AN ABSTRACT OF THE THESIS OF

Wendell R. Wrzesinski for the degree of Master of Material Science in Mechanical Engineering presented on 10-19-87.

Microwave Sintering of Alumina-titanium Cermets

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The influence of microwave radiation on the fabrication of cermet materials has been investigated for alumina-titanium cermets with compositions ranging from 20 to 80 wt. % titanium. An industrial microwave oven was characterized and adapted to process cermet materials. Physical and mechanical property determinations were made as a function of microwave processing time and compared to a furnace sintered sample. Electron microscopy was conducted on the composite materials in evaluating the extent of bonding between metal and oxide particles and particle sizing in the cermet. Sintering of composite materials through microwave radiation usage may be possible as a reduced cost, time-saving, processing technique.

Microwave Sintering of Alumina-titanium Cermets

by

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INTRODUCTION

Historically, much work has been done to develop a material that combines the higher melting point and oxidation resistance of a ceramic with ductility and high thermal conductivity of a metal. The resulting material or cermet (ceramic-metal) would be a high strength, high temperature composite material. A cermet, as defined by the ASTM commitee on cermets is defined as a heterogeneous combination of metal(s) or alloy(s) with one or more ceramic phases in which the latter constitutes approximately fifteen to eighty-five per cent by volume with little solubility between metallic and ceramic phases at the preparation temperature.(1)

Cermets or materials composed of high-melting temperature metal oxide powders and powders or alloys of metals can find use in tools and constructional elements (parts of jet engines, nozzles, cruicibles, thermal screens, etc.).(2) In one form or another aluminum oxide or alumina ceramic tool inserts have been available to the production engineer for some forty years. This is due to the fact

that alumina is hard and easily sintered. Ceramic tools are now available that contain a fairly large percentage of titanium carbide (30 to 40 wt. %) as an additive to aluminum-oxide.(3) Cermet tools are used successfully in a wide variety of machining applications, indicating that the available cermet tools have valuable properties. Other cermet composites have also received considerable attention. The first member of a series of chromium-alumina cermets became commercially available in 1950. This series was developed to take advantage of the high-temperature characteristics of chromium and alumina especially with respect to oxidation resistance, strength, and chemical stability.(1) Studies have been conducted on the use of zirconia as the ceramic phase of a modified metal oxide by the Aeronautical Research Laboratory where thermally and structurally stable materials have been sintered using titanium metal addition to the oxide.(1)

The feasibility of microwave sintering has been investigated previously by Stephanson (4) and others (5,6). Microwave processing could provide a product with less production time and energy, and thus lower cost. Information currently available suggests that microwave sintering is comparable to conventional pro-

duction of ceramic materials. Thus, microwave sintering offers significant advantages in terms of material properties and process times and therefore saving in overall cost.(7)

A specific advantage in terms of material properties gained through microwave sintering is the rapid heating which can offer exceptional densification and grain growth rates. Rapid processing can also reduce segregation of impurities at the grain boundaries thus improving material properties.(6) The sintering of composite material through microwave radiation may possibly be utilized as a densification step in a material processing scheme or may possible be used in place of fabrication processes for ceramic or metal composite materials.

In microwave heating, thermal energy is generated internally for electrically non-conducting materials as well as near the materials surface for metals. This is in contrast to conventional heating in which materials surface is directly heated and thermal energy is conducted to the interior of the specimen.(8) Thus, since microwave energy is absorbed by metal particles (9) and acts transparent or semi-transparent to ceramic materials, a cermet may be produced or densified uniformly through microwave processing. Microwave sintering of cermet composite

materials may offer superior material characteristics and would certainly reduce the time required for that processing step.(7)

This thesis studies the influence of microwave radiation on the fabrication of alumina-titanium cermets. It is organized into initial discussions on microwave radiation, sintering and bonding, and properties of alumina-titanium cermets followed by experimental procedures and analysis.

Experimental procedure consisted of characterizing a microwave oven and adapting it to process materials. Alumina-titanium materials were produced by microwave processing and conventional pressing and sintering techniques. Physical and mechanical properties were determined along with electron microscopy to evaluate the extent of sintering, bonding, and particle sizing in the cermet.

Previous work by Naerheim (10) has found that the addition of Ti to alumina may be an approach for increasing flexural strength of sintered alumina. Titanium was chosen for a metallic additive to alumina since Ti has a high melting point, similar thermal expansion, and has the ability to wet and form a strong bond with alumina.

MICROWAVE RADIATION AND ITS ABSORPTION BY SMALL METAL PARTICLES

The microwave band of the electromagnetic spectrum extends from approximately 300 MHz to 300 GHz. Air traffic control systems, police and military radar, earth-to-satellite television broadcasting systems, long-distance telephone equipment, and microwave ovens all generate microwaves.(11) Microwave radiation is alternatively known as low-energy ultra-high frequency radiation (UHF). The most common frequency for industrial, scientific, medical, microwave ovens, and industrial microwave heating is 2.45 GHz.

The use of microwave energy in the home and industry has become commonplace, but as an advanced tool for the thermal processing of materials has received limited application. A limitation of UHF radiation with respect to materials processing is that many ceramics and glasses are transparent to this wavelength of microwave radiation. Microwave radiation, on the other hand, is readily absorbed by small metal particles. Thus, composite small particle systems consisting of a metallic component dispersed within an insulating host is conductive to electromagnetic radiation.(9) Microwave energy for 2.45 GHz is approximately 1.0 J/mol. For electron excitation this requires

an electrically conducting metal or semiconductor with a very narrow band gap of approximately 1.013E-05 eV. In addition to direct electron excititation, other means of converting microwave energy to thermal energy include coupling the microwave frequency to a materials rotational and vibrational mode excitation of a material. Coupling agents may also be conductive to electromagnetic radiation and may be used to aid in microwave processing.

SINTERING IN ALUMINA-TITANIUM CERMETS

Sintering is defined as the bonding together of particles with heat and possibly pressure to reduce the porosity of the material. In sintering, compacted powders are held at temperatures normally above one-half the melting point for a length of time. Bulk and surface diffusion at the point of contact between grains lowers the total surface area, reduces the bulk volume, and increases strength.(12) The driving force behind sintering is the lowering of the systems total energy; i.e. lowering surface energy by forming large grains and elimination of smaller grains. In other words, decrease in total surface area comes about due to grain contact and growth. Atoms in the small grains are transferred to larger grains with pores being replaced by solid material.(13)

Mass transfer in sintering can be accomplished through one or more of four different mechanisms; viscous or plastic flow, diffusion (along grain boundaries and within grains), vaporization and condensation of surface atoms, and solution and precipitation.(6) Each of these mechanisms may predominate in certain systems with the remaining mechanisms present to a lesser or negligible extent.

