Metals and Ceramics Division

SURVEY OF CERAMIC MACHINING IN JAPAN

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TABLE OF CONTENTS

Executive Summary.	1
1.0 Ceramics Machining Research and Development Organizations.	2
1.1 Institute of Physical and Chemical Research (RIKEN).	2
1.2 Tokyo Institute of Technology.	4
1.3 Isuzu Ceramics Research Institute.	4
1.4 Mechanical Engineering Laboratory (MITI).	5
1.5 Keio University.	6
1.6 Institute of Vocational Training.	6
1.7 Japan Fine Ceramics Center, Nagoya.	8
1.8 Government Industrial Research Institute, Nagoya.	12
1.9 Aichi Industrial Research Institute.	12
1.10 Chubu University.	12
2.0 Trade Shows.	13
2.1 Nagaoya Ceramics Fair.	13
2.2 Japan International Machine Tool Fair.	14
3.0 Other Commercial Developments.	15
3.1 New, Patented Bonding Process for Manufacturing Grinding Wheels.	15
3.2 Ceramic Ball Valves.	15
3.3 Tools To Withstand Contact with Molten Aluminum.	15
3.4 Sintoblator, Ltd., Manufacturer of ELID Systems.	16
References.	17
Appendix - Key Researchers in Ceramic Machining in Japan.	19

EXECUTIVE SUMMARY

This report is a compilation of four subcontract reports provided by B. P. Bandyopadhyay who, while a visiting professor at Toyohashi University in Japan, conducted a survey of ceramic machining technology in that country from January 1 through December 31, 1992. Various aspects of machining technology were surveyed: types of parts being produced, types of ceramic materials being used, the nature of current ceramic machining research and development, and types of machine tools. The four separate reports compiled here were originally provided in a narrative, chronological form, and some of the information has been reorganized into topical areas for this compilation. This report is organized into three sections: The first describes ten ceramic machining research and development organizations and provides a reference list of their current technical publications; the second, two major trade shows; and the third, several other products and commercial developments noted during the course of Bandyopadhyay's stay in Japan. An Appendix lists key individuals who are currently conducting ceramic machining research in Japan.

1.0 CERAMICS MACHINING RESEARCH AND DEVELOPMENT ORGANIZATIONS*

The following ten organizations were visited during this survey:

1.1 Institute of Physical and Chemical Research (RIKEN)

The Institute of Physical and Chemical Research is also known as RIKEN. Established in 1917, RIKEN is a nonprofit institute supported by the government's Science and Technology Agency. The institute is a research complex consisting of about fifty laboratories of various disciplines. Research is conducted under active collaborations with universities, other research institutions, and industries.

The Materials Fabrication Laboratory at RIKEN, headed by Takeo Nakagawa, has done significant research for the processing of fine ceramics. The Cast Iron Fiber Bonded Diamond Grinding Wheel (CIFB-D) developed by this institute for creep feed grinding of ceramics is now commercially available. The manufacturer's name is Sintobator, Ltd. A heavy material removal rate (MRR), with good surface finish, has been reported with this type of a grinding wheel [1]:

$$\begin{aligned} \text{MRR} &= 6600 \text{ mm}^3/\text{min} \text{ and} \\ \text{R}_{\text{max}} &= 0.1 \text{ to } 2 \text{ } \mu\text{m}. \end{aligned}$$

A new complex grinding method named Ultrasonic Electrodischarging Grinding (US-ED-G) has also been developed at this institute. This method reduces the grinding force drastically. Therefore, US-ED-G will be helpful for grinding hard-to-grind ceramic materials that may appear in the future (e.g., TiB_2) [2].

Continued research in ceramic grinding has revealed that, though the CIFB-D wheel is sufficiently strong, it is not suitable for continuous use. This is due to the difficulty in chip removal and absence of self-dressing. This will lead to unstable grinding qualities. RIKEN has been successful in developing a new grinding technique that will address the self-dressing problem. This technology, capable of producing a mirror surface finish on various materials when they are ground even in conventional grinding machines, uses Electrolytic In-Process Dressing (ELID) and fine grain CIFB-D wheels. Hitoshi Ohmori is the principal investigator of the ELID project in RIKEN.

