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(A Possible New Method for Machining Space Age Materials)

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REPORT TO THE OFFICE OF TECHNICAL SERVICES,
U. S. DEPARTMENT OF COMMERCE, ON . . .

ULTRASONIC - ASSISTED GRINDING . . .

A Possible New Method for
Machining Space Age Materials

An Evaluation of Commercial
Applications

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Contract CC 4569

ULTRASONIC - ASSISTED GRINDING . . .

A Possible New Method for Machining Space Age Materials

Operators of grinding equipment have long known that deliberately induced vibrations in a grinding wheel will increase the rate of metal removal. In violation of safety rules, piece-rate workers have sometimes made adjustments to equipment to set up vibrations and hasten the grinding of hard materials.

It now appears that this phenomenon -- observed first by non-scientifically trained workmen -- can be put to work constructively and safely to help metalworking companies grind the new high-strength, thermal-resistant metals that have been developed for military, aerospace, and advanced industrial purposes. But rather than throwing a wheel off balance or employing some other dangerous practice to induce vibration, ultrasonic energy will be used to effect this end and speed up metal removal.

The process, which is currently in the research state, is called "ultrasonic-assisted" grinding -- or "assist" grinding by the technologists working on the development. It should not be confused with "ultrasonic impact grinding" -- also called "ultrasonic machining" -- which is a well-established production process.

In a program of research¹ under the sponsorship of the Manufacturing Technology Laboratory, Air Force Systems Command,

¹ Contract AF 33(600)-40122 ASD Project 7-757.

Aeronautical Systems Division, Wright-Patterson Air Force Base, the Sheffield Corporation, of Dayton, Ohio, a subsidiary of the Bendix Aviation Corporation, is investigating the effect of imposed high-frequency vibrations on the conventional grinding of "high thermal-resistant" materials. An objective of this study is to develop economical methods for producing and changing the configuration of the super alloys. As explained in the engineering reports (1 to 4) issuing from the study, if the objective can be obtained, the production cost of space vehicles and high-speed aircraft could be reduced, and materials presently available with excellent engineering characteristics could be more widely used. Obviously, similar advantages could be extended to other products that use tough, hard alloys in their construction.

There are, of course, existing methods for machining the high thermal-resistant materials, including conventional grinding and cutting, chemical and electrochemical machining, electrospark discharge, and ultrasonic impact machining. These, however, are either so limited in their application, ineffective, or costly in time, that it is impractical to use some of the better materials. It is clear that even though great progress has been made in machining practices in recent years, such progress has not stayed abreast of the new materials developed. It is hoped that ultrasonic-assisted grinding will be the breakthrough needed, and, at the present stage of development, this seems quite possible. The process may also be extended to the grinding of older materials -- including those that

workers have ground by surreptitiously throwing grinding wheels off balance-wherever the economics are favorable.

SOME BACKGROUND ON VIBRATORY GRINDING } to b

Loosening a bolt or embedding a piece of metal in a grinding wheel is an amateurish and hazardous way to speed up grinding rates by induced vibrations. Mechanically-created vibrations in the frequency order of 60 to 120 cycles per second have been tried under scientific supervision, and some published data are available on such experiments. In the present technology, however, any vibratory source other than the ultrasonic transducer would hardly be considered, especially in light of the machining accomplishments that have been achieved with the aid of high frequencies in the past ten years. Using ultrasonic energy to drive abrasive particles in the technique known as impact grinding, such materials as germanium, quartz, silicon carbide, ferrites, and synthetic gems have been readily machined in limited sizes. Ultrasonic-assisted grinding would be an extension of the vibratory frequencies and units used in ultrasonic impact grinding to conventional equipment. The principles of metal removal are different, but impact grinding is the precursor to the ultrasonic-assist concept and makes use of the same type of vibration-generating equipment.

Both impact and assist grinding are based on the vibratory energy developed by the ultrasonic transducer. Certain metals, when placed in a magnetic field, will contract and then return to normal

when the field is reversed. This property is known as "magnetostriction." An ultrasonic transducer is essentially a highly magnetostrictive metal fitted with an excitation coil. When alternating electrical current is supplied to the coil, the metal shortens and lengthens with each change of polarity, so that a mechanical vibration is produced. When the frequency of vibration is above 16,000 cycles per second, the air compression waves emanating from the vibrating metal are said to be "ultrasonic," meaning they are beyond the frequencies audible to the human ear. It is the mechanical motion of the vibrating metal, however, rather than the ultrasonic waves sent out through the air that is utilized in all ultrasonic grinding processes. This motion can be amplified through a tool cone and used either to vibrate a work piece or a grinding tool or to drive an abrasive-laden fluid against the work. The frequency of vibration is dependent upon the rapidity of alternation of the input current, and, for machining applications, usually ranges from 20,000 to 40,000 cycles.