BONDING IN ALUMINA-TITANIUM CERMETS

Metal to ceramic bonding may be analyzed by determining wettability of the alumina solid phase by the titanium liquid metal component and the surface energies of the system. The ceramic-metal bonding is a function of the ability of the metal to flow over the ceramic and the bonding strength of the interface. The flow is measured by the contact angle. Bonding strength is measured by the work of adhesion. If a drop of liquid metal is placed in contact with a solid substrate, as in Figure 1, at equilibrium the shape of the drop will depend upon gravitational and surface forces. The contact angle θ

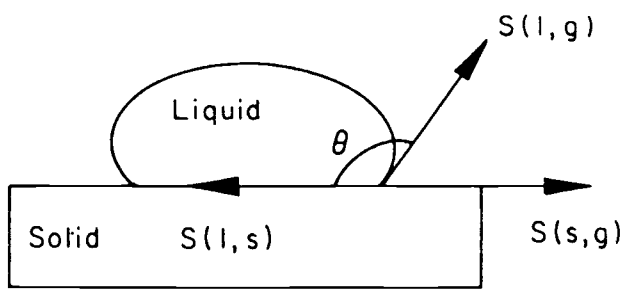

Figure 1. Schematic drawing of a liquid drop on a solid surface.

is measured from the liquid-solid-gas intercept through the liquid phase as shown in Figure 1 and is determined by the magnitude of surface forces present.(1)

An equation can be derived from Figure 1 using vector quantities:

$$s(s,g) = s(l,g)\cos(\theta) + s(s,l)$$

where s(s,g),s(l,g), and s(s,l) are the surface energies of the solid-gas interface, solid-liquid interface, and liquid-vapor interface, respectively. Wettability is defined by the contact angle, θ. As one measures bonding, the work of adhesion, W, can be considered to be the work required to separate a unit area of the solid-liquid interface into two surfaces as defined by the Young-Dupre' equation:(14)

$$W = s(l,g)(1 + \cos(\theta))$$

where W is the work of adhesion, s(l,g) is the surface energy of liquid-gas interface and θ is the contact angle.

Titanium is reported to wet and form a strong bond with alumina.(1,15) Surface tension of Ti at its melting point is equal to 1390 dynes/cm and alumina surface energy at room temperature is equal to 1112 dynes/cm. In contrast, surface tension at room temperature for water equals 73 dynes/cm. Wettability data can be applied to estimate a contact angle for the alumina-titanium system.

Assuming s(s,l) to be zero, 1390 dynes/cm for the surface tension of titanium (s(l,g)), and the value for the surface energy of alumina in a titanium atmosphere (s(s,g)) equal to 1112 dynes/cm, the contact angle θ is given by:

$$s(s,g) = s(s,l) + s(l,g)\cos(\theta)$$

$$1112 = 1390 \cos(\theta) \; ; \; \theta = 37 \text{ degrees}$$

Since the assumed value of zero for s(s,l) is probably in error, a smaller value for the contact angle, calculated from the vectors as in Figure 1, would be expected. With respect to wettability (small contact angles) the larger the solid surface energy compared to the liquid the better the wettability, thus titanium is able to wet and form a strong bond with alumina.

The contact angle of titanium metal on an alumina surface was determined experimentally. A small sample of Ti was place on a flat piece of alumina and heated in a vacuum induction furnace to approximately the melting point of titanium for an hour and furnace cooled. Some reaction occured between the titanium and the alumina (bonding was indicated) and the contact angle was determined to be less than 45 degrees.

PROPERTIES AND THERMODYNAMICS OF ALUMINA-TITANIUM CERMETS

Brittle behavior of alumina ceramics has limited their structural use. Alumina ceramics have poor resistance to mechanical and thermal shock. A possible way to increase strength and toughness in alumina base ceramics is through the addition of a ductile phase to improve the cementing of alumina particles together and hinder crack formation.(10) Titanium was chosen for a metallic additive because Ti has a high melting point, similar thermal expansion, and has the ability to wet and form a strong bond with alumina. Similar properties between the constituents of a composite prevent seperation due to gravity and stresses due to unequal thermal expansion. Properties of alumina and titanium are shown in Table 1.(16)

Table 1. Properties of alumina and titanium.

	Density,g/cc	Average Coefficient Linear Expansion,1/K	Melting Point,C
Alumina	3.8	8.8E-6	2040
Titanium	4.5	8.9E-6	1672

Thermodynamic considerations show a positive free energy of formation (dGf) at temperatures as high as 1265 K as shown in Table 2 for the reaction of Ti with

Table 2. Alumina-titanium thermodynamics.

3Ti(c,l) + Al2O3(a,l) = 2Al(c,l) + 3TiO(a)

T, K	DHf kcal/mol	DGf kcal/mol	Log K
0.00	10.682	10.682	0.000
100.00	10.691	10.660	-23.298
200.00	11.030	10.544	-11.522
298.15	11.400	10.210	-7.484
300.00	11.408	10.206	-7.435
400.00	11.725	9.754	-5.329
500.00	11.981	9.223	-4.031
600.00	12.246	8.680	-3.162
700.00	12.442	8.049	-2.513
800.00	12.714	7.411	-2.025
900.00	13.048	6.740	-1.637
933.61	13.180	6.502	-1.522
933.61	18.341	6.501	-1.522
1000.00	18.569	5.636	-1.232
1100.00	18.913	4.331	-0.861
1156.00	19.113	3.589	-0.679
1156.00	16.062	3.590	-0.679
1200.00	16.368	3.109	-0.566
1265.00	16.828	2.370	-0.409

alumina.(17) This indicated that Ti is stable when placed in contact with alumina for the given temperatures.

MICROWAVE CHARACTERIZATION

The microwave oven used was a Panasonic Model NE-9830 microwave/convection oven operating at 2450 MHz with 700 W of output power (full power). Oven interior was made of stainless steel having 1.32 cubic feet of interior capacity. Figure 2 illustrates the microwave apparatus ready for testing the cermet materials.