The ELID grinding process consists of three stages:

1. precision trueing the grinding wheel,
2. pre-dressing process of the wheel by electrolysis, and
3. grinding process with electrolytic in-process dressing.

The ELID process is capable of producing parts six times faster than conventional grinding for a given surface quality. The method can be used to grind hard and brittle materials such as silicon wafers, glass, silicon nitride, silicon carbide, zirconium oxide, titanium alloys, special die steel, stainless

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steel, quartz, ferrites for magnetic heads, and tungsten carbide materials. The method is commercially available, and the ELID attachment can be purchased from a vendor. The ELID system's essential elements are metal bonded grinding wheel, electrolytic power source, and electrolytic coolant. The cost of an ELID system is around 1 million yen. Thirty companies in Japan are using this ELID technology. Toyota Motor has expressed interest in this technology for grinding of their cam shafts to a mirror finish (not made from ceramics). This is expected to significantly reduce the vibration in the car.

Several papers have been published in English by H. Ohmori describing applications of his ELID method [3-5]. One recent paper on ELID grinding by Ohmori was presented at the Progress in Precision Engineering Conference held in Braunschweig, Germany, in May 1991 [5]. Ohmori was invited to the ISEM X conference to present his research. This conference was held in Magdeburg, Germany and his talk was on May 8, 1992. Some European companies are using Ohmori's ELID technique, one of which is in Munich, Germany (i.e., George Muller Nurnburg AG). Philips of the Netherlands has expressed interest in this technology also.

Applications of ceramic materials, ground by ELID technique, include:

1. ZrO_2 for gage blocks produced by Mitutoyo;
2. tungsten-carbide in micrometers and for seals in engines;
3. silicon wafers for integrated circuits (ground to mirror surface in 2 min);
4. ferrites for magnetic heads;
5. tungsten-carbide dies for injection molding of compact discs;
6. Mo used for optical parts;
7. tungsten-carbide, silicon, and silicon-carbide (a mirror spherical surface for high-energy rays like X rays);
8. SiAlON [rolling mill (parts) produced by Hitachi for rolling aluminum]; and
9. sharp edge cutting tools from cubic boron nitride and diamond produced by Makino Seiki Company using ELID technology.

NACHI is a manufacturer of high precision grinding machines. The spindle of these machines is mounted on aerostatic bearings. By using ELID technology, a surface finish of R_{max} in the order of $0.02 \mu m$ can be produced.

Another area of research for machining ceramics at RIKEN is the development of a Vibrational Grinding System. The ceramic workpiece is provided with a low-frequency sine wave vibration (i.e., a frequency around 300 Hz or less than 1 kHz) and peak-to-peak amplitude of $15 \mu m$ for hole grinding. The grinding wheel used was the CIFB-D wheel. Al_2O_3 and Si_3N_4 were machined. Three advantages of the process are the following:

1. Grinding forces are reduced.
2. No chipping of the workpiece occurs, even at the corners.
3. It is cheaper than ultrasonic vibration systems.

The main disadvantage is the noisy operation.

Presently a workpiece of 100 mm diam can be accommodated on the vibrating table. Research is continuing on increasing the size of the vibrating table, which will allow machining of larger workpieces. Funding for the research is provided by private companies, totaling about

10 million yen a year, which is used for the purchase of instrumentation. Grinding machines and tooling are donated by the companies. Salary and other expenses are supported by the government. NACHI sells the system.