In impact grinding, a "cutting" tool is attached to the end of the vertical-standing tool cone. This cutting tool never cuts -- or even touches the work. Its face has the exact inverse shape of the cut to be made. A slurry containing an abrasive is pumped between the tool face and the work. The abrasive particles are struck by the vibrating tool and impelled against the work, thereby accomplishing the grinding. The particles may strike the work with

impact forces up to 150,000 times their own weight, yet the grinding force required seldom exceeds ten pounds. This small force, together with the nature of the process, plus the absence of direct tool-to-work contact and the presence of the cool abrasive, make impact grinding a "cold-cutting" process. The work material is not heated, stressed, or distorted in any way.

Ultrasonic impact grinding has been successfully used to machine a great number of materials harder than 59 R_C. Softer materials are not amenable to grinding by the method, because of their tendency to absorb the impact of the abrasive particles and deform, rather than chip. Hard carbides, however, are readily ground. The process has been extremely useful in drilling, trepanning, slicing, broaching, engraving, and shaping hard metals and ceramics and has enabled machining that otherwise would be impossible. (For details on ultrasonic impact grinding and its applications, see References 5, 6, 7, 8, 9, 10, and 11.) However, it is limited to fairly small work pieces, requires a shaped cutting tool for each operation, and is not adaptable to many of the machining requirements in fabrication from super alloys.

A process is needed that will enable the grinding of these alloys on the standard types of grinding machines used today -- center, centerless, internal, rotary, and surface types. Giving these machines an ultrasonic "assist" would seem to be a logical approach to solving the problem.

THEORETICAL BASIS

Although no universally accepted theory as to why vibration of an abrasive wheel should hasten the grinding of metal has evolved, certain points of explanation have been advanced. First, ultrasonic energy induced in a grinding surface would be superimposed over the normal cutting energy. An abrasive particle, vibrating parallel to the wheel's axis, would, in a sense, be moving back and forth across a point on the work piece, touching more surface in any instant of time. If there is additionally a perpendicular component to the motion, the particle would be thrust against the work with the added energy of that component. Another factor -- and one that is well supported by experimental evidence -- is the effect of the vibration on dislodging particles of metal and broken grit from the wheel and keeping maximum abrasive surface exposed.

The "cooling" effect also appears to be important. It has been established through research that when a turning tool is energized ultrasonically, the friction -- and thus frictional heat -- generated by the chips is reduced. It is generally agreed that the extreme heat developed at the edge of conventional cutting tools used for turning and milling is the cause of the rapid tool breakdown experienced when machining at high speeds and when machining extremely hard materials. Thus, any lessening of the heat produced, whatever the theoretical mechanism, prolongs tool life.

ADVANTAGES OF ULTRASONIC-ASSISTED GRINDING

Most of the experimental evidence of significant advantages from ultrasonic-assisted grinding comes from the government research program at the Sheffield Corporation. These advantages are delineated in the engineering reports (1 to 4) that have been issued. All of these reports are available to government contractors and sub-contractors from the Armed Services Technical Information Agency and to others through the Office of Technical Services, U. S. Department of Commerce. Some of these advantages were found to be (with the high thermal-resistant metals used):

- . Increased grinding ratios, up to five or six times those obtained with conventional equipment.
- . Faster metal removal.
- . A significant decrease in grinding temperatures.
- . A decreased power requirement --down to approximately one-third (1/3) of conventional.
- . An elimination or lessening of surface burns.

(Metals used in the Sheffield research program included H11 Die Steel, hardened to R_c 56-58; Titanium Alloy Ti-6Al-4V, hardened to R_c 35-40; Precipitation Hardened Stainless Steel 15-7 Mo; and René 41, hardened to R_c 40-42. The metals were ground on conventional equipment with and without supplementary high-frequency

vibrations created by coupling an ultrasonic transducer to the grinding wheel. Vibrations from 60 cycles per second up to 40,000 cycles per second in a number of different modes were applied. Details of the testing procedures and an analysis of the data are presented in the Phase II Technical Engineering Report, issuing from the project (4).

Grinding ratios (volume of metal removed/volume of wheel lost) attained by the ultrasonic vibrations of the grinding wheel proved to be decidedly superior, regardless of the wheel used. The best grinding ratios were obtained when the wheel was subjected to agitation. When the work piece was vibrated, the ratios were about the same as with conventional grinding, and when both the wheel and work piece were vibrated the ratios were inferior.