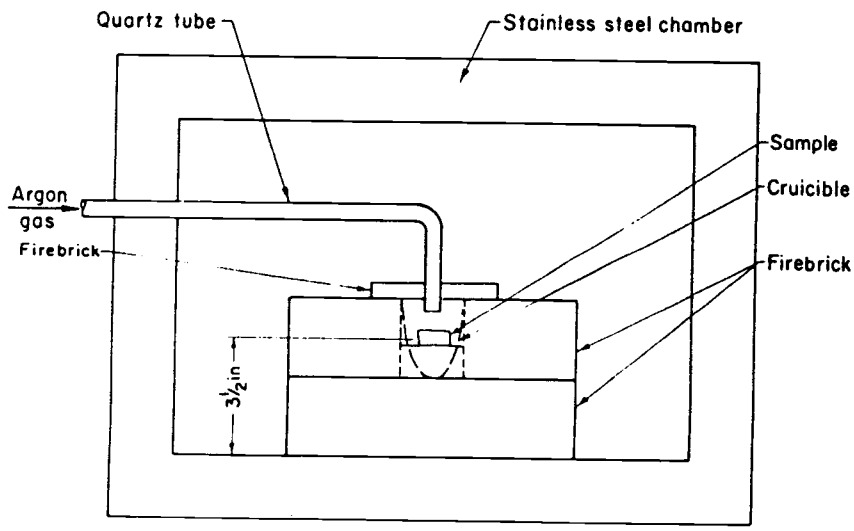

Figure 2. Microwave oven prepared for microwave processing

Characterization of the microwave oven was initiated by determining the location and magnitude of microwave energy or the power profile in the oven as shown in Figure 3. It was assumed that microwave energy would be centered

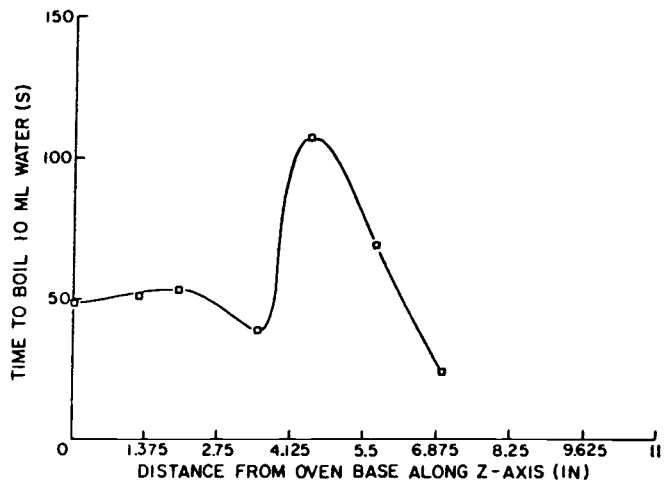

Figure 3. Power profile along z-axis of microwave oven.

in the unit and tests consisted of measuring the time to boil water at various heights from the oven base along a vertical z-axis. Maximum energy input to the sample was determined to be at 3.5-in from the oven base and at the microwave source near the top of the oven. All samples were tested 3.5-in from the base of the oven.

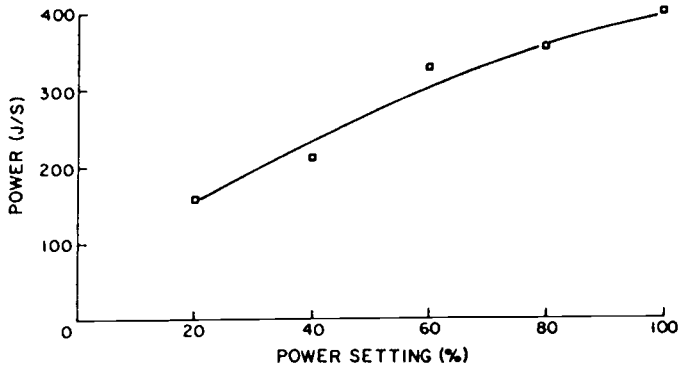

Figure 4. Power setting vs. power output

Dependence of the power setting on power output to the specimen is shown in Figure 4. Power output was determined by heating water at appropriate power settings in an insulated styrofoam container and measuring the temperature before and after microwaving. Temperatures were maintained well below the boiling point of water and power output was then calculated from the following equation:(18)

$$\text{Power Output} = m(Cp)dT/t$$

where Cp is the heat capacity of water (Cp(water, 0 C)) equals 4.2178 kJ/kg-K), m the mass of water (g), t is the time (s), and dT equals temperature change (K).

Maximum power output to the specimen was approximately 400 W at the 100 percent power setting (high) and decreased to less than 200 W at the 20 percent power setting (low). Power output remained constant with respect to weight of water tested.

EXPERIMENTAL PROCEDURE

Experimental procedure consisted of preparing alumina-titanium powder with compositions ranging from 20 to 80 wt. % Ti. Powders were cold compacted and microwave processed for various times up to 1 hour and temperatures measured immediately after processing. Conventional furnace sintered samples were also processed for comparison. Physical properties, such as apparent specific gravity and bulk density, were determined along with mechanical properties, specifically transverse rupture strengths (TRS). Optical and electron microscopic evaluation was conducted on the powder and sintered compacts (cross-sections and fractured surfaces).

Alumina-titanium powder was produced by taking alumina and titanium (each -100 mesh) powders, ball milling in acetone for 4 hours in an alumina lined ball mill with alumina balls, and subsequent drying. Compositions were formulated of 20, 50, and 80 wt. % Ti. Cold compaction of the alumina-titanium powders was undertaken using a hydraulic press (13 ksi die pressure) to approximately 60 % theoretical density. Samples were pressed into 1-in diameter by 1/2-in cylindrical discs and also 0.3-in by 0.3-in by 0.9-in transverse rupture strength (TRS)

specimens. Compaction of the TRS specimens was facilitated through using a binder of 4 wt. % polyethylene glycol on hexane.

Compacted samples were microwave processed in an Ar atmosphere for 15, 30, and 60 minute time periods and allowed to cool slowly in an insulated environment. Temperature measurements were taken with a type K thermocouple immediately after the conclusion of testing. In addition, a sample of alumina-Ti (20 wt. %) was furnace sintered at 1450 C for 1 1/2 hours under Ar and furnace cooled for comparison purposes.

Physical and mechanical properties were determined in accordance with ASTM standards. Physical properties of the samples were determined in accordance with ASTM C373, "Water Absorbtion, Bulk Density, Apparent Porosity, and Apparent Specific Gravity of Fired Whiteware Products".(19) Mechanical properties were accomplished in accordance with ASTM B406 "Transverse Rupture Strength of Cemented Carbides".(20) All mechanical testing was done using a Tinius-Olsen machine at a crosshead speed of 0.05 in/minute.

Electron microscopy was conducted using AMR models 1000 and 1000A scanning electron microscopes in conjunction with a Kevex energy dispersive x-ray analyzer.

DATA SUMMARY AND OBSERVATIONS

The 20 wt. % Ti powder prepared for compaction is shown in Figure 5. Figure 5 consists of a backscatter electron photomicrograph taken with a scanning electron microscope (SEM). The angular bright phase is Ti, as determined by energy dispersive x-ray analysis (EDAX), interdispersed with alumina particles which are more platelike. Particles appear less than 10 microns in size with Ti particle being larger than the alumina particles.