1.2 Tokyo Institute of Technology

Some of the basic research on the production of ceramics is carried out at Tokyo Institute of Technology under the leadership of Yohtaro Matsuo. Studies were performed in several areas including:

1. The effect of additives on microstructure and mechanical properties of ceramics. The bases of these investigations were fracture mechanics and fracture statistics. Recently, micro mechanics has been used for the analysis.
2. The effect of Cyclic Cold Isostatic Pressing. This method is said to improve the structural reliability of sintered ceramics [6].
3. The effect of annealing on surface-machining damage. The major advantages are crack healing and reduction of residual stress [7].

Funds for the research are provided by both government and private companies. The government's contribution is about 6 to 10 million yen per year; the contribution from companies may be up to 2 million yen per year without any obligation to the companies.

1.3 Isuzu Ceramics Research Institute

The Isuzu Ceramics Research Institute is very similar to the High Temperature Materials Laboratory in Oak Ridge. Representatives of the institute stated from 1982 through 1985, silicon nitride ceramics with a bending strength of 750 MPa were produced. Recently, a new method developed at the laboratory produced silicon nitride with a bending strength of over 1 GPa. The reasons for this improvement were said to be (1) high powder purity and (2) improvement of the sintering process (i.e., sintered at high gas pressure). The research institute also applies finite element methods to determine the bending strength, tensile strength, and fatigue strength, which enables them to determine the maximum stress level on specific parts. It has been stated that in Japan, a ceramic material with a fracture toughness = 11 MPa $\sqrt{\text{m}}$ has been developed.

A copy of a technical paper entitled "Studying of Grinding Process and Strength for Ceramic Heat Insulated Engine" was obtained [8]. This paper discusses the relationship between the grinding-affected layer, the strength, and the grinding parameters. It has been suggested that the affected layer be removed by precise grinding or lapping to improve the strength of the ceramic (see Fig. 1, reproduced from Fig. 18 of the paper).

According to the institute staff, an important area of research is the healing of cracks after grinding. There are three main ways in which the crack healing is accomplished:

1. in situ laser heating for crack healing,
2. chemical healing, and
3. heating.

Unfortunately, no further information on flaw healing was available during the visit.

Figure 1. Relationship between grinding efficiency and grinding time for obtaining an average bending strength of 890 MPa in silicon nitride [8].

1.4 Mechanical Engineering Laboratory (MITI)

The Mechanical Engineering Laboratory of the Ministry of International Trade and Industry (MITI) is one of the national research institutes in Tsukuba Science City, which is about 60 km northeast of Tokyo. Originally known as "Government Mechanical Laboratory", it was founded in 1937. Its purpose was original research for the rapid improvement of Japanese industry and reduction of its dependence on foreign technology. The research in this institute may be divided into three categories:

1. Large-scale Projects, which are performed by several laboratories (typical funding allotted for such a project may be up to 1000 million yen per year, but the amount allotted to each lab is not very high;
2. Special Researches for which 10 to 15 million yen per project may be allotted; and
3. Ordinary Researches for which funding varies from 1 to 2 million yen per project (the projects are mainly funded by the government).

MITI can have collaborative projects with the industries but not financial support only from industries.

The laboratory has developed a high-performance creep-feed grinding of difficult-to-machine materials with a new type of wheels. These grinding wheels have a number of slots/segments, and in each slot cooling holes are drilled through the fluid chamber of the wheel working surface. The fluid supplied into the fluid chamber is forced out from the slots into the grinding zone by the centrifugal force performing effective cooling. Creep-feed grinding was performed with four types of ceramics. The details of their research can be obtained from two articles [9, 10]. Two brief reports have been obtained: one on machining of ceramics [11] and the other on application of ceramics for machine tools [12]. Another paper entitled "A Simulation System for the Establishment of Grinding Operation Standards" was also obtained [13].

1.5 Keio University

Keio is a famous, private university founded in 1858. I. Inasaki is quite renowned in the field of grinding, especially grinding of ceramics. As current chairman of the Abrasive Technology Committee of the CIRP, he has been asked to deliver a keynote address on the future of abrasive technology at the CIRP annual meeting next year.

