Advances and Benefits of Newly Developed Ceramics for Industrial Applications

By

Zoltan Z. Kish, *Ph.D.*

kishzz@hotmail.com

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1. Summary

In response to the increase demands of higher performance materials for industrial applications, a novel patented materials process **- ASPRO™ Conversion Technology** has been developed at ATS Spartec – AHCS Inc. (a division of ATS Spartec Inc.) to produce new advanced ceramics with superior properties. The process transforms high dense monolithic ceramic components to a new state by applying a combination of temperature and pressure. Potentially, the ASPRO™ Conversion Technology can be applied to any solid materials with near full density, including materials with nanostructure, and improve their properties. The ASPRO™ conversion technology is able to modify the atomic structure and chemical bonds in the treated materials leading to the unique combination of properties. These include high density and high thermal shock resistance, high level of toughness, hardness, chemical and wear resistance, and modified thermal and electrical properties required by structural and electronic applications. The advances made through developed materials process now overcome the previous technical weaknesses of components to meet criteria for ceramics in internal combustion engines and enable the use of **low-cost alumina ceramics** as engine components.

The ASPRO™ treated alumina cylinder liners have been successfully installed and tested in the internal combustion engines, which can lead to low emission and efficient vehicles. The developed ceramic liners have higher strength and the extremely low friction and smooth surface in comparison to metal cylinder liners. The ASPRO™ Conversion Technology offers low-cost alumina ceramic components for substitution of metals, expensive ceramic materials (e.g., silicon carbide, silicon nitride) and unreliable ceramics (e.g., zirconia, aluminum titanate) due to the phase transformation or decomposition at high temperature cycling. The use of the ASPRO treated ceramic components can improve performances of internal combustion engine components, reduce emissions and fuel consumption. Some of these components can be used as cylinder liners, cylinder head liners, piston parts, turbocharger liners, valve bodies, valve seats, catalyst substrate, and mechanical seal. The converted ceramic materials provide reliability, efficiencies, enhanced material properties, better start-up in cold conditions, less noise, high deformation stability, high oxidation/corrosion resistance, high temperature operation, weight reduction, and cost savings by using the low-cost alumina instead of more expensive ceramic alternatives. Especially, the potential benefit of the ASPRO™ treated ceramic components is evident for diesel engine applications. Our resent test results indicate that the ASPRO™ Conversion Technology can be applied to enhance the required properties for ceramic cutting tools, and as a result the ASPRO™ treated ceramic cutting tool inserts can offer significant advantages in cutting speed, quality, maintenance requirements and longevity for machining hard materials. The ASPRO™ treated ceramics have been tested also as ceramic lining of a "Shot-Sleeve", the component that transfers the molten aluminum from the crucible to the mold. The ASPRO™ process could modify the properties, which are important to enhance the function of electronic components. Therefore the ASPRO™ Conversion Technology exhibits the potential to extend the performance of advanced ceramic materials and subsequent products in structural uses, including engines, pumps, power-generating equipment, cutting tools, materials processing, and electronic applications while increasing efficiencies and achieving very favorable cost/benefit ratios.

Applications of ASPRO™ Treated Ceramic Materials

Alumina Ceramic Engine Components

- Cylinder Liners
- Piston Bodies
- Valves
- Turbo Charger Liners
- Catalyst Substrate

Materials Processing

- Cutting Tools
- Crucibles
- Bearings
- Pumps
- Mechanical Seals
- Metal Casting

Electronics

- Insulators
- Ceramic Packaging of Integrated Circuits
- Capacitances
- Ceramic Sensors
- Magnetic Ceramics
- Semiconductors
- Superconductors

ATS Spartec – AHCS Inc.

2. Introduction

Industry demands high performance materials that exhibit high thermal shock and corrosion/oxidation resistance, superior mechanical, electrical, optical, and magnetic properties. The application areas include automotive and aerospace components, machining tools, wear components, chemical and metal processing, medical and electronic products. Ceramics can fulfill the demand of industry in high performance materials. Ceramics are inorganic materials consisting of metallic and nonmetallic elements and can be divided into two classes: traditional and advanced ceramics. Traditional ceramics are made of a significant clay component and include the following types: pottery, whiteware, glazes and porcelain enamels, structural clay products, cement and concrete, refractory bricks. Advanced ceramics are distinguished by their high chemical purity, careful processing and high values of the useful properties for advanced structural and electronic applications, including for examples: alumina, zirconia, silicon nitride, silicon carbide, aluminum nitride, semiconductors, high-temperature superconductors, etc. There is a growing demand for ceramic materials to serve in high temperature structural applications mainly due to their high melting point and excellent mechanical strength at high temperature. Applications for advanced ceramic materials can provide significant saving, increasing productivity, ease ecological problems, and expand the product markets. Especially, manufacturing of advanced heat engines featuring high reliability, optimum power and minimum fuel consumption has subsequently led to the use of ceramics. However, ceramics usually exhibit poor thermal shock resistance, which limits their use as structural components in, for example, heat engine and turbine. If the current ceramic technology is used, there are limitations to alter the existing material properties. Ceramics exhibiting high thermal shock resistance are typically those with correspondingly low level of density, high porosity, and low mechanical strength and wear resistance. Therefore it is important to develop inexpensive ceramic materials that can meet the major selection criteria for applications, which include enhanced thermal, physical, electrical properties, and high mechanical performances.

3. Objective

The purpose at ATS Spartec – AHCS Inc. has been to develop a new materials process - **ASPRO™ Conversion Technology,** new advanced ceramic materials with enhanced properties to extend the use of ceramic materials for a new field of applications, including alumina ceramic engine components, ceramic cutting tool inserts, materials processing, medical, and electronics.

4. Technology

A novel patented materials process - ASPRO™ Conversion Technology has been developed at ATS Spartec – AHCS Inc. to produce high performance low-cost ceramics to meet industrial requirements for materials superior properties[1-21]. The ASPRO™ process is a new and revolutionary technology for treating finished components. The process transforms high dense monolithic ceramic components to a new state by applying a combination of temperature and pressure. The ASPRO™ conversion technology is able to modify the atomic structure and chemical bonds in the treated materials leading to the unique combination of properties [1-21]. These include high density and high thermal shock resistance, high level of toughness, hardness, chemical and wear resistance, and modified thermal and electrical properties required by structural and electronic applications. Potentially, the ASPRO™ Conversion Technology can be applied to any solid materials with near full density, including materials with nanostructure, and improve their properties. Successful experimental trials of ASPRO™ treated alumina liners in the internal combustion engine and in the shot sleeve for casting of molten aluminum have provided important evidence of the effectiveness of the technology responding to extreme thermal shock. This technology creates new advanced ceramic materials with enhanced properties to extend the use of ceramic materials for a new field of applications, including alumina ceramic engine components, chemical processing, and electronics.

A new model of material system has been used in the development of ASPRO™ Conversion Technology [22, 23] (Fig.1). The state of a material system depends upon the established equilibrium of the interconnections among the different chemical and physical factors, such as type and structure of the atoms, chemical bonds and physico-chemical interactions. The physico-chemical interactions are determined as interactions among the particles in the material system by the substance and energy that can be modified by pressure, temperature, radiation or any other type of energy and duration time of applied energy. Accordingly, these interconnections determine the state of matter, i.e. the state of substance, which means a kind of substance and its form of existence: polycrystalline, single crystal, glass, liquid, and gas states. Every state of substance has corresponding crystal structure or space location of the particles (atoms, ions, molecules) for amorphous solids and parameters of properties. Finally, material crystal structure and parameters of properties determine a field of practical applications.

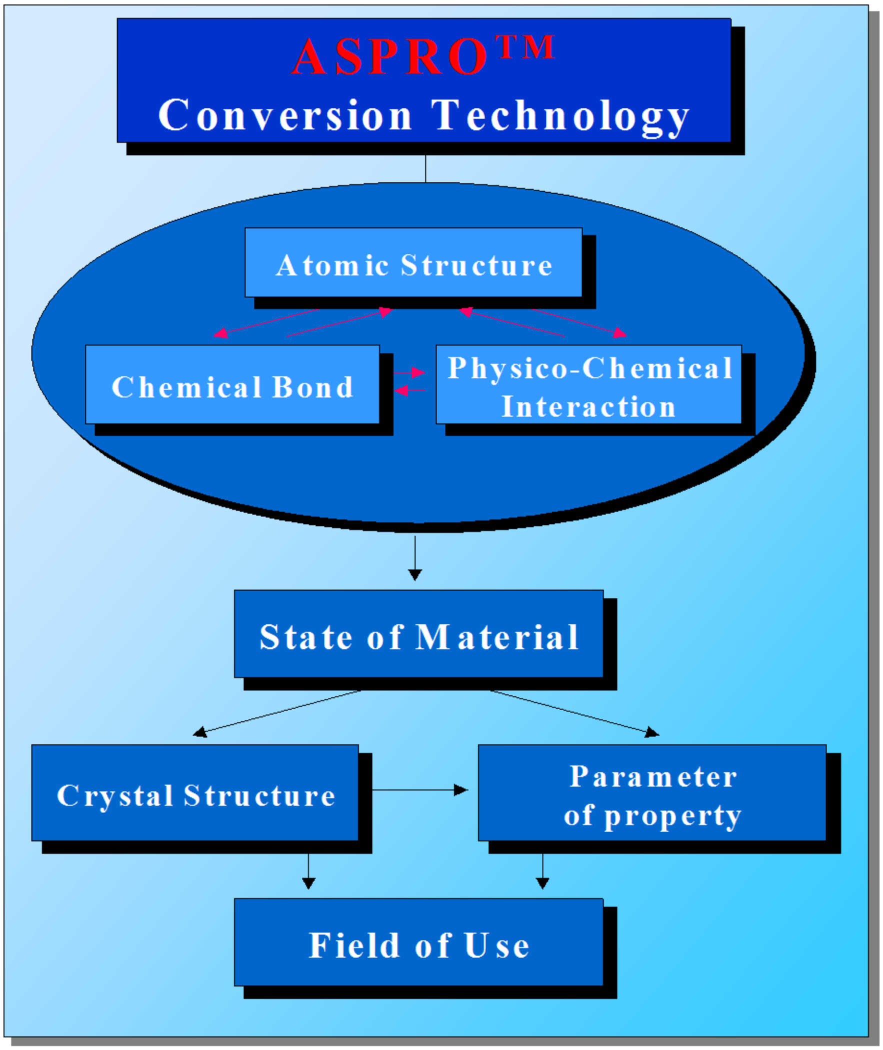


Fig. 1. Interactions in the Materials System treated by ASPRO™ Conversion Technology.