Figure 5. Alumina-titanium (20 wt. %) powder.

An optical photograph taken at 50X of the furnace sintered, 20 wt. % TI sample is shown in Figure 6. The micrograph illustrates the uniform dispersion of the Ti metal in the alumina matrix.

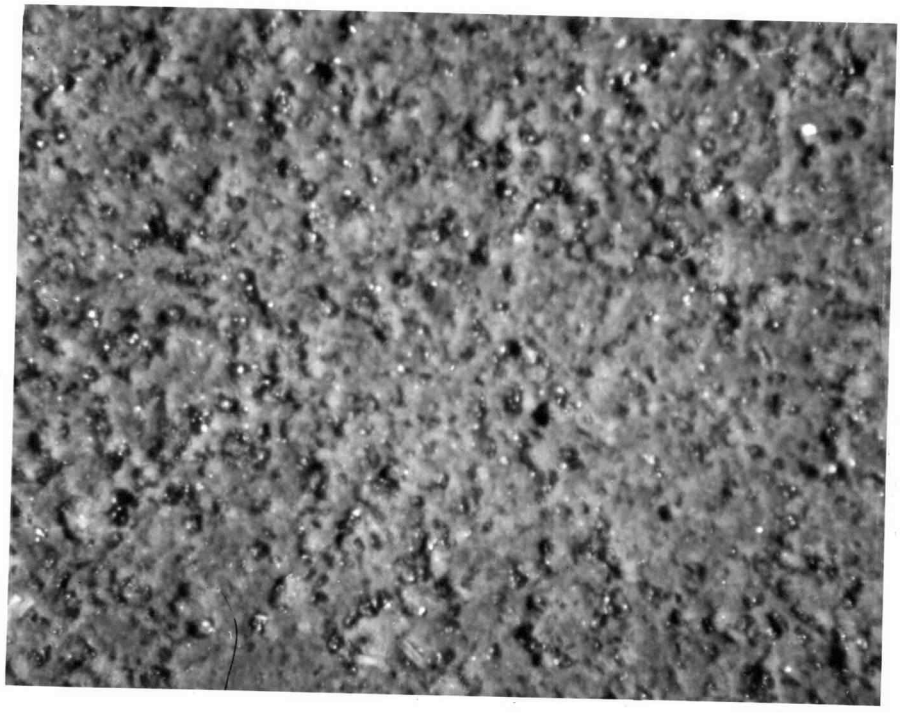

Figure 6. Furnace sintered alumina-Ti (20 wt. %) specimen at 50X.

Alumina-titanium compacted specimens (1-in discs) of 20, 50, and 80 wt. % Ti were microwave processed for either 15, 30, or 60 minutes under Ar at the high power

setting. Temperatures were measured immediately after completion of testing and results are shown in Table 3.

Table 3. Temperature immediately following microwave processing

Sample Composition	Processing Time (min)	T (C)
Alumina-Ti (20 wt. %)	15	385
"	30	872
"	60	902
Alumina-Ti (50 wt. %)	15	785
"	30	905
"	60	978
Alumina-Ti (80 wt. %)	15	635
"	30	925
"	60	1007

Samples appear to have more coupling and absorbed more energy with increased Ti concentration (higher temperatures) and an increase of heat capacity with time microwave processed. Figure 7 and 8 illustrate disc shaped compacts composed of 50 and 80 wt. % Ti, respectively, that have been microwave processed for 15, 30, or 60 minutes. The samples on the left have been processed for 15 minutes, center samples for 30 minutes, and the samples shown on the right for 60 minutes.

Samples showed an increase in alumina concentration at the exterior sample surface, compared to the initial compacts, with increasing time microwave processed. This

Figure 7. Alumina-Ti (50 wt. %) specimens microwave processed for 15, 30, and 60 minutes.

This can be attributed to the coalescence of titanium which was evident at the samples interior. Also some uneven swelling with respect to the sample was noted with increasing temperature in Figures 7 and 8 possibly occurring from the movement of titanium within the sample.

Figure 9 shows a plot of apparent specific gravity vs. time for the microwave processed samples. Apparent specific gravity is based on apparent density, which is mass per apparent volume or mass per actual material

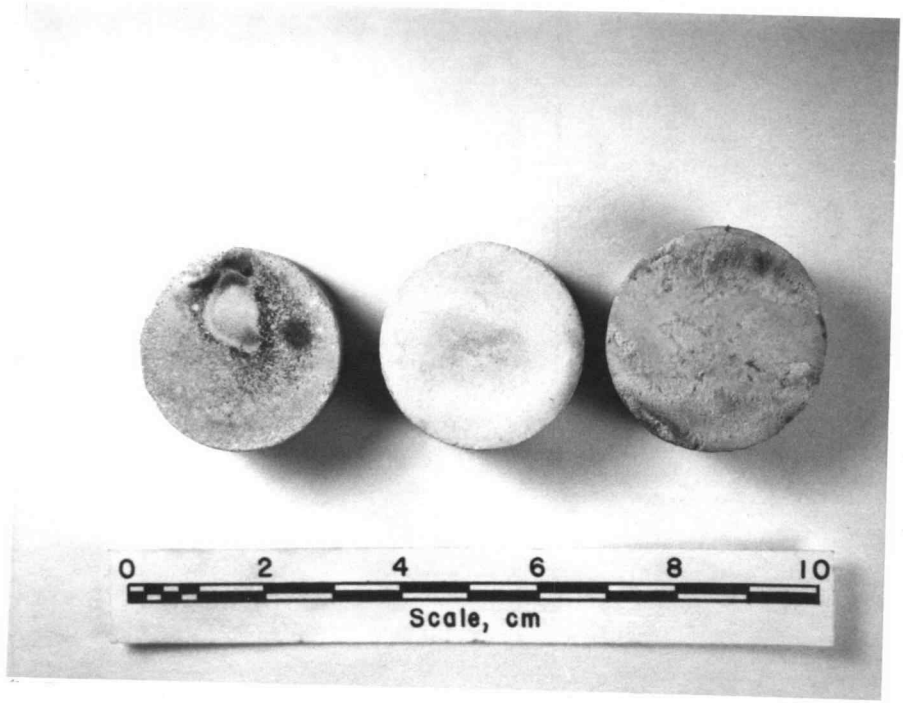

Figure 8. Alumina-Ti (80 wt. %) specimens microwave processed for 15, 30, and 60 minutes.

and closed pores, compared to the density of water. With increasing microwave processing times an increase in the apparent specific gravity is noted foreach composition processed. This increase was approximately linear with respect to processing time for each Ti concentration processed. Bulk density is shown in Figure 10 as a function of processing times. Bulk density is mass per total volume, which includes all pores as well as occupied space. Bulk density decreases with microwave