Professor Inasaki advocates speed-stroke grinding instead of creep-feed grinding. Speed-stroke grinding is characterized by a high work speed and a small depth of cut. This method significantly reduces the grinding force. Five technical papers by Inasaki describe in detail the type of research being carried out on the area of grinding of ceramics [14-18]. One paper describes a new preparation method for producing resinoid-bonded CBN wheels [19]. The author has integrated the trueing and dressing processes for CBN grinding wheels with the use of a metal-bonded diamond wheel and steel wire brushes.

According to Inasaki, the research on ceramic machining started 7 or 8 years ago, and peaked 4 or 5 years ago. The research is almost complete in this area. Several sources of funding are available (e.g., government, university, cooperative research with industries, and various foundations). His annual budget was around 20 million yen (about \$160,000). He had 11 final year undergraduate students, 12 graduate students, and a research fellow. Generally there is no overhead charge, and salaries for the research personnel are paid from a separate fund. Very expensive instruments or machine tools are usually provided by industries.

1.6 Institute of Vocational Training

Kuniaki Unno, professor of the Institute of Vocational Training, was visited by Bandyopadhyay in September. A 1-kW laser is used for machining small holes of 100- μ m diam in Si_3N_4 . This process is expected to find application in the semiconductor industry. Autofocusing is the objective of the research.

Ultrasonic Grinding of Ceramics for machining holes is the other area of research. Hole size of 10-mm diam is machined by a metal-bonded diamond-grinding tool of 140-grit size and 100 concentration. The frequency of vibration is 20 kHz; maximum amplitude is 50 μ m. The time required to machine a hole in a glass of 5-mm thickness is 1 s, while machining a hole in Si_3N_4 of the same thickness is 5 s. The material is removed by brittle fracture, and the surface finish depends on diameters of the abrasive and the fracture toughness of the ceramics. A sketch of the cutting tool is shown in Fig. 2.

Fig. 2. Sketch of the tool used in ultrasonic grinding of ceramics.

For efficient grinding of ceramics, the following requirements are essential from a machine tool:

1. autobalancing system,
2. high rigidity, and
3. high damping.

The accuracy of spindle revolution should be about $0.2 \mu\text{m}$, and the spindle rigidity is $20 \text{ kgf}/\mu\text{m}$.

Hydrostatic bearings are accurate but low in rigidity (i.e., around $5 \text{ kgf}/\mu\text{m}$). The hydrodynamic bearings are not good when the rpm is changed. Therefore, the concept of hybrid bearing has been developed where hydrostatic, and hydrodynamic effects, and also mechanical bearings can be used. The hybrid spindle design has been patented in Italy. Toyoda Machine Works, Ltd. has developed their own hybrid spindle bearing design. The automatic dressing of a metal-bonded grinding wheel can be accomplished by the ELID system; therefore, automatic dressing of a vitrified bonded grinding wheel will be required in the future.

Research in the institute is carried out to determine the applied external pressure required to have ductile mode grinding. Figure 3 shows the relationship between the material removal rate and the external applied pressure on the wheel. Al_2O_3 , and Si_3N_4 have very narrow ductile mode zones; therefore, the grinding is performed in the brittle zone. However, ZrO_2 has a wide ductile mode zone.

In Fig. 3, the value of P_1 depends on the following factors:

1. fracture toughness,
2. hardness,
3. elastic modulus, and
4. condition of the wheel.

In a metal-bonded grinding wheel the pressure is high because elastic deformation is less; therefore, brittle mode grinding occurs. On the other hand, with a resin-bonded grinding wheel, ductile mode grinding may be easily obtained. With a fine mesh and a good dressing condition also, it is easy to get ductile mode grinding. With ductile mode grinding there will be minimum grinding defect.

Presently, the institute is involved in developing grindability data to establish a data base for grinding of ceramics. This institute belongs to the Ministry of Labor. Financial support for research is not available from the government.