The understanding of the Material–Process–Property–Application relationships, as interconnections among the type and structure of the atoms, chemical bonds and physico-chemical interactions in the material systems and resulting materials properties, is very important in development of new processes and new materials with enhanced properties for new field of applications. Based on this research and development approach, the optimum technological treatment conditions can be determined in order to get materials in corresponding forms and produced low-cost alumina based ceramic with appropriate properties for corresponding industrial applications. This method of the research and development can be used to any materials process and product development. If the market requires a new material for a specific application, the interaction in the material system could be analyzed in order to determine appropriate materials compositions, state, processes, properties, and design.

5. Testing

Finished ceramic materials, such as alumina, aluminum nitride and silicon nitride, treated by the ASPRO™ process, have been subjected to a battery of characterization tests. The tests, such as physical, thermo-physical, mechanical testing, chemical, microstructure and unique physico-chemical analyses as neutron diffraction, photothermal radiometry, X-ray diffraction and X-ray absorption fine structure analysis using synchrotron radiation, were completed. The properties of ASPRO™ treated ceramic materials and developed engines have been analyzed by leading scientists and engineers at ATS Spartec – AHCS Inc., foremost scientific research institutions in Canada, and engine manufactures in the U.S.A. The research and development of the ASPRO™ treated materials has been supported by the National Research Council of Canada, Materials and Manufacturing Ontario, and the Ontario Centre for Environmental Technology Advancement.

6. Materials and Prepared Samples

Alumina ceramic liners with three different compositions, 90% (Series L), 96% (Series M), and 98.5% (Series P) Al_2O_3, have been researched. Original ceramic liners were prepared at CoorsTek with dimensions, O.D.= 86.59 mm, I.D.=77.04 mm, Length = 107.76 mm.

The materials had been subjected to four various conditions of the ASPRO™ Treatment and noted by the samples designations in the Table 1.

Table 1.

ASPRO™ Treated Ceramic Sample Sets

Materials	Samples				
	Original	Condition 1	Condition 5	Condition 6	Condition 7
	Marked	Marked	Marked	Marked	Marked
90% Al_2O_3	L-0	L-1	L-5	L-6	L-7
96% Al_2O_3	M-0	M-1	M-5	M-6	M-7
99% Al_2O_3	P-0	P-1	P-5	P-6	P-7

7. Properties

Original (L-0, M-0, P-0) and treated alumina samples at different conditions by ASPRO process have been subjected to a battery of characterization tests. A unique combination of properties for the L, M, and P sets of alumina samples are presented in the Tables 2, 3, and 4 [3].

Properties of ASPRO^{TM} Treated Alumina Ceramics

(90% Al_2O_3**)**

Table 2.

Properties	**Units**	**L-0 Alumina 90% Al_2O_3**	**L-1 Alumina 90% Al_2O_3**	**L-5 Alumina 90% Al_2O_3**	**L-6 Alumina 90% Al_2O_3**	**L-7 Alumina 90% Al_2O_3**	**Measurement Uncertainty**
Density, 20 °C	g/cm^3	3.590	3.583	3.582	3.599	3.587	± 0.1%
Elastic Modulus, 20 °C	GPa	274	273	276	278	276	± 0.5%
Poisson's Ratio		0.223	0.220	0.229	0.215	0.217	± 0.5%
Hardness	GPa	11.1	11.0	11.3	10.5	11.4	± 3.3%
Fracture Toughness	MPa m$^{1/2}$	3.1	3.3	3.7	3.7	3.2	± 20%
Thermal Shock Resistance, ΔTc	°C	<300	>650	-	-	>650	
Thermal Expansion Coefficient	1x10^{-6}/°C						± 3-5%
35-300°C		7.70	7.66	-	7.08	7.68	
300-500°C		7.76	7.48	-	7.00	7.62	
500-800°C		7.90	7.86	-	7.98	6.86	
Thermal Conductivity	W/m K						± 4-5%
20°C		16.82	16.82	15.71	14.03	16.36	
100°C		14.51	13.95	13.39	12.08	13.66	
200°C		12.39	11.49	11.30	10.29	11.33	
300°C		10.81	9.78	9.78	8.96	9.67	
Specific Heat	J/kg K						± 2.5%
20°C		701.9	702.7	714.2	725.7	660.7	
100°C		846.5	848.4	864.7	830.6	786.7	
200°C		966.0	962.5	952.4	894.3	849.4	
300°C		1057.8	1037.8	994.2	903.6	900.0	
Corrosion/oxidation Resistance		Very High	Very High	Very High	Very High	Very High	
Maximum Use Temperature	°C	1700	1700	1700	1700	1700	

Notes:

L-0 is original alumina ceramics prepared at CoorsTek without ASPRO treatment;
L-1 is ASPRO treated alumina ceramics at Condition 1;
L-5 is ASPRO treated alumina ceramics at Condition 5;
L-6 is ASPRO treated alumina ceramics at Condition 6;
L-7 is ASPRO treated alumina ceramics at Condition 7.

Properties of ASPRO Treated Alumina Ceramics

(96 wt.% of Al_2O_3)

Table 3.

Properties	**Units**	**M-0 Alumina 96 wt. % Al_2O_3**	**M-1 Alumina 96 wt. % Al_2O_3**	**M-5 Alumina 96 wt. % Al_2O_3**	**M-6 Alumina 96 wt. % Al_2O_3**	**M-7 Alumina 96 wt. % Al_2O_3**	**Measurement Uncertainty**
Density, 20 °C	g/cm^3	3.712	3.716	3.610	3.708	3.717	± 0.1%
Elastic Modulus, 20 °C	GPa	320	319	297	319	320	± 0.5%
Poisson's Ratio		0.216	0.217	0.229	0.220	0.225	± 0.5%
Hardness	GPa	12.1	12.3	11.3	12.1	12.4	± 3.3%
Fracture Toughness	$MPa \cdot m^{1/2}$	4.0	3.4	5.6	3.8	3.4	± 20%
Thermal Shock Resistance, ΔTc	°C	<300	>650	>650	-	>650	
Thermal Expansion Coefficient	$1x10^{-6}$/°C						± 3-5%
35-300°C		7.36	7.15	8.05	7.89	7.71	
300-500°C		8.05	6.94	8.02	8.03	7.72	
500-800°C		8.71	8.54	7.40	8.26	7.98	
Thermal Conductivity	W/m·K						± 4-5%
20°C		23.68	21.49	21.83	22.84	21.64	
100°C		18.86	17.64	18.71	17.57	18.42	
200°C		15.03	14.41	15.88	13.64	15.53	
300°C		12.49	12.18	13.79	11.15	13.42	
Specific Heat	J/kg·K						± 2.5%
20°C		724.7	712.3	790.0	660.8	637.8	
100°C		871.1	868.0	934.5	770.4	743.8	
200°C		989.5	986.5	1047.3	834.1	825.4	
300°C		1064.7	1070.4	1118.7	844.6	862.8	
Corrosion/oxidation Resistance		Very High	Very High	Very High	Very High	Very High	
Maximum Use Temperature	°C	1700	1700	1700	1700	1700	

Notes: M-0 is original alumina ceramics prepared at CoorsTek without ASPRO treatment;
M-1 is ASPRO treated alumina ceramics at Condition 1;
M-5 is ASPRO treated alumina ceramics at Condition 5;
M-6 is ASPRO treated alumina ceramics at Condition 6;
M-7 is ASPRO treated alumina ceramics at Condition 7.

Properties of ASPRO™ Treated Alumina Ceramics
(98.5% Al_2O_3)

Table 4.

Properties	**Units**	**P-0 Alumina 98.5% Al_2O_3**	**P-1 Alumina 98.5% Al_2O_3**	**P-5 Alumina 98.5% Al_2O_3**	**P-6 Alumina 98.5% Al_2O_3**	**P-7 Alumina 98.5% Al_2O_3**	**Measurement Uncertainty**
Density, 20 °C	g/cm^3	3.860	3.857	3.850	3.859	3.863	± 0.1%
Elastic Modulus, 20 °C	GPa	362	367	351	383	367	± 0.5%
Poisson's Ratio		0.236	0.222	0.237	0.229	0.223	± 0.5%
Hardness	GPa	14.1	14.1	14.5	13.7	14.8	± 3.3%
Fracture Toughness	$MPa\ m^{1/2}$	2.7	2.6	2.6	2.8	2.6	± 20%
Thermal Shock Resistance, ΔTc	°C	<300	>650	-	-	>650	
Thermal Expansion Coefficient	$1x10^{-6}/°C$						± 3-5%
35-300°C		7.96	7.90	7.86	7.68	7.74	
300-500°C		7.35	7.62	7.61	7.75	7.88	
500-800°C		7.27	7.88	7.71	7.84	8.12	
Thermal Conductivity	W/m K						± 4-5%
20°C		38.55	28.89	37.91	31.95	28.89	
100°C		22.19	23.62	25.06	25.19	23.62	
200°C		14.50	19.23	17.61	19.92	19.23	
300°C		10.77	16.22	13.57	16.47	16.22	
Specific Heat	J/kg K						± 2.5%
20°C		749.9	692.3	725.3	734.4	676.2	
100°C		895.4	844.9	860.9	881.3	801.0	
200°C		1017.3	960.1	984.3	996.7	903.7	
300°C		1087.0	1028.8	1044.8	1061.3	950.0	
Corrosion/oxidation Resistance		Very High	Very High	Very High	Very High	Very High	
Maximum Use Temperature	°C	1700	1700	1700	1700	1700	

Notes:
P-0 is original alumina ceramics prepared at CoorsTek without ASPRO treatment;
P-1 is ASPRO treated alumina ceramics at Condition 1;
P-5 is ASPRO treated alumina ceramics at Condition 5;
P-6 is ASPRO treated alumina ceramics at Condition 6;
P-7 is ASPRO treated alumina ceramics at Condition 7.

The ASPRO process transforms high dense bulk ceramic components to a new state with a unique combination of desired mechanical, thermo-physical and properties, including high thermal shock resistance for high dense ceramics.

The results of chemical composition analyses are presented in the Table 5.

Table 5.