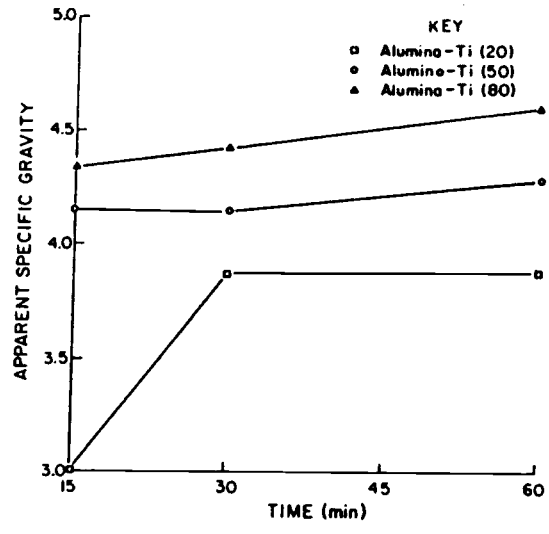

Figure 9. Apparent specific gravity vs. microwave processing time.

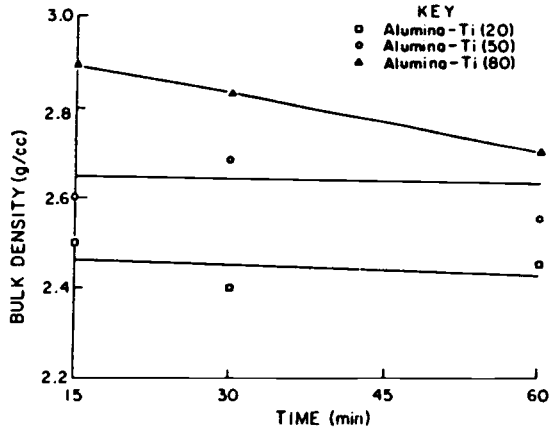

Figure 10. Bulk density vs. microwave processing time.

processing time for the alumina-titanium (80 wt. %) samples and appears relatively constant for the other compositions tested. The resulting bulk density of the furnace processed specimen equalled 2.44 g/cc compared to microwave processed material (20 wt. % Ti) bulk density ranging from 2.4 to 2.5 g/cc.

TRS specimens were compacted from 50 and 80 wt. % Ti compositions. Figure 11 shows prepared TRS specimens of 50 wt. % Ti microwave processed for 15, 30, and 60 minutes as shown from lift to right in Figure 11.

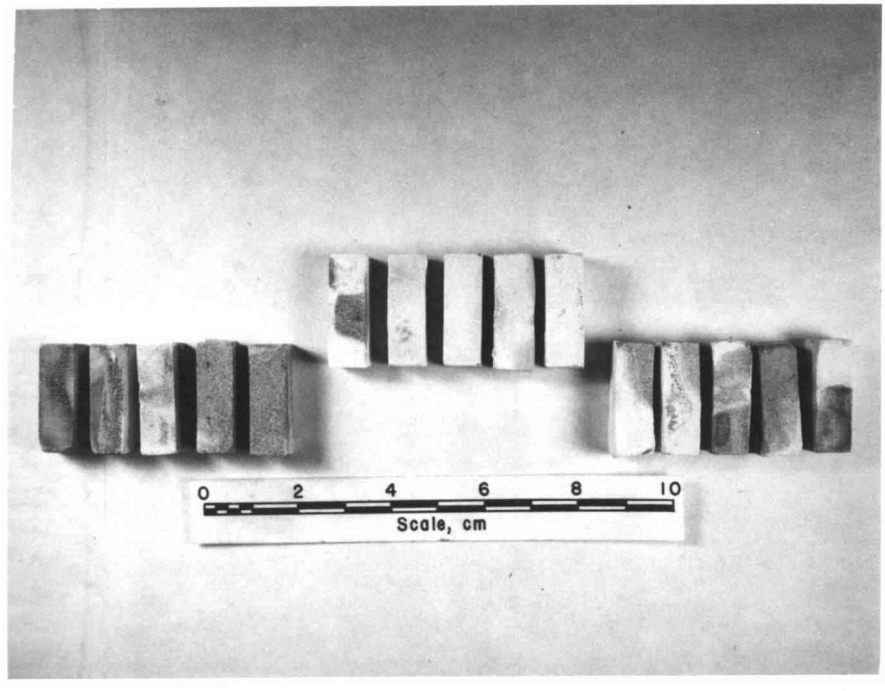

Figure 11. TRS specimens of alumina-Ti (50 wt. %) microwave processed for 15, 30, and 60 minutes.

TRS results are shown as a function of time microwave processed in Figure 12 for 50 and 80 wt. % Ti samples (raw data is listed in the appendix). Figure 12 consists of a plot of mean transverse rupture strengths (95 % confidence interval vs. time microwave processed. Mean transverse rupture strengths equalled 458, 398, and 293 psi for the 50 wt. % Ti samples and 909, 958, and 1313 psi for the 80 wt. % Ti samples tested for 15, 30, and 60 minutes, respectively. Samples before processing had

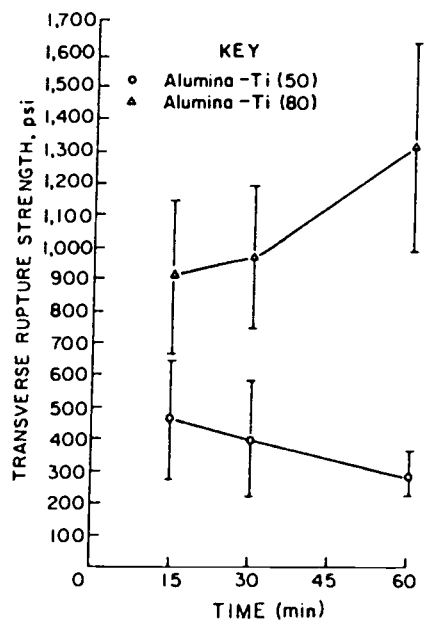

Figure 12. TRS results vs. time processed.

negligible transverse rupture strength. A significant increase in strength was noted for the 80 wt. % Ti samples compared to the 50 wt. % Ti samples. Also, longer microwave processing time appears to have the affect of increasing the strength of the 80 wt. % Ti samples and decreasing the strength of the 50 wt. % Ti samples.