1.7 Japan Fine Ceramics Center, Nagoya

About 30% of the employees at the Japan Fine Ceramics Center (JFCC) in Nagoya are from various companies. The organization structure and principal research topics are summarized in Figs. 4 and 5. Brochures obtained during the visit provided additional information [20, 21]. They have excellent testing facilities such as X-ray radiography for residual stress, ultrasonic microscope, high- temperature creep test laboratory, X-ray CATSCAN, tensile testing for life prediction of ceramics, thermal shock testing, etc. The tensile testing is performed with the test specimens machined from Kyocera material Si_3N_4 . According to JFCC reports, similar tests are being carried out at other laboratories abroad, even at ORNL. The objective is to develop standards for testing methods and a database. A CATSCAN photograph of a Si_3N_4 specimen is shown in Fig. 6. The system can identify a defect of minimum size of 20 μm , the diameter of a tungsten wire (natural crack). Detailed information was not available.

Figure 3. Relationship between material removal rate and applied pressure for various materials.

ORGANIZATION

The organization is a flexible and efficient one, so that the staff may devote themselves to their work with zeal.

Figure 4. Organization of the Japan Fine Ceramics Center.

PRINCIPAL RESEARCH RESULTS

- * Succeeded, for the first time in the world, in taking photographs continuously of the high-temperature structural ceramics at the moment of collapse by using the transmission electron microscope (TEM)
..... Functional Ceramics Div.
- * Developed the ceramic thin film forming technology by using the molecular beam epitaxi (MBE) process, suggesting brighter prospect for the combination of high performance thin films such as artificial lattice, functionally gradient materials, etc.
..... Functional Ceramics Div.
- * Clarified the strengthening mechanism of fine ceramic through analysis of the inter-granular structure of the silicon nitride sintered body
..... Functional Ceramics Div.
- * Synthesized of silver doped bismuth type superconducting bulk material having the world highest level IC by means of the JFCC's original floating zone melting technology
..... Functional Ceramics Div.
- * Gave indications for engineering of new fine ceramics materials through quantitative analysis of fine ceramics manufacturing processes from adjustment of the material preparation to sintering
..... Process Technology Div.
- * Developed and started distribution of a reference standard material, enabling transversal evaluation of the results of the test and research on the machining of fine ceramics
..... Process Technology Div.
- * Developed the SEVNB method and CVN method for revolutionary improvements in evaluation accuracy, through fracture toughness test
..... Structural Ceramics Div.
- * Developed the friction and abrasion properties evaluation equipment for use under special environments (high temperature, high pressure, underwater)
..... Structural Ceramics Div.
- * Established the flaw detecting technology in X-ray flaw detection methods and ultrasonic flaw detection methods, far surpassing conventional detection capability
..... Nondestructive Testing Div.

Figure 5. Accomplishments of the Japan Fine Ceramics Center.

Figure 6. CATSCAN of a circular silicon nitride part showing internal flaws.

1.8 Government Industrial Research Institute, Nagoya

Katsushi Kubo of the Government Industrial Research Institute, Nagoya (GIRIN) hosted Bandyopadhyay's visit. This institute is under the Ministry of International Trade and Industry (MITI) similar to that in Tsukuba. There are 180 people on the research staff; 100 of them are involved in ceramics. They have laboratories to investigate the mechanisms of sintering, a laboratory for preparation of specimens for mechanical testing of ceramics, and a creep-testing laboratory. Besides these laboratories, the institute has a carbon dioxide laser of 2-kW power for machining ceramics. "Damageless machining" is the focus of that research. The institute found that thermal shock is a problem in laser machining. Preheating the workpiece is proposed to minimize the thermal shock. Two articles on the effect of ceramics grinding on strength were obtained [22, 23]. A Ceramic Gas Turbine Project started 5 years ago (i.e., Moonlight Project) is expected to be completed in 1996.