The Results of Chemical Composition Analyses for L, M, and P Samples

Materials	SiO_2	Al_20_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	**TOTAL**
	%	%	%	%	%	%	%	%	%	%	%	%
L-0	6.43	89.7	0.13	2.34	0.80	0.24	0.05	0.06	<0.01	<0.01	<0.01	99.75
M-0	3.08	95.6	0.05	0.86	0.30	0.13	0.02	0.02	<0.01	<0.01	<0.01	100.06
P-0	0.79	98.7	0.01	0.41	0.15	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	100.06

The results of the chemical analyses of the researched alumina ceramics indicate that the main component of the researched ceramics is aluminum oxide (Al_20_3). The L, M, and P series of samples contain 90%, 96%, and 99% of Al_20_3 correspondingly. The analyzed alumina ceramics also contain second phase. The amount of the second phase increases in the following order: P $\Rightarrow$ M $\Rightarrow$ L samples. In the alumina ceramics the main components of the second phase are silicon dioxide (SiO_2), magnesium oxide (MgO), and calcium oxide (CaO) and less significant amounts of other oxides.

The ceramic samples were made up of Al_2O_3 grains surrounded by a second phase located at grain boundaries and three-grain junctions. Alumina ceramic can be considered as multiphase with a minor amount of second phases (it can be glassy phases), appearing as continuous boundary materials. The amount of grain boundary phase decreased in the order: L samples $\Rightarrow$ M samples $\Rightarrow$ P samples. There is no evidence that ASPRO treatment can change the chemical composition and grain size of the treated ceramic samples. However, the treatment may change the material state. In L5, M5, and P5 samples a network of cracks is evident, with a spacing between cracks of approximately 0.5 mm. Minor additions of different oxides (for example: SiO_2, MgO, CaO) to alumina significantly increase its concentration in grain boundaries, as it was determined by the Energy Dispersive X-ray Spectroscopy. At room temperature, these phases remain as separate microstructural components of formulating intergranular phase or grain-boundary. The grains are nearly pure Al_2O_3. The mean size of alumina grains was 6 μm. The grain boundary phase contain a major amount of SiO_2 in addition to the Al_2O_3 phases and minor amount of MgO and CaO phases. Two-phase ceramics are in general less brittle than single-phase materials and, usually, have higher fracture toughness. However, the increase of second phase has some limit to improve the material performance. The composition of M ceramic is more optimal than L composition. The effects of the ASPRO™ treatment are different on L ceramics than on P and M due to the fact that the glass phase significantly changes, which influences the thermal physical properties. Researched alumina ceramic polycrystalline material consists of ceramic grain networks embedded in glassy matrices. Cracks in ceramics nucleate preferentially at microstructural and chemical heterogeneities. A typical example is L ceramics containing excess amorphous phases. They may act as creep inhomogeneities, which induce local stress concentrations and crack nucleation. Hole nucleation occurs predominantly at three-grain pockets. Excesses of amorphous material may accelerate the crack growth. In ceramic materials the boundaries and boundary regions between grains and phase have a large, often controlling, importance to many properties and processes, including mechanical properties, such as fracture strength, toughness, plastic deformation, and high-temperature creep; thermal properties: specific heat, thermal conductivity, and thermal shock resistance; electrical properties: conductivity, dielectric constant and dialectic loss.

The value of density and elastic modulus increasing in the order: L samples $\Rightarrow$ M samples $\Rightarrow$ P samples, as a result of reduced amount of second phase in the material composition. Reduction of the elastic modulus mostly correlates with the density changes. We should note that density and elastic property changes are not so significant and do not reduce the material strength, but indicate on structural changes in the materials. The reduction of the density and elastic modulus could be a result of micro crystal defects. On other hand, the increased value of elastic modulus could be explained by compression residual stress in the materials. These effects, possibly, have been formed during the ASPRO process. It is intriguing that the value of Poisson’s ratio changes, as a result of the ASPRO process, which correlates with the structural change and change of ductility. At higher temperatures, this effect can be enhanced. The effect of ductility or plastic flow at elevated temperature is known to be considerable. As a result thermal shock resistance can be increased at elevated temperatures. The stress resistance of ASPRO treated ceramics may be due in part, to the development of some ductility at elevated temperature. The temperature level of thermal stress tests may have a considerable effect.

Thermal shock refers to the thermal stresses that occur in a component as a result of exposure to a temperature difference between the surface and interior or between various regions of the component. The temperature gradients in the ceramic liners have been established by rapid heating using melted aluminum and the flame of an oxygen-gas torch as shown in Fig. 2. After the thermal shock test, the fractures on the ceramic liners have been evaluated.

Fig. 2. Thermal shock tests using molten aluminum and an oxygen-gas flame.

Thermal shock tests performed with both untreated and treated ceramic samples showed that the ASPRO treatment significantly improves the thermal shock resistance of the alumina ceramic material by a factor of >2.1, from the critical temperature difference (ΔT_c) of less than 300°C to over 650°C, as measured by rapid heating using melted aluminum (Fig. 3). The thermal shock resistance is a measure of the maximum temperature difference that a material can withstand without catastrophic failure. The ASPRO treated ceramic, as cylinder liner, withstands the thermal shock in the internal combustion chamber during engine operation and the thermal stress initiated by the flame of an oxygen-gas torch. These successful experimental trials have validated the effectiveness of the ASPRO treatment in withstanding the extreme thermal shock.

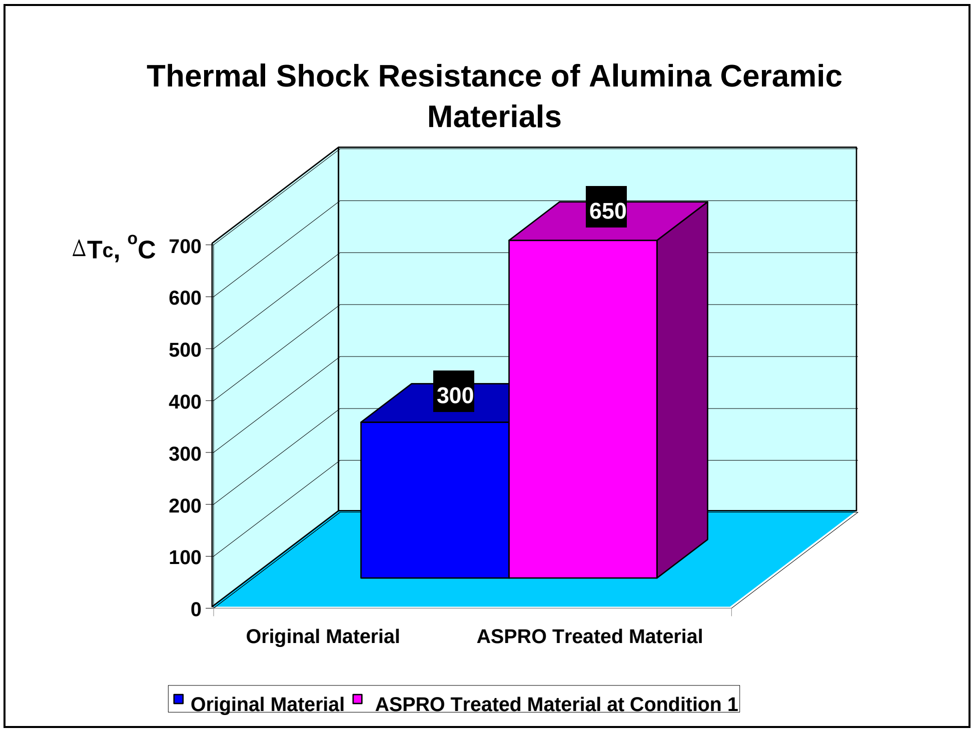


Fig. 3. Thermal shock resistance comparison of ASPRO™ treated alumina ceramics.

The relative thermal expansions for treated non-treated alumina samples shown in Fig. 4, 5 and 6.

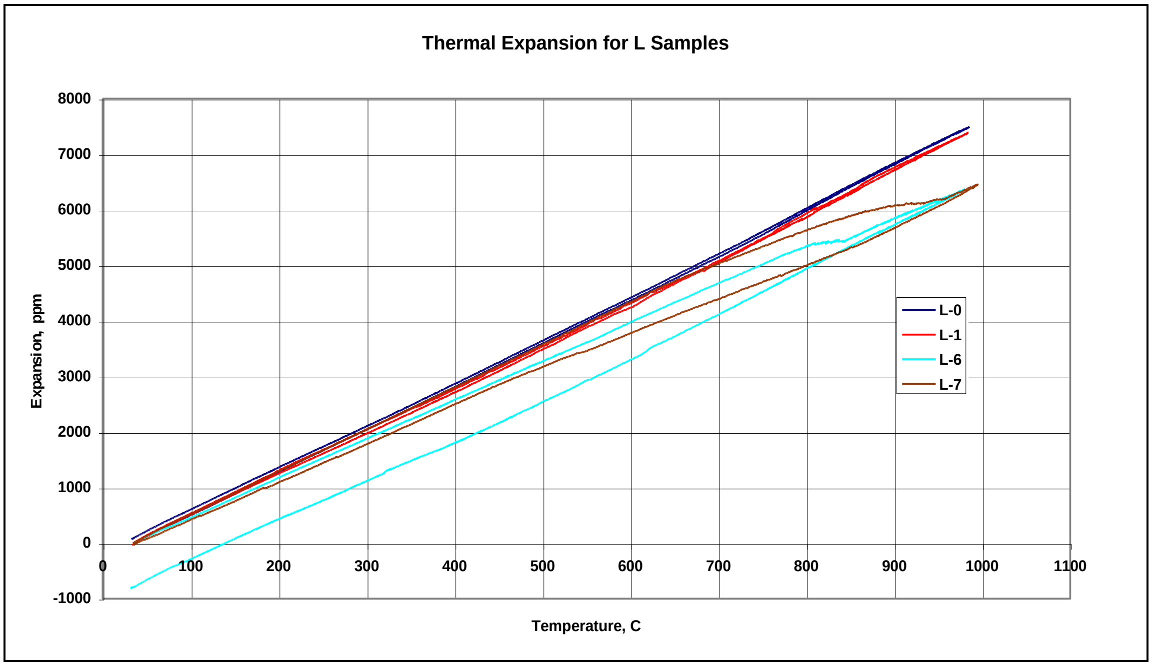


Fig. 4. Thermal expansions for L alumina ceramics (90% of aluminum oxide)