MICROSTRUCTURAL EVALUATION

Comparison of the alumina-Ti (20 wt. %) microwave processed samples with 15 minute processing time to the furnace sintered sample (1 1/2 hours at 1450 C) is facilitated through the use of Figures 13 and 14. These figures show a fracture surface through backscatter electron display using the SEM of samples furnace treated and microwave processed. Ti is represented in the figures as the light phase and alumina the darker phase as determined by energy dispersive x-ray analysis (EDAX). A

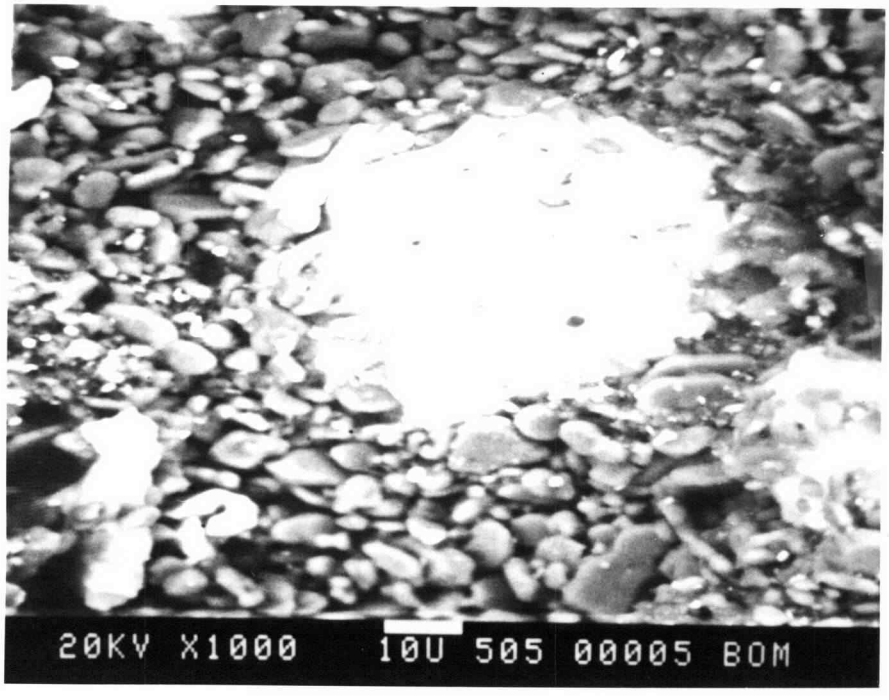

Figure 13. Alumina-Ti (20 wt. %) fractured surface of specimen microwave processed for 15 minutes.

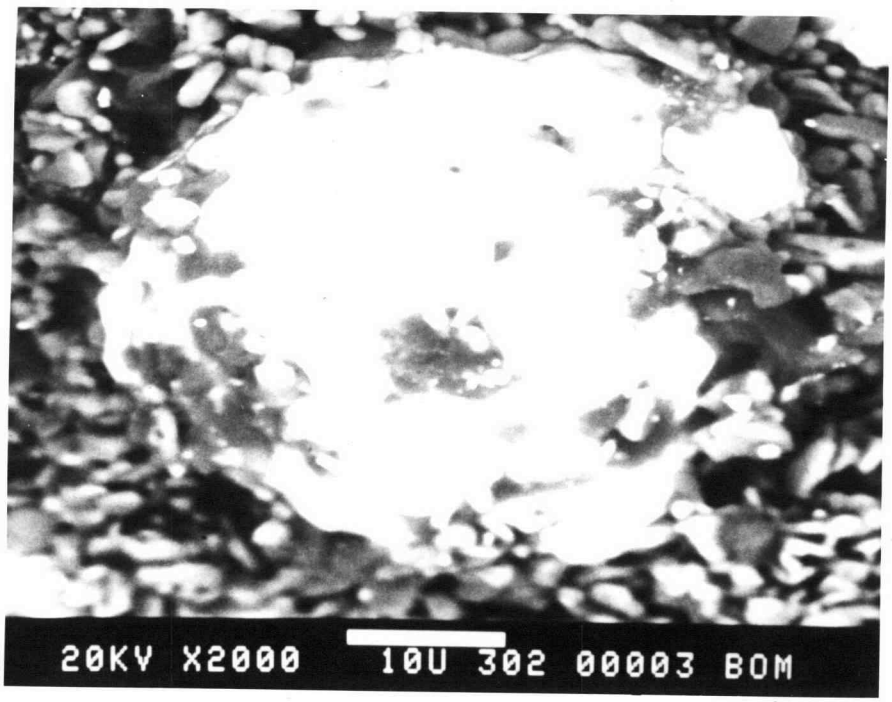

Figure 14. Alumina-Ti (20 wt. %) fractured surface of furnace sintered specimen.

sintering and coalescence of the Ti (from approximately 10 micron in powder form) is noted in either sintering preparation process along with similar bonding for the furnace sintered and microwave processed sample. The extent of sintering appears to be greater for the furnace sintered sample with the size of the Ti phase present in the photomicrographs being approximately 50 % larger in the furnace sintered sample.

A secondary electron display using the SEM of an alumina-Ti (80 wt. %) sample at 100X is shown in Figure

15. An increased magnification photomicrograph (1000X) of the same characteristic region is shown in Figure 16. Both figures illustrate the uniform dispersion of Ti and alumina in the structure. Alumina platelets are wetted

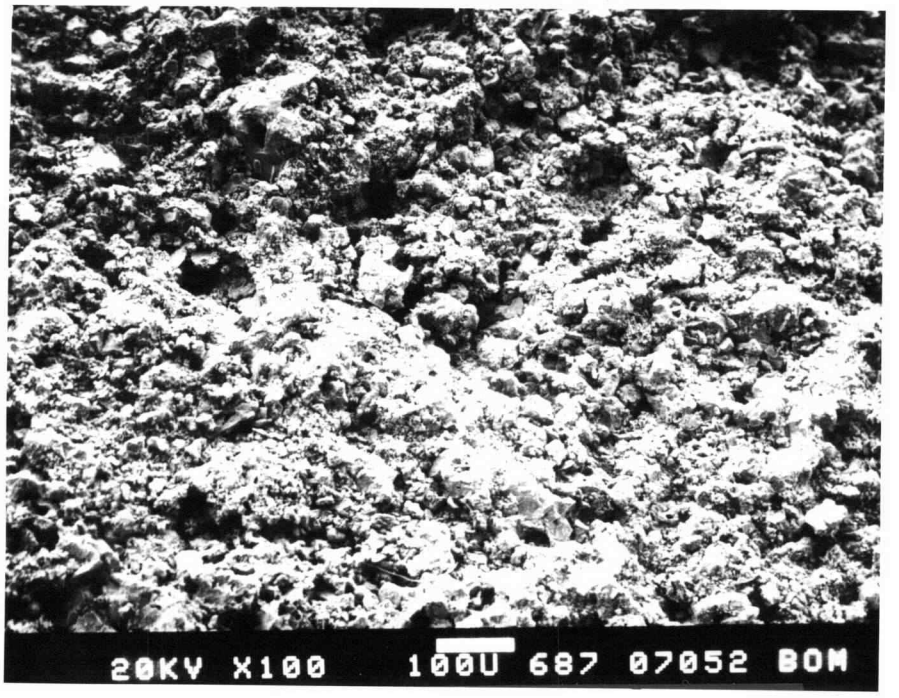

Figure 15. Alumina-Ti (80 wt. %) at 100X.

and bonded throughout the matrix to the Ti. Figure 17 shows an alumina-Ti (20 wt. %) sample at 1000X also taken with a secondary electron display. The alumina platelets are seen more clearly bonded to the larger Ti particles.