In general, vibration of the grinding wheel, as opposed to vibration of the work piece, was found to be superior in nearly every respect. With about one-fifth the amplitude, a vibrating wheel outperforms a vibrating work piece. The ultrasonic wheel also permits the application of vibration to external, internal, and centerless, as well as surface grinders.

Speed of metal removal may be correlated with grinding ratios, but, as the Sheffield Corporation points out, faster stock removal should always be related to some criteria or parameter that permits comparison. A few obvious ones are production rate versus cost; production rate versus tolerance; production rate versus distortion, heat checks, fatigue properties, surface finish, and others.

According to George C. Brown and James N. Behm (7), in experimental work ultrasonic assistance has facilitated the grinding of such materials as Inconel, titanium, 17 PH stainless steel, Unitemp 212, beryllium, columbium, molybdenum, and tantalum. When grinding these materials by conventional methods, stock removal rates are low and wheel dressing is frequent. In those cases where ultrasonic assistance makes possible satisfactory grinding where it was practically impossible before, the speed of metal removal is, of course, infinitely faster, even though relatively slow compared with the rates for easily ground materials.

With light cuts, in the order of .0003-inch, ultrasonic vibration during grinding gives surface finishes that are neither superior or inferior to those produced by conventional grinding, although the visual appearance seems to be superior for the ultrasonically ground piece. At heavier cuts, in the order of .0009-inch, surface finish is generally superior on vibration-assisted grinds. The surface finish improvement is also accompanied by pronounced chatter reduction. Just as in the use of ultrasonics with a milling or turning tool, frictional heat is reduced, and burning with ultrasonic-assisted grinding is practically eliminated.

The effect of vibration in keeping the wheel clean adds to cutting rate, wheel life, and efficiency. Vibrating the grinding wheel ultrasonically apparently produces cleansing results similar

to those achieved by the "Ever-Grind" system, developed by the Cavitron Corporation, Long Island City, New York (12). This system uses an ultrasonic transducer in close proximity to the cutting surface to transmit vibrations through the coolant to the grinding wheel. It is used as an accessory on surface grinding machines and has proved very effective in preventing particle build-up. It should not, however, be confused with ultrasonic-assisted grinding in which the transducer is a part of the wheel spindle, rather than an accessory.

RESEARCH PROBLEMS

The superiority of wheel vibration over workpiece vibration practically eliminates the latter from serious consideration as a grinding technique. Because of the varying shapes, sizes, and masses of workpieces, as well as difficulties in transmitting high-level energies to detached bodies, workpiece vibration is awkward and does not give the flexibility needed for a production process.

Wheel vibration gives the flexibility required, but it also has limitations which must still be resolved. In wheel vibration, the transducer is incorporated into the spindle construction. Such an assembly induces the problem of isolating the vibration from the spindle bearings. If proper vibration isolation is not attained, undue bearing loads and wear may be expected. This was recognized as a critical limitation, and, consequently, major research effort has been directed toward its solution. Research results, as yet unpublished, indicate that this problem may shortly be overcome.

Another problem is development of a suitable grinding wheel. Improvements in the method of attaching abrasive discs to their hubs are being investigated in order to make ultrasonic-assisted grinding practical. Simple mechanical attachment is not adequate, since the vibration loosens the attachment and sets up hammering, which soon destroys the wheel. Paper pressure pads must be avoided, since they are a serious impediment to efficient vibration transfer. The use of an epoxy resin to bond the wheel to its hub appears to be a feasible method of assembly. Resin bonding has adequate strength within the amplitude range of vibration tolerated by standard vitrified grinding wheels.

Still another problem -- although not of major consequence -- is the diameter and thickness of wheel that can be used at a given frequency. At 20,000 cycles per second, a wheel eight inches in diameter may be used, and it may be worn down to four inches in diameter before replacing. In all of these areas research is showing that the application of engineering design techniques and the use of newly developed materials can provide a new and practical metalworking concept.

THE OUTLOOK

The outlook for ultrasonic-assisted grinding is very good, despite certain inherent limitations and problems that must still be solved through research. Commercial use of the technique to grind tough alloys appears imminent. The first application will probably be in the defense industries, but after the process has been proved in defense production its use could very well be extended to civilian

production where improved grinding ratios, longer wheel life, and faster cutting would offer economic advantages. It is expected that new types of wheels will be developed to extend the potential of the process.

Within a few years at the most, the research sponsored by the government in this area should be paying rich rewards in the form of reduced machining costs and the capability of using superior materials more extensively in product design.

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* Available from the Office of Technical Services, U. S.
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