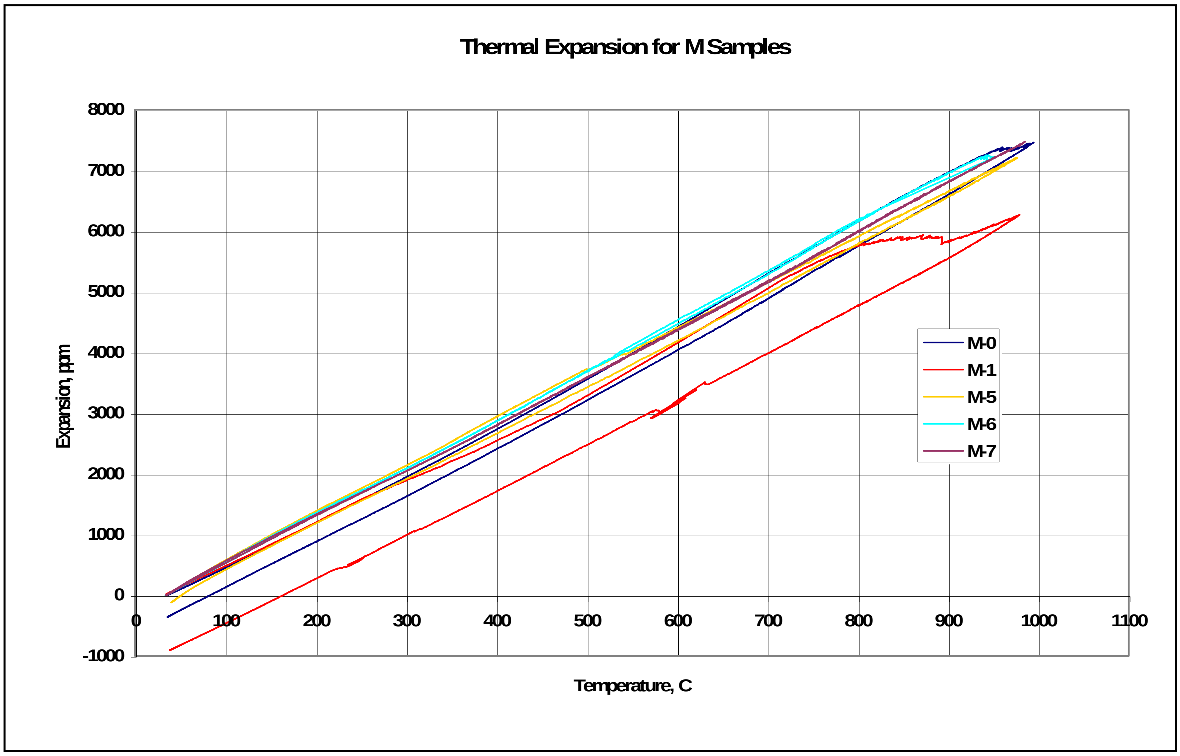


Fig. 5. Thermal expansions for M alumina ceramics (96% of aluminum oxide)

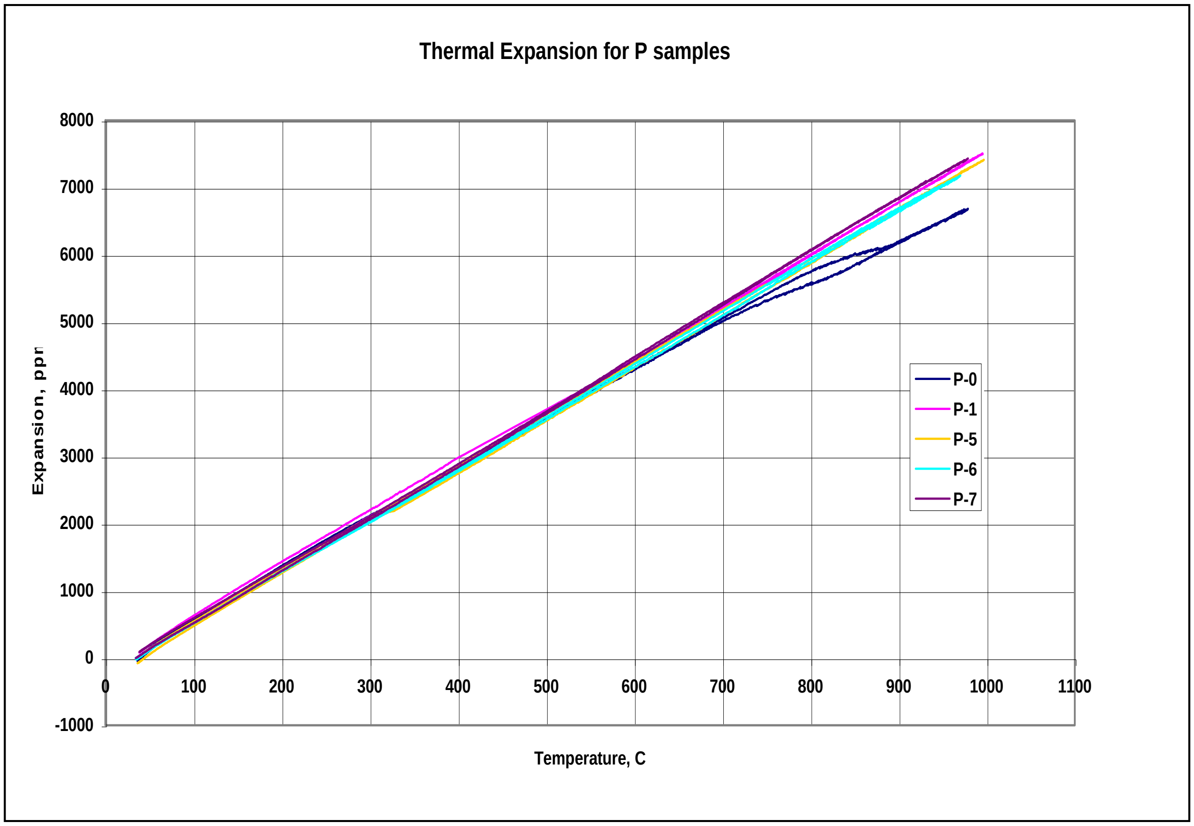


Fig. 6. Thermal expansions for P alumina ceramics (99 % of aluminum oxide)

The reduction of thermal expansion could be a result of residual compression. Each grain is restrained by the surrounding grains so that, instead of grain separation, micro-stresses are developed which are proportional to the difference between the stress-free expansion or contraction and actual dimension change. On other hand, if polycrystalline material consists of microcracks or other type of microstructure defects (which may be developed during ASPRO treatment of materials), the overall observed expansion coefficient is lower than the expansion coefficient of the individual crystals. On heating, these cracks tend to close, and at low temperatures abnormally low expansion coefficient is observed. Lattice defects and microcracks directly translated into expansion behavior.

The experimental data for thermal conductivities are presented in Fig. 7, 8,and 9.

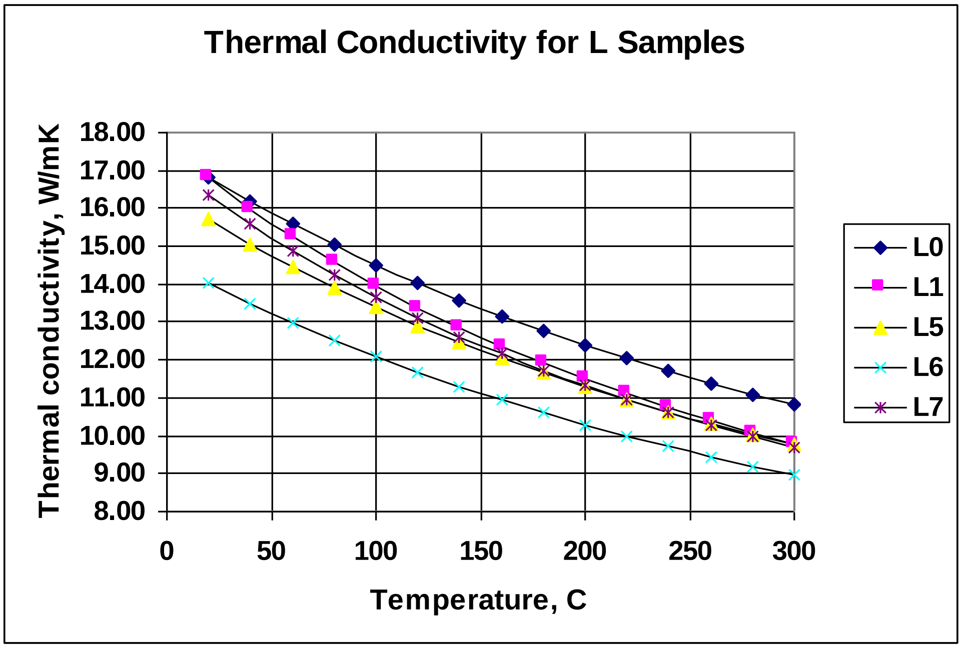


Fig. 7. Thermal conductivities for L alumina ceramics (90% of aluminum oxide)

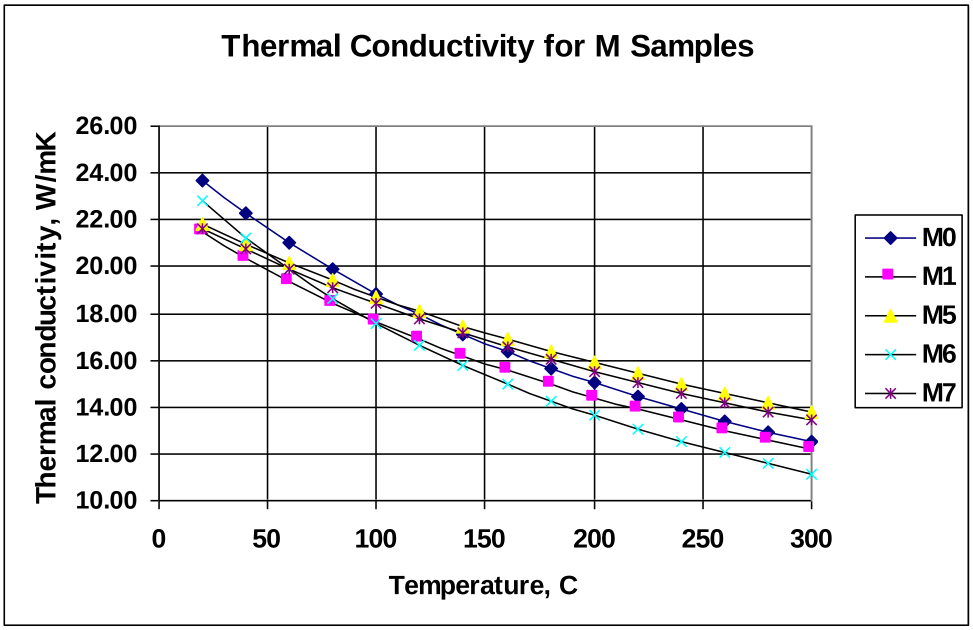


Fig. 8. Thermal conductivities for M alumina ceramics (96% of aluminum oxide)