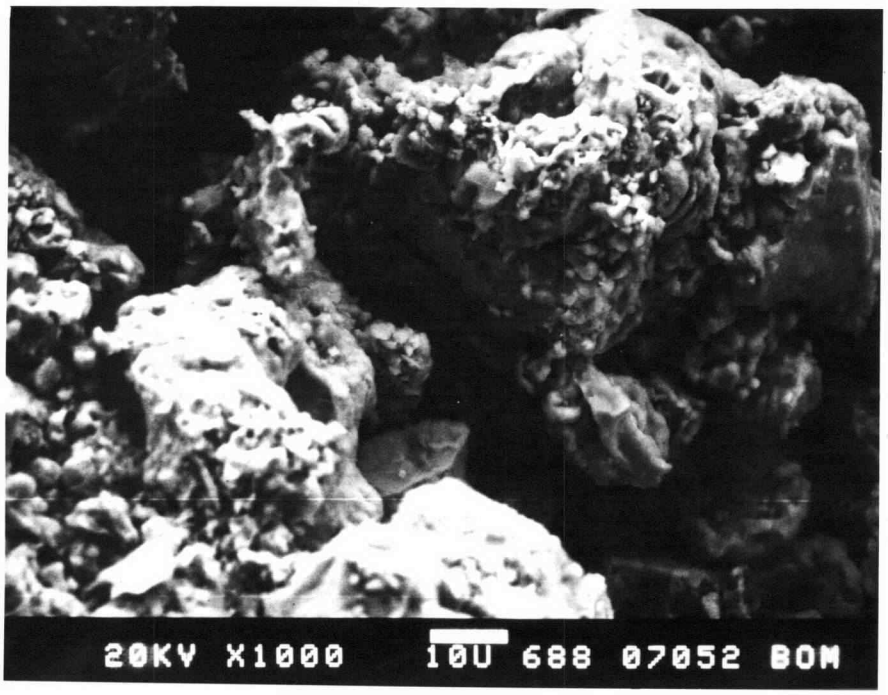

Figure 16. Alumina-Ti (80 wt. %) at 1000X.

One representative Ti particle is shown at 2000X in Figure 18 where the bonding of the Ti to the alumina can be observed. The titanium particle is greater than 10 microns in size.

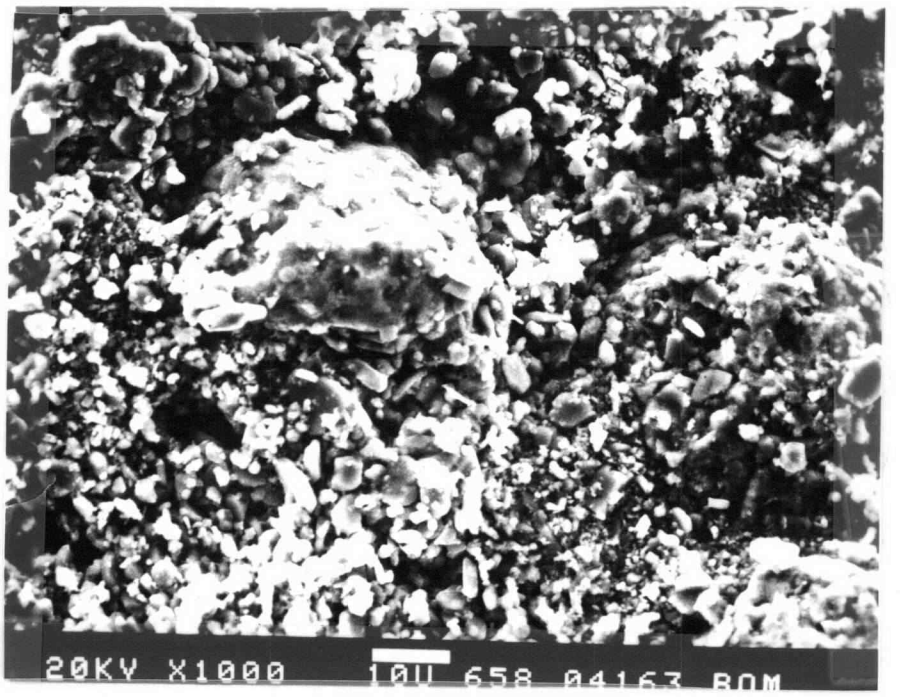

Figure 17. Alumina-Ti (20 wt. %) at 1000X.

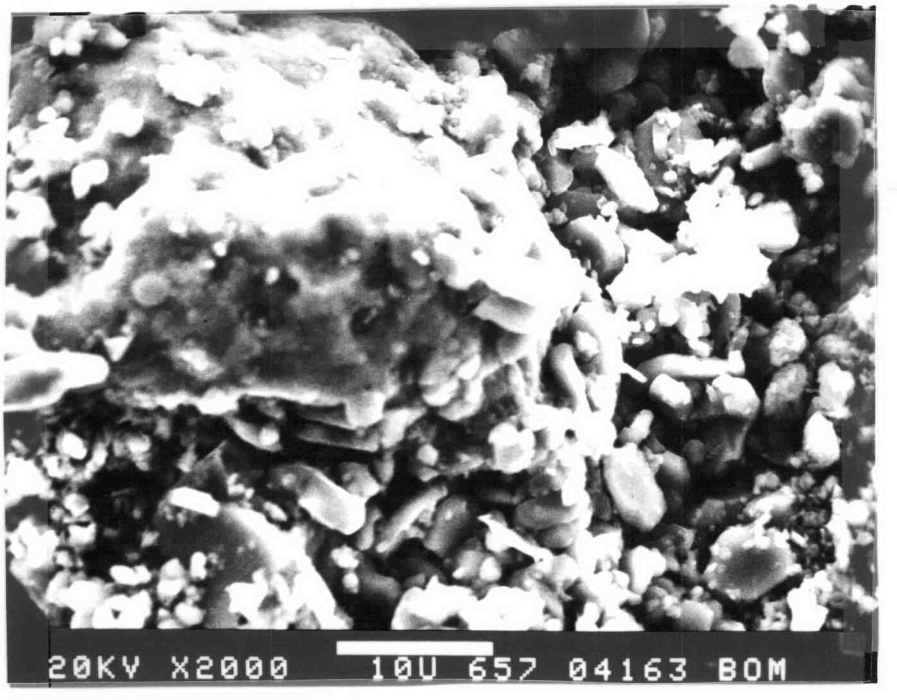

Figure 18. Alumina-Ti (20 wt. %) at 2000X.

