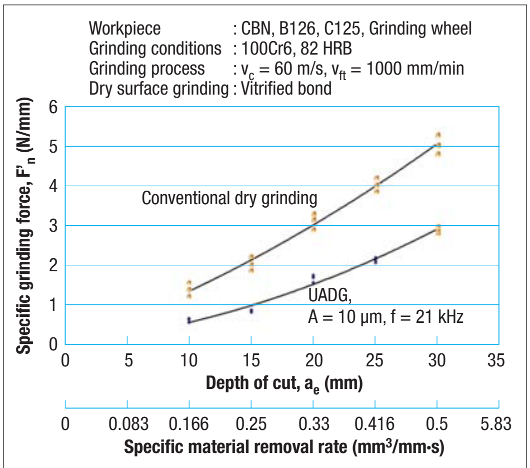

Fig 10 Specific grinding forces as a function of depth of cut a_e, v_{ft} = 1000 mm / min

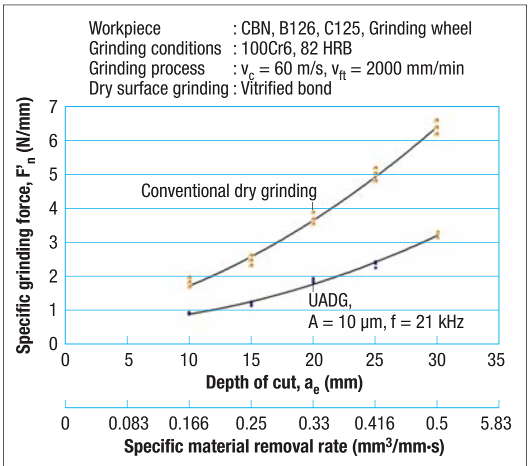

Fig 11 Specific normal grinding forces as a function of depth of cut a_e, v_{ft} = 2000 mm / min

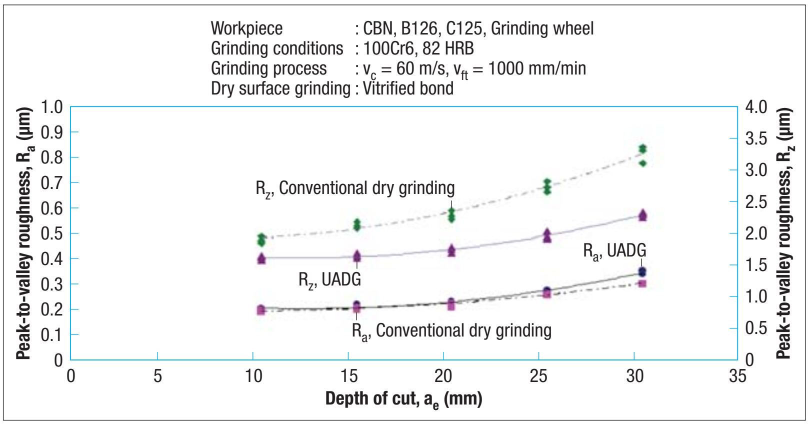

Fig 12 Surface roughness values R_a and R_z as a function of depth of cut a_e, v_{ft} = 1000 mm/min (UADG: A = 10μm, f = 21 kHz)

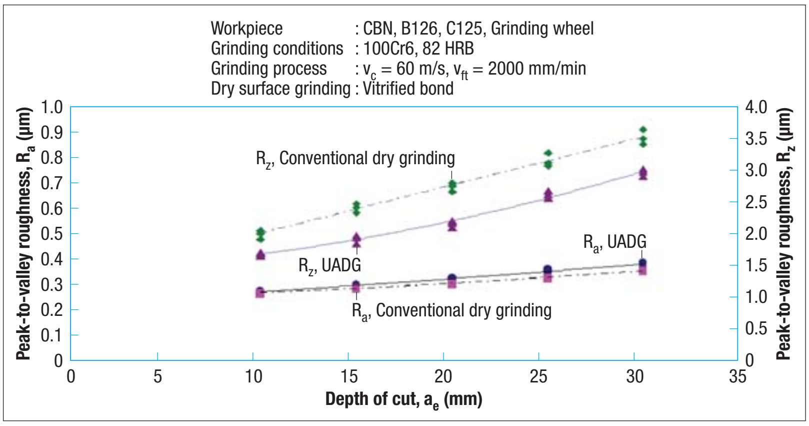

Fig 13 Surface roughness values R_a and R_z as a function of depth of cut a_e, v_{ft} = 2000 mm/min (UADG: A = 10μm, f = 21 kHz)