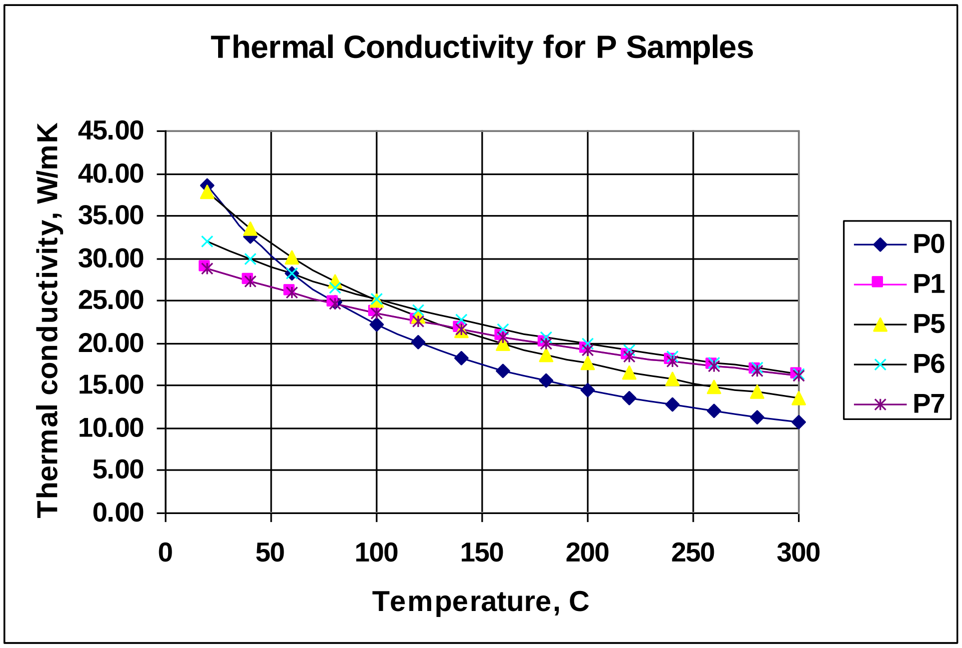


Fig. 9. Thermal conductivities for P alumina ceramics (99% of aluminum oxide)

Unexpected, relatively lower thermal conductivity values were obtained at higher temperature for untreated ceramic in comparison to treated samples. It can be supposed that this effect is a result of the ASPRO treatment of specimens. The mechanisms of surface segregation and diffusion of admixtures or crystal lattice defects, and mismatch between grains of alumina can explain the results of the thermal conductivity measurements. The heat flow can be adsorbed and distributed on the surface of microcracks, grain boundary and any other defects, which influence on the direction of heat flow propagation and change the thermal conductivity. The laser photothermal radiometry (PTR) measurement results indicated that the ASPRO™ treated ceramic samples had lower thermal resistance at grain boundaries than the untreated samples under transient state conditions, such as in thermal shock experiments, while its effect to steady state thermal conduction is negligible [10]. These results show that the ASPRO™ treatment reduces the thermal resistance between alumina grains in the ceramic sample, and thus decreases the thermal gradient across the intergrain region. Therefore it reduces the local thermal stress there, which results in an improvement of the thermal shock resistance.

The results of the specific heat capacity measurements are presented in Fig. 10, 11, and 12.

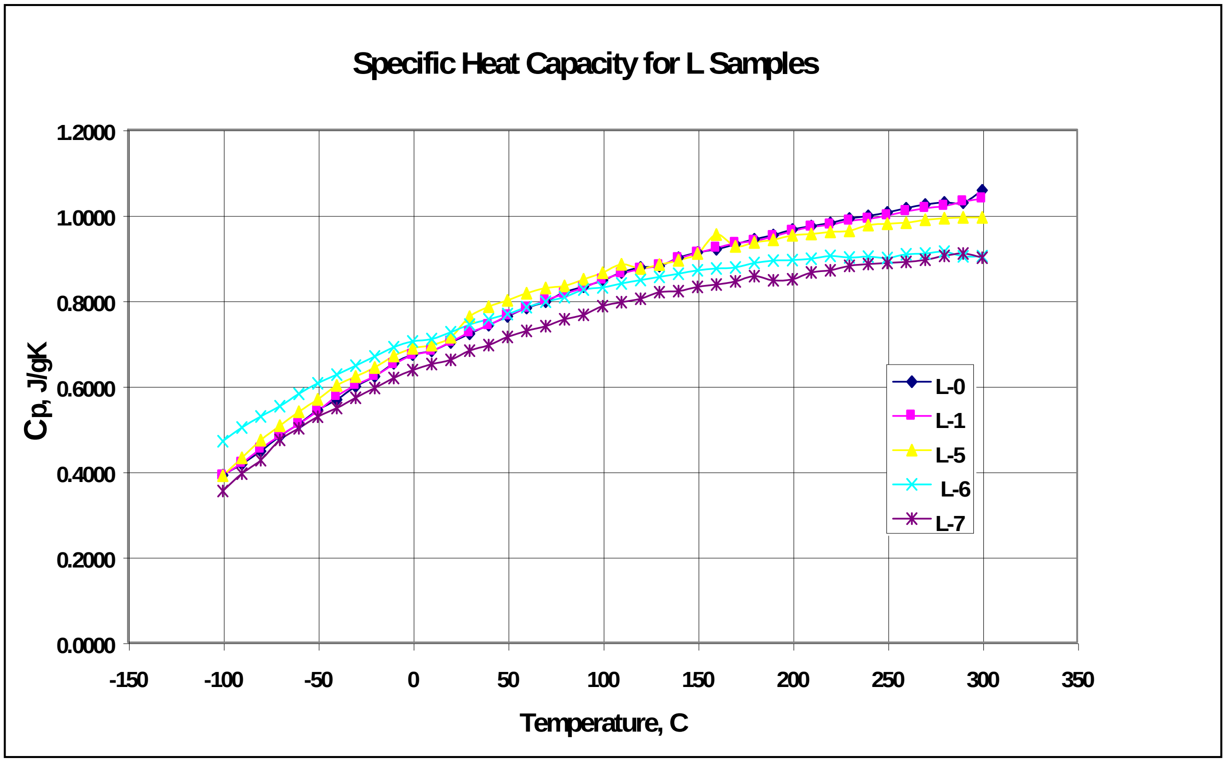


Fig. 10. Specific heat capacity for L alumina ceramics (90% of aluminum oxide)

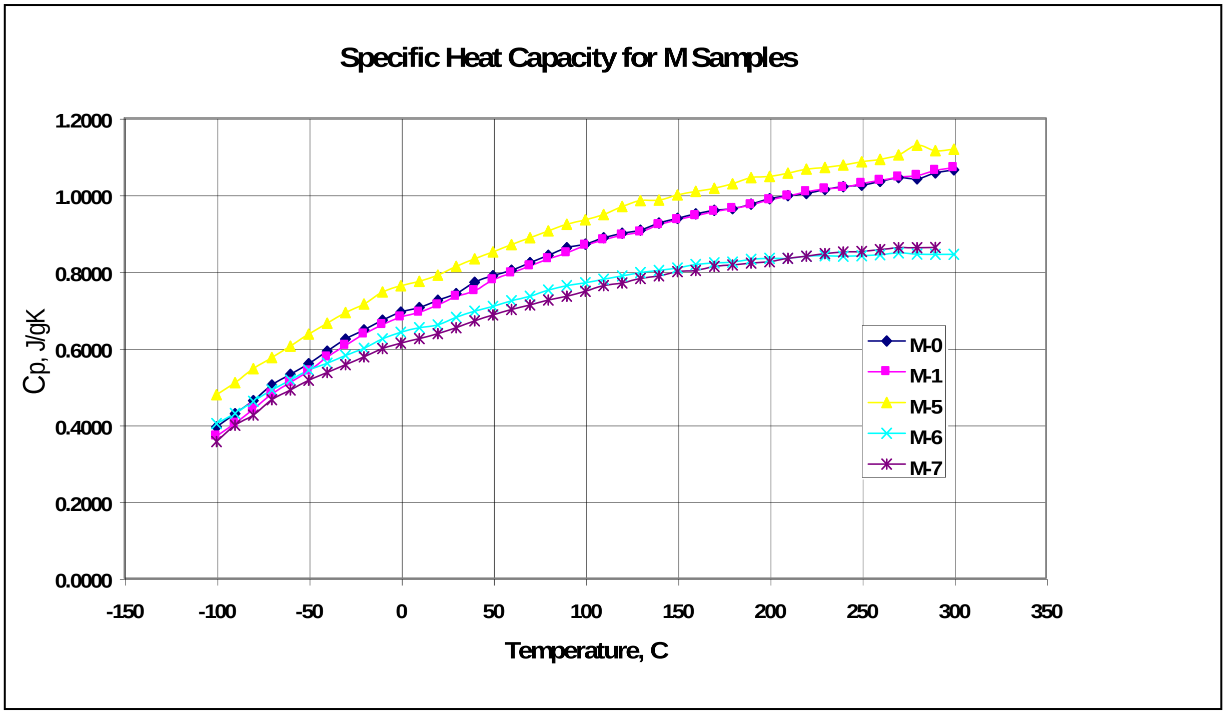


Fig. 11. Specific heat capacity for M alumina ceramics (96% of aluminum oxide)