DISCUSSION

Microwave sintering has been investigated for alumina-titanium cermets with compositions ranging from 20 to 80 weight percent titanium. Samples microwave processed in an industrial microwave oven have been shown to posses similar microstructures to conventionally sintered samples. Titanium has been shown, through microstructural and fracture surface evaluation, to be well dispersed and to wet and form a good bond with alumina during the microwave sintering process. Maximum values for physical properties such as bulk density and apparent specific gravity are obtained in a relatively short time, approximately 15 minutes, for the microwave sintering process. Samples mechanically tested, after 15 minutes of microwave processing, have a minimum transverse rupture strength of 450 psi.

CONCLUSIONS

A microwave oven can be easily adapted into a bench scale microwave processing unit.

High temperature heating can be achieved rapidly through the microwave sintering process.

Coupling and densification of alumina-titanium cermets can be accomplished through microwave processing.

Microwave sintering of cermets is possible and could save time and produce improved material characteristics.

An alumina-titanium cermet product can be produced from cold compaction and microwave sintering having a bulk density of at least 2.4 g/cc and transverse rupture strength of 450 psi after 15 minutes of testing.

Electron microscopy illustrates a coalescence of the Ti metal upon microwave sintering with the Ti being well dispersed throughout the matrix. Alumina appears well bonded to the titanium within the structure.

SUGGESTED FUTURE STUDIES

Suggested future studies include:

Isostatic pressing of starting materials to approach theoretical density on onset of microwave processing. (This has been accomplished with a sample of ZrO_2-Ni (50 wt. %) which after microwave processing resulted in a dense material with extensive cracking).

Vary power input for microwave processing to optimize processing conditions and reduce cracking.

Use of a variable microwave source to improve coupling between the materials and the source. Also, use materials with increased dielectric properties for improved coupling.

Microwave process in conjunction with pressure such as in hot isostatic pressing to provide a combination of formation techniques.

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APPENDIX

APPENDIX

Table A1. Microwave power center determination.

Location in oven	Time for 10 ml water to boil(s)
Center base	48
Center 1 1/4" up	51
Center 2" up	53
Center 3 1/2" up	39
Center 4 1/2" up	107
Center 5 3/4" up	69
Center 7" up	24

Table A2. Power setting vs. power output for 100 ml water

Time(s)	Initial T(C)	Final T(C)	Setting	Power(W)
30	19	47	High	412.8
60	19	75	High	400.1
60	19	69	MHigh	354.5
60	18	64	Med	327.4
60	18	48	MLo	211.6
60	21	43	Lo	157.9

Table A3. Power vs. weight of water heated

Time(s)	Initial T(C)	Final T(C)	Water(g)	Power(W)
30	23	36	178.6	326.4
30	23	38	143.3	302.2
30	23	47	109.5	369.5
30	23	51	87.9	345.8

Table A4. Physical properties of alumina-titanium cermets

Description	Sat. Wgt.(g)M	Sus. Wgt(g)S	Dry Wgt.(g)D	Ext. Vol.(cc)V	Bulk Density(g/cc)B	App. S.G. T	App. Porosity(%)P	Water Absorption(%)A
Al_2O_3-Ti(20)15	3.2	2.0	3.0	1.2	2.50	3.00	16.7	6.7
" 30	24.2	15.5	20.9	8.7	2.40	3.87	37.9	15.8
" 60	17.8	11.5	15.5	6.3	2.46	3.88	36.5	14.8
Al_2O_3-Ti(50)15	23.2	15.4	20.3	7.8	2.60	4.14	36.5	14.0
" 30	23.4	15.7	20.7	7.7	2.69	4.14	35.1	13.0
" 60	25.7	17.0	22.3	8.7	2.56	4.28	39.1	15.2
Al_2O_3-Ti(80)15	23.2	16.0	20.8	7.2	2.89	4.33	33.3	11.5
" 30	24.9	17.1	22.1	7.8	2.83	4.42	35.9	12.7
" 60	26.5	18.0	23.0	8.5	2.71	4.60	41.2	15.2

V = Exterior Volume,cc = M - S
P = Apparent Porosity, % = ((M - D)/V)(100)
A = Water Absorption, % = ((M - D)/D)(100)
T = Apparent Specific Gravity = D/(D - S)
B = Bulk Density, g/cc = D/V

Table A5. Transverse Rupture Strength Test Data

Sample	Thickness(in)h	Width(in)b	Max Load(in)P	TRS(psi)
AT(50)15-1	0.293	0.304	19.00	410
" 2	0.300	0.310	17.75	358
" 3	0.299	0.309	33.50	682
" 4	0.305	0.316	17.00	325
" 5	0.292	0.307	24.00	516
AT(50)30-1	0.312	0.331	15.75	275
" 2	0.295	0.317	28.00	571
" 3	0.291	0.314	24.50	518
" 4	0.316	0.332	22.50	382
" 5	0.314	0.316	13.50	244
AT(50)60-1	0.298	0.307	17.25	356
" 2	0.293	0.319	15.75	323
" 3	0.310	0.313	12.75	238
" 4	0.298	0.315	15.75	317
" 5	0.311	0.311	12.25	229
AT(80)15-1	0.289	0.305	52.00	1148
" 2	0.292	0.304	35.00	760
" 3	0.296	0.305	48.75	1026
" 4	0.288	0.304	42.25	943
" 5	0.289	0.307	30.50	669
AT(80)30-1	0.292	0.310	58.25	1240
" 2	0.293	0.310	35.25	745
" 3	0.292	0.311	47.50	1008
" 4	0.296	0.311	44.25	913
" 5	0.295	0.310	42.50	886
AT(80)60-1	0.300	0.314	72.25	1438
" 2	0.298	0.317	55.50	1109
" 3	0.295	0.316	83.00	1698
" 4	0.295	0.318	61.75	1255
" 5	0.306	0.315	55.75	1063

TRS = $(3/2)PL/bh^2$, psi
Crosshead rate = 0.05 in/min
Span (L) = 0.375 in