1.9 Aichi Industrial Research Institute

Motohiro Suganuma, an expert on the scanning acoustic microscope (SAM), hosted a visit at the Aichi Industrial Research Institute. Hitachi manufactures one type of SAM. Knoop indentation was performed on a Si_3N_4 specimen with a force of 9.8 N. The depth of the damage was found to be 17 μm . Figure 7 shows the relationship between the diameter of indentation damage and the bending strength. Suganuma would like to use this concept to predict the bending strength indirectly by measuring the size of the damage by nondestructive evaluation.

1.10 Chubu University

Y. Namba hosted a visit to Chubu University. He has developed a glass ceramic spindle with zero thermal expansion. Two of his interesting papers on the subject were obtained [24, 25]. He is working more with optical and electronic industries. He has obtained a surface finish of $R_{\text{max}} = 10$ A for optical glass.

Figure 7. Relationship between indentation diameter and flexural strength for silicon nitride.

2.0 TRADE SHOWS

2.1 Nagoya Ceramics Fair

The Ceramics Fair was held in Nagoya from March 11 through 15, 1992, at which time several important developments were shown:

Isuzu Ceramic Research Institute demonstrated ceramic parts to be used in ceramic engines. The company exhibited the car of the future, *TERRAZA*, in the 1991 Tokyo Motor show. This car will be marketed in 1995. The company will be manufacturing the cams on the cam shaft from ceramics (e.g., ZrO_2 plus Al_2O_3). The shaft itself will be made from steel. A company representative explained that the crack size after grinding is of the order of 30 μm , which is very difficult to detect with ultrasonic testing. However, Isuzu is removing these grinding cracks by lapping, which increases the strength of the part significantly (e.g., the strength of a Si_3N_4 part may reach up to 1 GPa using this technology). For parts like the exhaust manifold, the port liner, and the turbine scroll, the company is using low-thermal-conductivity material like Al_2TiO_5 . The thermal conductivity of this material is about 1/10th that of Si_3N_4 .

Meiwa Industries manufactures ceramic coiled springs. Wicera engineering exhibited ceramic chains to be used in conveyers. The chain sprockets will be made from steel. The company also manufactures files from ZrO_2 . Kyocera also exhibited the following:

1. a ceramic ultraprecision straightness measuring machine,
2. a fine ceramic air bearing for measuring instruments, and
3. a ceramic air spindle unit (100 to 7200 rpm).

Fine, Sodick, and Toshiba exhibited ceramic surface plates of various sizes, high-precision ceramic V-blocks, and ceramic grinding centers. The "Magical V-Chuck" (vacuum chuck), produced by FSK, will simplify work mounting during the grinding process. Hoechst CeramTech provided a brochure totally in English. Panasonic demonstrated artificial marbles for mounting their speakers.

A few companies demonstrated some diamond saw machines for slicing brittle materials. Other interesting machine tools displayed included the Super High Speed Ceramics Driller NDR 103 by Hitachi and CNC FM 505 Grinding Center by Brother. For the latter machine, coolant is provided from inside the spindle as well as from the outside. The amount of coolant supplied is 20 l/min from the outside, and 10 l/min at high pressure approximately 50 kg/cm² from the inside of the spindle. Before the grinding operation, automated dressing of the grinding wheel is accomplished. The grinding center can do core drilling, internal grinding, cylindrical grinding, etc. With the Super High Accuracy Grinding Center JV-5G by Toyoda, materials machined and their surface finishes were silicon carbide ($R_{\text{max}} = 0.6 \mu\text{m}$), ZrO_2 ($R_{\text{max}} = 1.0 \mu\text{m}$), Al_2O_3 ($R_{\text{max}} = 0.8 \mu\text{m}$), and Si_3N_4 ($R_{\text{max}} = 1.0 \mu\text{m}$).

A CNC Cam Grinder GC-34N was exhibited by OKUMA. The same machine can be used for grinding ceramics and steels. A Diamond Pellet Grinding Machine was exhibited by SPEEDFAM Company. This unique machine performs plane grinding and lapping in one process.