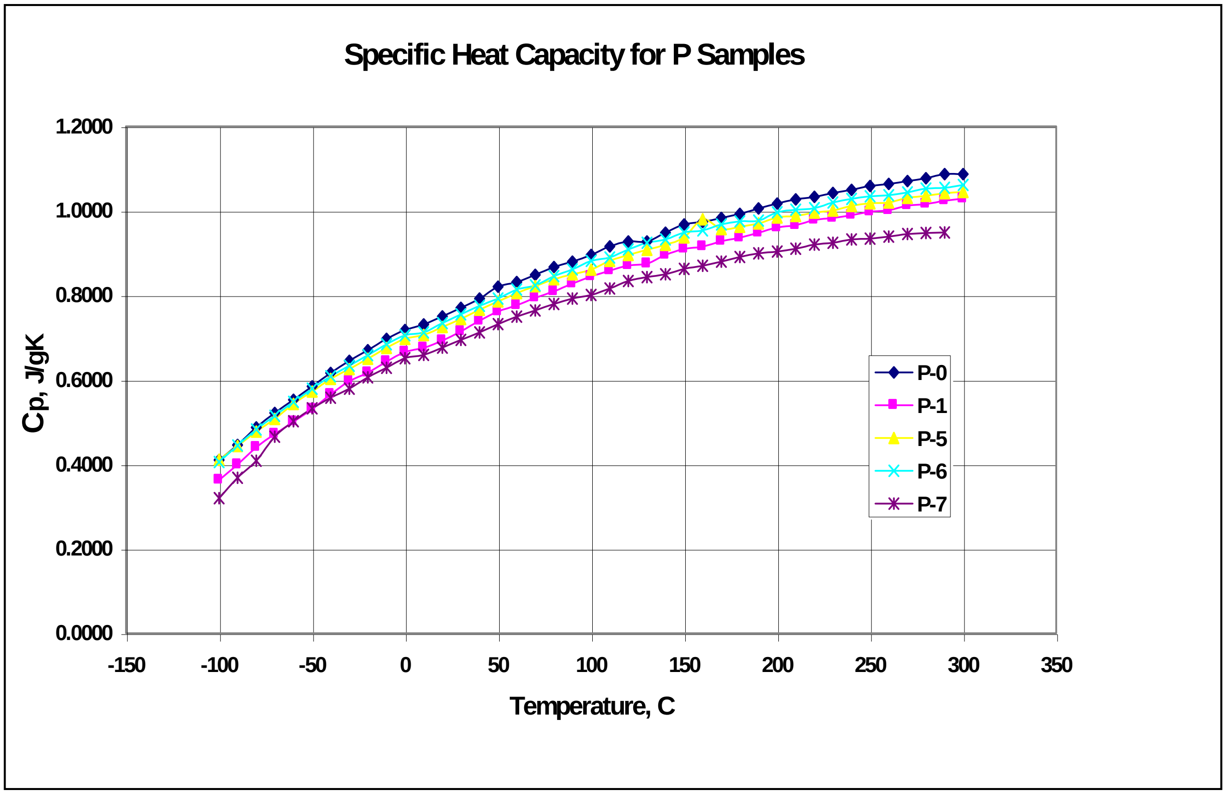


Fig. 12. Specific heat capacity for P alumina ceramics (99% of aluminum oxide)

The suggested mechanisms affecting heat capacity, as a result of ASPRO treatment, can be explained as follows: (1) vibrational energy by which atoms vibrate around their lattice positions with an amplitude and frequency that depend on temperature, (2) raising the energy level of electrons in the structure, and (3) changing atomic positions and forming lattice defects, dislocations, and microcracks. All these changes correspond to altering the internal energy of ASPRO treated ceramics and are accompanied by changes in configurational entropy. Development of crystal structure defects and disorders contribute to the increased heat capacity at higher temperatures. It is possible that at higher temperature (>300ºC) the influences of ASPRO treatments would be more significant on heat capacity and thermal conductivity of alumina ceramics and, therefore, would be appropriate for high temperature applications.

The ASPRO treated ceramics may include various lattice imperfections, which give rise to anharmonicities and result in phonon scattering. Increase energy dissipation from thermal elastic waves by phonon-phonon interaction corresponding to phonon scattering may reduce the stress concentration in the lattice during the thermal stress. The change in volume due to lattice vibration is closely related to the increase in energy content. Changes in the thermal conductivity with temperature are parallel to changes in heat capacity and thermal expansion. Consequently, lattice defects directly translate into thermo-physical behavior. These facts may explain the fact that ASPRO treated materials posses a high thermal shock resistance.

The ASPRO treated ceramics is the result of the Materials – Process – Properties association development as the interconnection among the type and structure of the atoms, chemical bonds, and physico-chemical interactions and resulting new material properties. The high thermal shock resistance of high dense ASPRO treated ceramics could be a combination of the following factors: firstly, high strength to prevent a crack initiation and secondly, an ability to adsorb and redistribute the fracture energy and reduce the elastic energy concentration, which results to reduce or stop the crack propagation.

The temperature dependence of the physical properties and the relative thermal shock resistance of materials may well be interchanged for various temperature levels. The thermal stress resistances of ASPRO treated ceramics may be due in part to the development of favorable factors at used elevated temperature. As a result of ASPRO treatment so many other mechanisms can contribute to improvement of thermal shock resistance, such as crack branching, crack deflection, crack bridging, residual stress, energy absorption and distribution. Consequently, more than one mechanism plays a role in thermal shock resistance processes, and interaction between mechanisms must be considered, which can be synergistic.

The neutron diffraction and x-ray diffraction measurements revealed a significant difference in the crystallographic textures of ASPRO treated materials. Normal processing of alumina (e.g., sintering, or hot isostatic pressing) is not expected to alter the preferred orientations of the crystallites that comprise the polycrystalline bulk materials. The x-ray absorption spectroscopy indicates that transformed alumina exhibits noticeable differences in their aluminum K-edge absorption spectrum. The difference is attributed to a change in the aluminum local environment. The change affects the outer unoccupied electron orbital of aluminum. The ASPRO™ Conversion Technology modifies the atomic structure and chemical bonds in the treated materials.

As the research results indicate the ASPRO™ Conversion Technology has the potential to tailor materials in order to achieve required values of selected properties. The analyses of the Material – Process – Property Relations using a new model of interactions in material systems (Fig. 1) is providing opportunities to gain further understanding into the phenomena created by ASPRO™ Conversion Technology and for extending the use of ASPRO™ treated ceramic materials. Based on this approach, the developed new ASPRO™ Conversion Technology provides the ability to produce advanced ceramics to meet industrial requirements for materials requiring superior properties.

8. Target Markets

The specific markets targeted by ATS Spartec - AHCS for introduction of ASPRO™ conversion technology are those, which require a change of the critical properties of advanced materials. The ASPRO™ conversion technology is ideally suited in terms of cost and the presentation of the desired material properties. The target markets can be classified into two distinct areas of applications:

1. Structural
2. Electrical/electronic.

9. Structural Applications

9.1 Automotive Components

Automotive industrial applications are increasingly demanding higher performance materials that exhibit superior mechanical, thermal, electrical, optical, and magnetic properties. ATS Spartec – AHCS Inc. has advanced the use of ceramic materials for the internal combustion engines. The advanced development of **ASPRO™ Conversion Technology** is leading to the substitution of ceramics for metals in different structural applications, particularly for the use of engine components. The use of advanced ceramic materials can provide significant economies, increase productivity, ease ecological problems, and expand product markets. In the automotive industries, there is an increasing demand for new, lightweight materials with superior properties. Materials used for internal combustion engines must exhibit a variety of desirable characteristics to satisfy the operation of modern day engines. These must include: increased operating life times, low friction, outstanding wear resistance, high operation temperature, strength, thermal shock and corrosive environment resistance. The engine components must be able to retain these desirable characteristics at the high temperatures commonly encountered in internal combustion engine operations. Manufacturing of advanced engines featuring high reliability, optimum power and minimal fuel consumption has subsequently led to the use of ceramics.

Ceramic applications for internal combustion engines can be classified in two categories:

1. Substituting such conventional metal parts as the engine cylinders, pistons, valves and turbo-chargers.
2. Reducing the ecological problems, such as decreasing hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter emission, and decreasing fuel consumption.

The use of ceramic engine components instead of metals could have the following advantages:

- Stability at elevated temperature
- High strength and wear resistance
- Lower mass density and friction
- High corrosion/oxidation resistance, especially, for oxide based ceramics, such as alumina.

In addition, the ceramic components in comparison with the ceramic coating could provide a number of benefits:

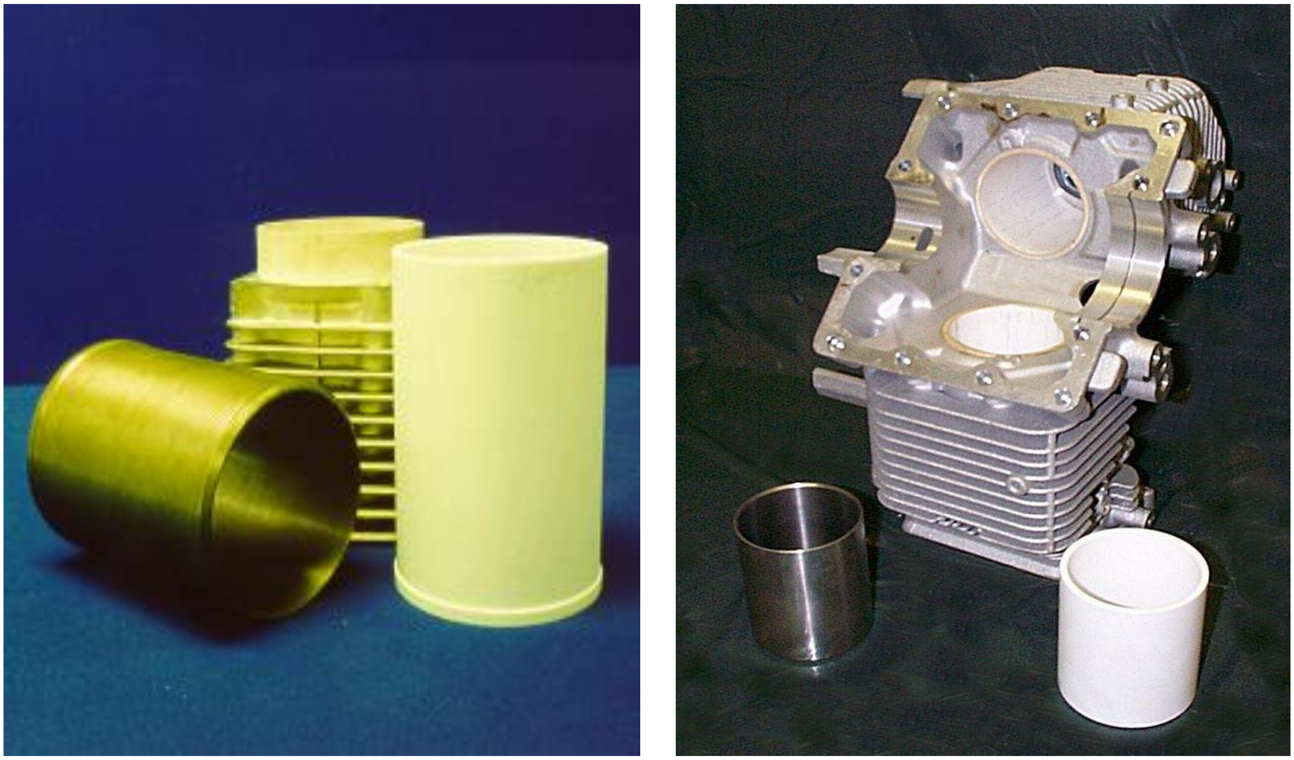
- Overcoming mismatch in properties between ceramics and metals. For example, the ceramic coating could deform and crack during temperature cycling in the heat engine, as a result of the thermal expansion differences between the ceramic layer and metal substrate.
- Overcoming the lack of adhesion between the ceramic coating and metal surface.
- Overcoming restrictions in material dimensions and machining.
- Increasing the material performances due to the higher density, wear and chemical resistance.
- Reducing costs.