Kinematics of ultrasonic-assisted grinding

The oscillating movement of the workpiece (ultrasonic vibrations) transverse to the feed direction leads to wave-shaped (sinusoidal) movements of the abrasive grits on the surface of the workpiece. In broad terms the cross section of a ground surface (grinding traces) can be shown by peaks and valleys. In ultrasonic-assisted grinding the abrasive grits engage the protruding grinding traces (peaks) laterally. These grinding traces (peaks) have no lateral support and can be shifted and removed relatively easily. In conventional grinding, the active abrasive grits have to shift and remove the material which is supported by the masses of material in front of it during the chip-forming process itself. Therefore, in this case more work has to be performed (plastic deformation of the masses of material around the chip) in order to remove chips (Fig 14).

Fig 14a shows the path of an abrasive grit in ultrasonic-assisted grinding. Fig 14b shows the path of a number of grits that engage the surface of the workpiece simultaneously or one after the other.

In conventional grinding the feed is rectilinear. With small feed distances the movement of a grit can also be shown as being rectilinear. In nature, however, movements are rarely rectilinear. If one observes radiation in nature (electromagnetic radiation such as light, a laser beam, radio waves, etc., but also sound waves), it can be seen that the radiation spreads in the form of waves. This law of nature is used in ultrasonic-assisted grinding.

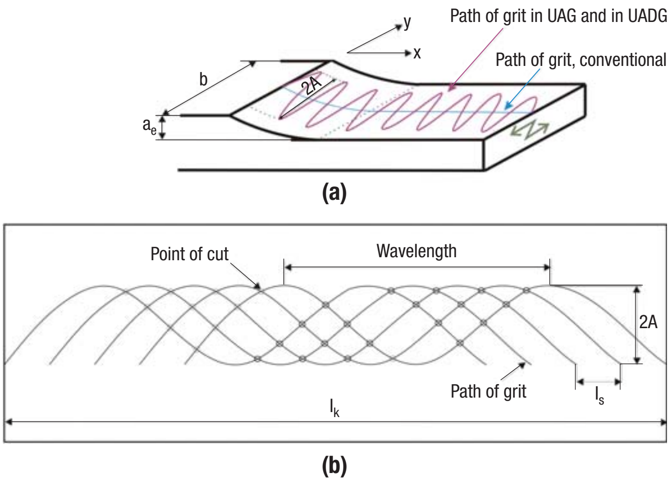

Fig 14 Path of a cutting edge in ultrasonic-assisted grinding (a) Path of a number of grits that engage the surface of a workpiece simultaneously or one after the other (b)

Summary

Hitherto it was generally thought that ultrasonic-assisted cutting could only be used for the machining of brittle-hard materials. In a large number of tests the KSF has investigated the use of UAG for grinding using coolant and also in dry grinding. The material used was 100Cr6 in the soft state. The main results obtained with ultrasonic-assisted grinding are:

- The grinding forces are 30-50% less using UAG compared with conventional grinding.
- The surface roughness values (in particular R_z) are also less by about 30-50% compared with conventional grinding.
- The structure of the surface has a different appearance with a greater ratio of contact area, which is to be studied in further depth.
- In ultrasonic-assisted grinding the abrasive grits move in the form of waves (sinusoidal). This wave-like movement of the path of the grit leads to an interrupted cut, which results in a reduction in grinding forces and surface roughness values. ◆

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References

[1] B. Azarhoushang, J. Akbari: Ultrasonic-assisted drilling of Inconel 738-LC, International Journal of Machine Tools and Manufacture, Volume 47, Issues 7-8, June 2007, pp 1027-1033.

[2] H. C. Mult, G. Spur, S. E. Holl: Ultrasonic Assisted Grinding of Ceramics, Journal of Materials Processing Technology 62 (1996) pp 287/293.

[3] H. Onikura, O. Ohnishi: Drilling mechanisms in ultrasonic-vibration assisted micro drilling, Journal of JSPE, 64 (11) (1998) pp 1633-1637 (in Japanese).