2.2 Japan International Machine Tool Fair

The Japan International Machine Tool Fair was held in Tokyo in November 1992. Osaka Diamond displayed diamond wheels for high-speed grinding and also new hybrid diamond wheels. The hybrid diamond wheel has both metal bonds and resin bonds. At present, the cost of a hybrid wheel is about 40% higher than that of a conventional resin-bonded diamond wheel for a diameter of 200 mm and a width of 25 mm. Diamond and CBN tools are made by Mitsubishi materials.

A very interesting grinding machine was displayed by JUNKER MASCHINEN. The company claims a G-factor of 60,000 can be obtained. The grinding wheel width is only a few millimeters, and point contact is made during grinding. All these machines are provided with autobalancing of the wheels. Toyoda uses U.S. technology for autobalancing. The representative of Toyoda Machine Works, Ltd., Takao Miura, said that more information on autobalancing can be obtained from Grinder for Industries, Wixom, Michigan, [(313) 624-5755]. Nagase Integrex Company manufactures grinding machines with an autobalancing system that combines a liquid-injection-type balancing unit with a microcomputer-based imbalance measuring unit.

3.0 OTHER COMMERCIAL PRODUCT DEVELOPMENTS

3.1 New, Patented Bonding Process for Manufacturing Grinding Wheels

A technical bulletin on P.B.S., which is a patented bonding process to manufacture grinding tools, was obtained [26]. The process claims that the diamond particles are very strongly bonded into the wheel by fusing a hard, nickel-chromium alloy, instead of just being encapsulated, as in electroplated wheels. This type of grinding tool is available in various forms. They can be used for milling, drilling, etc. They can also be used for grinding of ceramics, but no technical data is available.

3.2 Ceramic Ball Valves

Fujikin Incorporated manufactures fine ceramic ball valves. These valves have the following features: excellent corrosion resistance, superior erosion resistance, and low cavitation. Various sizes and types of ceramic valves are manufactured. The company has two branch offices in the United States: Englewood, New Jersey (201) 569-6360; and San Jose, California (408) 283-0270.

3.3 Tools To Withstand Contact With Molten Aluminum

Hitachi Metals, Inc., has developed new SiAlON ceramics parts to be used as jigs and tools that come into direct contact with molten aluminum. The properties of SiAlON developed by Hitachi Metals HCN-10 are shown in Table 1.

Table 1.
PROPERTIES OF HITACHI HCN-10

Property	Value	Units
Density	3.26	g/cm ³
3-point bend strength	90.0 (883)	kgf/mm ² (MPa)
Weibull coefficient	11.	
Fracture toughness (K _{IC})	6.0	MPa m ^{.5}
Thermal expansion coeff.	3.0	x 10 ⁻⁶ / deg C
Thermal conductivity	0.04	cal/ cm-s-deg C
Young's modulus	294.3	GPa

Research is being conducted by Hitachi for the development of automotive parts from SiAlON.

3.4 Sintobrador, Ltd., Manufacturer of ELID Systems

Sintobrador, Ltd., in Toyokawa manufactures and markets the ELID grinding system. At present, 50 companies in Japan are using this system, and another 50 companies have started testing the system. For the efficient operation of ELID grinding, the gap between the electrode and the grinding wheel is critical. The company has recently developed ELID-OPTIMA for automatic adjustment of the gap. No detailed technical information is available at this moment. The ELID grinding system has been successfully applied to the following grinding operations: rotary surface grinder, machining center, surface grinder, in-feed grinder, lap-grinder, and internal grinder. This company also markets the new advanced grinding wheel known as Mighty Cerax. This is a cast iron fiber bonded diamond grinding wheel. These grinding wheels are manufactured by the sintering process. First, the wheel hardness is monitored and then the tensile strength of the specimen is measured. The tensile strength test specimen is produced simultaneously during the sintering process.

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