However, if the current technology is used, there are some limitations to alter the existing material properties and produce ceramic engine components, for example:

- Zirconia and aluminum titanate are not reliable due to the phase transformation or decomposition at high temperature cycling in combustion engines.
- Silicon carbide and silicon nitride are significantly more expensive compared to the cost of metals and alumina and display surface damages when expose to harsh oxidation/corrosion conditions presented in the internal combustion engines.
- Low thermal shock resistance of high dense ceramics.

In order to overcome these deficiencies, it lead ATS Spartec – AHCS Inc. to the development of inexpensive ceramic materials that can meet the major selection criteria for automotive applications, including enhanced thermal, physical, electrical properties, and high mechanical performances.

The alumina ceramic cylinder liners were successfully installed and tested in internal combustion engines for a motorcycle and OHC twin engine. The value of ASPRO™ technology in the manufacture and operation of the internal combustion engines shows great promise. The properties of the new ASPRO™ ceramic materials are ideally suited for applications in internal combustion engines. ASPRO™ treated alumina cylinder liners have been successfully installed and tested in different internal combustion engines (Fig. 13).



a) b)

Fig. 13. Components of the internal combustion blocks with the ASPRO™ treated alumina ceramic liners: a) motorcycle engine components, b) OHC twin engine components.

The developed inexpensive alumina ceramics meet the selection criteria for the engine components, including high temperature operation, thermal shock and corrosion/ wear resistance, low friction, light weight an high strength [14]. The motorcycle engine (Fig. 13a), with ASPRO™ treated alumina ceramic cylinder liners, were subjected to diverse road conditions and severe shock loading. After 25,000 km, the treated alumina ceramic liners have not displayed any signs of distress. Additionally, an OHC twin engine with ASPRO treated alumina ceramic liners (Fig. 13b) has been successfully tested for more than 80 hours without any sign of the ceramic degradation (Fig. 14). Further testing of this engine is in progress. The OHC twin engine is used for industrial applications.

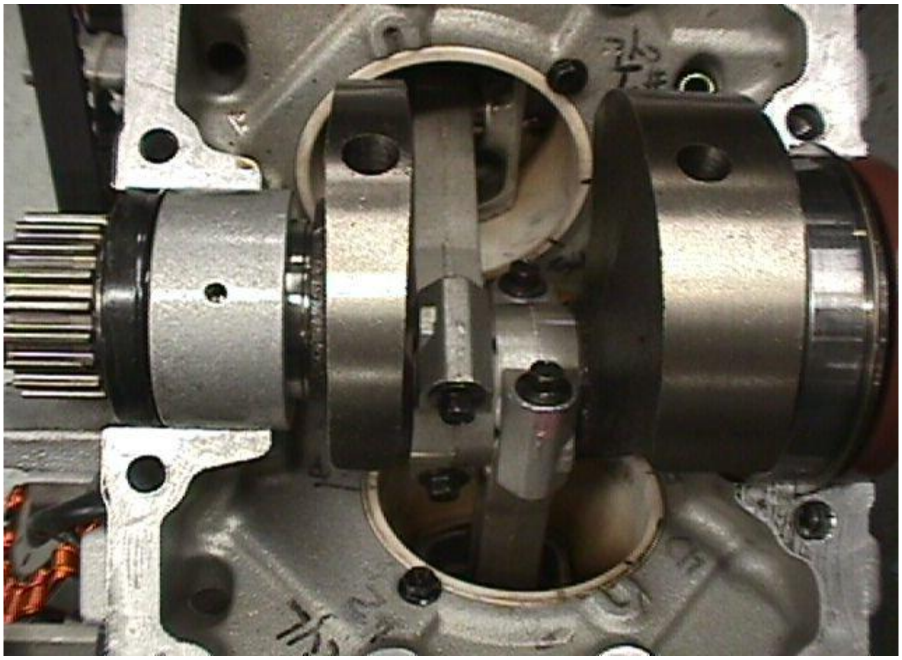


Fig. 14. The actual engine with ASPRO treated ceramic liners after more than 80 hours testing.

The ASPRO™ Conversion Technology offers low-cost alumina ceramic components as substitutes for metals or expensive ceramic materials (e.g., SiC, Si_2N_3). The ASPRO™ treated alumina ceramic liners have lower friction and smoother surface in comparison to metal cylinder liners. The use of the ceramic components allows more complete combustion, thus reduced fuel consumption and emissions and improved performance of internal combustion engine components [14-17]. Other benefits in combustion engines include better start-up in cold conditions, less noise, outstanding wear and oxidation/corrosion resistance, reduced weight, longer life, and high temperature operational capability. The comparison of ceramic and gray iron properties indicates that the use ASPRO treated alumina ceramic components provides many benefits in comparison with gray iron liner as a result of more optimal properties for ceramic materials. The properties of ceramics and gray iron are presented in the Table 6.

Table 6.

Properties of Gray Iron and Ceramics

No.	**Properties**	**Units**	**ASPRO Treated Alumina (M-1) at condition 1 96% Al_2O_3** [3]	**Original Non-Treated Alumina 96% Al_2O_3** [3]	**Gray Iron ASM Class 20** [18, 19]
1.	Density, 20 °C	g/cm^3	3.716	3.712	7.15
2.	Elastic Modulus, 20 °C	GPa	319	320	66 - 97
3.	Hardness	GPa	12.3	12.1	1.6
4.	Thermal Shock Resistance*, ΔTc	°C	>650	<300	>650
5.	Thermal Expansion Coefficient	1x10^{-6}/°C			
	20°C				10.8
	35-300°C		7.15	7.36	
	300-500°C		6.94	8.05	
	500-800°C		8.54	8.71	
6.	Thermal Conductivity	W/m K			
	20°C		21.49	23.68	33
	100°C		17.64	18.86	
	200°C		14.41	15.03	
	300°C		12.18	12.49	
7.	Specific Heat	J/kg K			
	20°C		712.3	724.7	
	100°C		868.0	871.1	500
	200°C		986.5	989.5	
	300°C		1070.4	1064.7	
8.	Corrosion/oxidation Resistance		Very High	Very High	Low
9.	Maximum Temperature Use	°C	1700	1700	500

* The thermal shock test was conducted by rapid heating using melted aluminum having a temperature of above 650°C.

Based on materials properties, the ASPRO treated ceramic components could provide the following benefits:

1. ***Lower Density*** **provides reduced weight, which could lead to reduced fuel consumption, emission, and increased performance.**
2. ***Higher Elastic Modulus*** **provides less deformation, dimensional stability, reduced stress, increased strength and durability, which could lead to reduced fuel consumption, emission and maintenance, and increased performance.**
3. ***Higher Hardness*** **provides increased wear resistance, surface finished, reliability and durability.**
4. ***Enhanced Thermal Shock Resistance*** **of ASPRO treated alumina in comparison with original non-treated ceramics is comparable with the thermal shock resistance of the metal and enables the use of low-cost alumina ceramics for engine components.**
5. ***Lower Thermal Expansion*** **provides reduced stress during engine operation, which could lead to increased reliability and durability and reduced maintenance**
6. ***Lower Thermal Conductivity*** **may increase performance and reduce fuel consumption as a result of reduction of heat dissipation.**
7. ***Higher Specific Heat*** **provides better heat absorption.**
8. ***Higher Corrosion/Oxidation resistance*** **provides reduced surface damages and maintenance, increased reliability and durability.**
9. ***Higher Maximum Temperature Use*** **provides capability to operate the engine at higher temperature, increased reliability and durability, which could lead to reduced fuel consumption, emission and maintenance, and increased performance.**

As a result of these, the ASPRO™ treated ceramic components can be used as cylinder liners, cylinder head liners, piston bodies, turbo-charger liners, valve bodies, valve seats, catalyst substrate and mechanical seals. The ASPRO™ Conversion Technology is a process that enhances the performance, use and durability of engine components.

Based on our research and development over the last several years, the ASPRO™ Conversion Technology provides a viable cost effective alternative to metal or expensive ceramic components in internal combustion engines. The ASPRO™ treated alumina ceramic components can be produced and integrated into an engine at a cost that is comparable with metal components. The use of the ceramic components instead of the traditional metal components will significantly reduce weight, as the alumina ceramics are significantly lighter than metals. Manufacturing processes can be designed in such a way that, at a low production cost level; the extremely tight dimensional tolerances demanded for ceramic parts in automobile constructions can be achieved.

The advances made through ASPRO™ treated materials now overcome the previous technical weaknesses and enable the use of low-cost alumina ceramics in cylinder liners and other components for internal combustion engines.