[4] T. Tawakoli, E. Westkaemper, A. Rasifard: Ultrasonic Assisted Dressing of vitrified CBN Grinding Wheel, 40th CIRP International Seminar on manufacturing Systems, Liverpool, UK, 2007.

[5] E. Uhlmann: Surface Formation in Creep Feed Grinding of advanced Ceramics with and without Ultrasonic Assistance, Annals of CIRP, Vol.47/1/1998.

[6] L. B. Zhang, L. J. Wang, X. Y. Liu, H. W. Zhao, X. Wang, H. Y. Luo: Mechanical model for predicting thrust and torque in vibration drilling fibre-reinforced composite materials, International Journal of Machine Tools & Manufacture, (41) (2001) pp 641-657.

The performance of sawing aids in hard rock working with diamond tools

The possibility of lowering the mechanical strength of crystalline materials by suitably acting on their environment was highlighted as early as the 1930s by the research of the Russian physicist Rehbinder, who produced evidence that the shear strength of crystals was considerably lowered by the presence on the crystal surfaces of suitable chemical compounds. Subsequent investigations, mostly carried out in the USA, confirmed Rehbinder's findings and gave them a sound theoretical interpretation that established the fundamentals of the new branch of technology called 'mechanochemistry'. The diamond tool machines employed in quarrying and working of hard dimension stone appeared as promising devices for the application of mechanochemistry owing to the fact that diamond tools demolish the stone by just applying shear stresses on their surfaces. Several tests, carried out in the second half of the last century in the authors' laboratory with a bench machine that simulated the action of diamond tools on granite and orthogneiss specimens yielded encouraging results and provided a wealth of information on the factors affecting mechanochemical effects produced on various hard stones by a variety of chemical compounds. This laboratory phase was followed, from 1996 onwards, by test runs on commercial machines in machine factories and quarries, and finally a full application of sawing aids was performed in quarries operated in Sardinia by various companies. The chemical compounds, of which the sawing aids consist, are added to the flushing fluids and the water solutions or dispersions thus obtained are highly diluted to the order of 10^{-3} M. These solutions or dispersions therefore should be not harmful for the environment. However, should the environmental regulations be particularly strict, recycling of flushing fluids according to a simple flowsheet is described for hard dimension stones working plants. The productivity improvements of diamond tool machines on hard dimension stones range from 40% to more than 100%, depending on various factors on which the paper provides adequate details. Paper by **G. Rossi, G. Loi, P. Trois** and **G. S.Andrissi**.

The influence of the physico-chemical environment on certain mechanical properties of crystalline solids was discovered in the 1930s by the Russian physico-chemist P. A. Rehbinder [1] and the solid state physics and physico-chemical fundamentals were studied by several researchers [2-21] who envisioned its major technological potential, naming this new branch of science and technology 'mechanochemistry'. Shear strength of crystalline solids is significantly reduced when certain chemical compounds are adsorbed on their surfaces and this effect has been exploited in oil well drilling in the Soviet Union [22]. In actual fact, drilling tools, especially diamond bits, demolish the stone chiefly by applying shear stresses thereto [23] (Fig 1).

The advent, in the late 1900s, of diamond impregnated tools – such as diamond discs and diamond wire that act on the rock in a manner that can be defined as 'abrasion' [24] – raised the interest of our Tool/Rock Interaction work Group (TRIG) that had been investigating the relationships between tools and rocks for several years. Research commenced in the 1970s culminated in the successful application of mechanochemistry to commercial dimension stone operations involving diamond disc and diamond wire machines. This paper describes TRIG's work and the technological progress achieved.

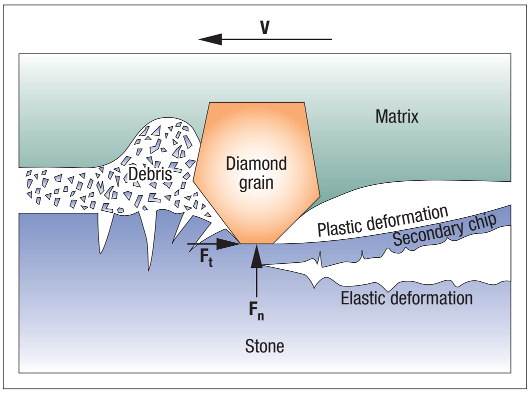

Fig 1 Tool/rock interaction:
V = linear velocity of diamond wire;
F_n = normal force per grain;
F_t = tangential force per grain (after [23])