Successful experimental trials of ASPRO™ treated alumina liners in the internal combustion engine and castings of molten aluminum have provided important evidence of the effectiveness of the technology in responding to extreme physico-chemical impacts. The gained advantages of the ASPRO™ conversion technology materials for the use in the internal combustion engines include:

- Reduction of emissions of hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter emission
- Noticeable decrease in fuel consumption
- Cost saving arising from the use of low-cost alumina ceramics, lighter weight, and better functioning ceramic components
- Eliminate machining of the liners after installation
- Improved cold start
- Reduced noise level
- Outstanding wear and oxidation/corrosion resistance
- Reduced lubrication
- Increased surface finish
- Dimensional stability
- Reduced weight and stresses
- High temperature operational capability
- Multi fuel capability
- Improved reliability and reduced maintenance

The ASPRO™ treated materials, particularly inexpensive alumina ceramics, can be applied as the following engine components:

- Cylinder Liners
- Valve seat inserts
- Piston bodies
- Cylinder head liners
- Turbo charger inserts
- Valves
- Pump bodies
- Catalyst substrates
- Mechanical seals
- Fuel delivery systems

The developed internal combustion engines with ASPRO™ treated ceramic components are presented in Figure 15 - 17.

“ The ASPRO™ Initiative”

Road tested for many years, the ASPRO™ Conversion Technology enhances the physico-thermal properties of full dense alumina ceramics. This leads to the successful use of ASPRO™ treated ceramic as a cost effective alternative material to conventional metal parts applied in internal combustion engines.

An approach to meet applicable emissions standards

USES

- Cylinder liners
- Cylinder head liners
- Piston liners
- Turbo charger liners
- Valve bodies
- Pump bodies
- Catalyst substrate
- Mechanical seal

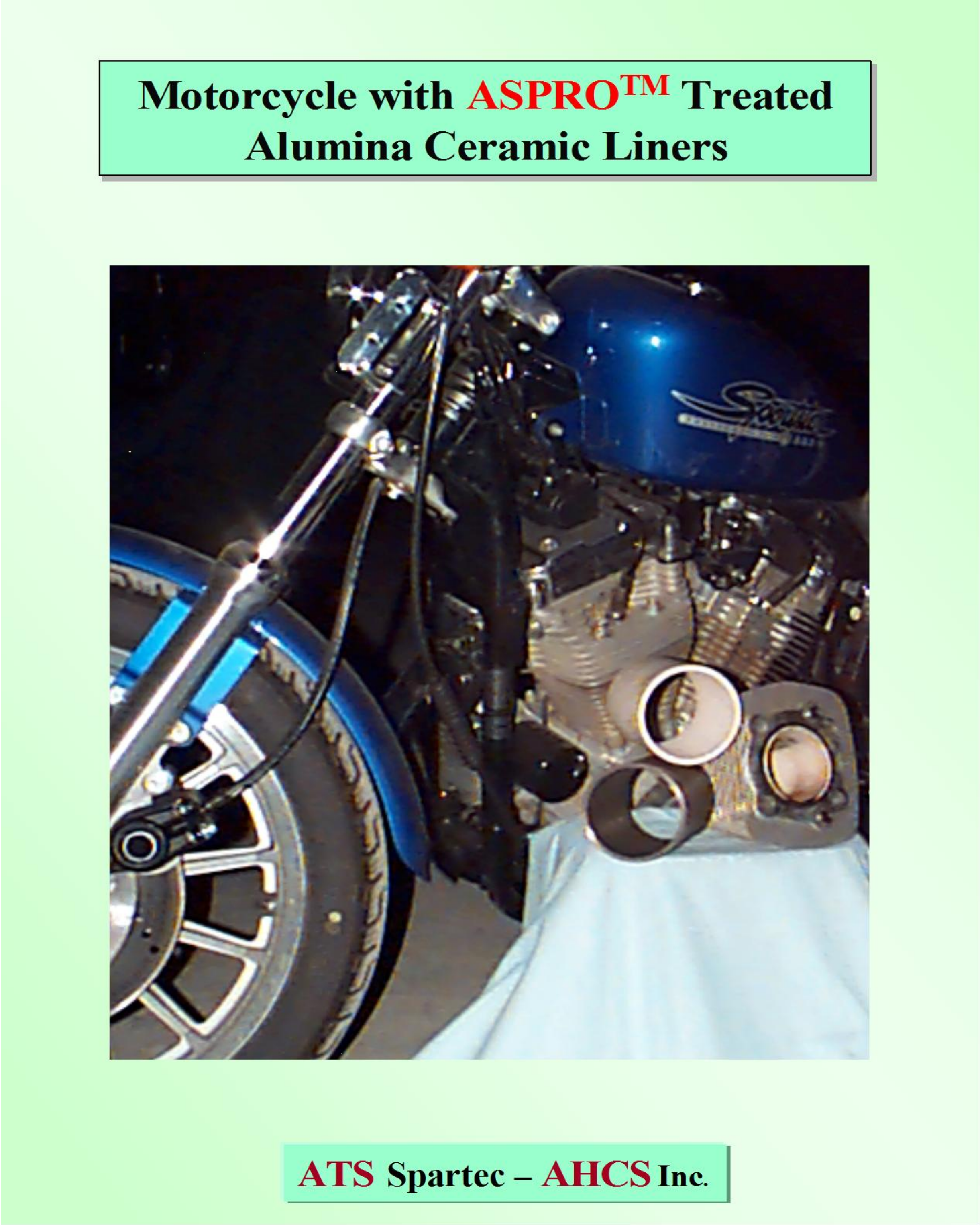
BENEFITS

- Outstanding thermal shock, wear, and corrosion resistance
- Reduced fuel consumption
- Reduced emissions
- Reduced noise level
- Improved cold start
- Reduced lubrication
- Reduced friction
- Dimensional stability
- Reduced weight and stresses
- High temperature operational capability
- Multi fuel capability
- Longer life
- Improved reliability

ASPRO™
Conversion Technology

“Ceramics for the New Age”

Fig. 15. The uses and benefits of ASPRO™ treated ceramics for internal combustion engines.



Motorcycle with ASPRO™ Treated Alumina Ceramic Liners

ATS Spartec – AHCS Inc.

Fig.16. The motorcycle with ASPRO™ treated alumina ceramic cylinder liners

OHC Twin Engine with ASPRO™ Treated Alumina Ceramic Liners

ATS Spartec – AHCS Inc.

Fig. 17 OHC twin engine with ASPRO™ treated alumina ceramic cylinder liners.

9.2 Power Generation Systems

The properties required for power generation systems are similar to those needed for automotive components. The materials must exhibit a combination of good strength, damage tolerance, creep resistance, and oxidation and corrosion resistance at elevated temperature. Power generation systems include possible applications of advanced ceramics for:

- Stationary engines
- Heat-recovery systems/heat exchangers
- Burners and combustors
- Separation and filtration systems
- Insulators

9.3 Aerospace Applications

Aerospace requirements for ceramics are quite broad, encompassing electronics, wear, and thermostructural applications. Ceramics are considered an enabling technology for advanced aircraft and space propulsion engines and space power systems, because of their potential to allow increased engine operating temperature, the benefits are quite significant Potential applications for ceramic include:

- Aircraft and space propulsion
- Space power
- Aerospace vehicle
- Space structures

9.4 Shot Sleeves

The first subject application was the ceramic lining of a “Shot-Sleeve”, the component that transfers the molten aluminum from the crucible to the mold. In the process of evaluating these ceramic materials, a process was developed (trademarked as “ASPRO^{TM} Conversion Technology”) to enhance the original materials ability to withstand the enormous thermal shock of molten aluminum. The ASPRO^{TM} treated fully dense aluminum oxide (alumina) ceramic materials had survived more than 700 cycles of the casting process.

9.5 Ceramic Cutting Tools

Manufacturing efficiency is critical in today’s world economy. Manufacturers are under intense competitive pressure to produce higher quality parts at ever-faster production rates. In the field of metal machining there is an increasing demand for high-technology cutting tools that can cut metals with unprecedented levels of speed and precision. The use of ceramic cutting tools offers significant advantages in cutting speed, quality, maintenance requirements and longevity. High-speed machining elevates the temperature at the tool/workpiece interface and, therefore, the thermal shock resistance of tool materials would be expected to play a more important role in the tool life [30]. Silicon nitride, silicon carbide cutting tools show a greater strength, wear resistance, and fracture toughness than the traditional aluminum oxide (alumina) cutting tools. However, silicon nitride and silicon carbide are not recommended for the machining of irons and steels, because they are considerably more soluble in iron. On other hand, aluminum oxide has a very low degree of chemical solubility in iron and cost significantly less and, consequently, is more suitable for machining iron and steel components. Currently, the dominant factor that limits the widespread use of alumina cutting tools in the metal cutting industry is their lack of adequate thermal shock resistance, which may result in catastrophic tool failure. Therefore, it is desirable to improve performance for existed ceramic cutting tool inserts.

In response to this demand the objective of this work was to improve the performance of commercially available alumina based cutting tool inserts using a novel patented materials process - **ASPRO™ Conversion Technology** [1]. The process transforms highly dense monolithic ceramic components to a new state by applying a particular combination of temperature and pressure. The ASPRO™ treated ceramic is the result of the Material–Process–Property–Application relationship development. Potentially, the ASPRO™ Conversion Technology can be applied to any solid materials with near full density and improve their properties. The ASPRO™ conversion technology is able to modify the atomic structure and chemical bonds in the treated materials leading to the unique combination of properties [15]. These include high density, high thermal shock resistance, high level of toughness, hardness, chemical and wear resistance, and modified thermal and electrical properties required by structural and electronic applications. Successful experimental trials of the ASPRO™ treated alumina liners in internal combustion engines and castings of molten aluminum have provided important evidence of the effectiveness of this technology in responding to extreme thermal shock. As it was shown in our recent work [10] using the laser photothermal radiometry (PTR), the improvement in thermal shock behavior of ASPRO™ treated ceramics is the result of the reduction of thermal resistance between ceramic grain boundaries under transient conditions, as occurring in thermal shock experiments. It reduces the applied stress intensity by adsorption and quick distribution of the applied energy. Therefore the ASPRO™ process can provide a higher performance ceramic and expand the envelope of their applications, as ceramic cutting tool inserts.

The ceramic cutting tool inserts have been tested by a face milling, as an interrupted cutting operation, which subjects the inserts to thermal shock, as opposed to a continuous turning operation. The tests were accomplished in the down milling and dry modes. The ceramic cutting tool inserts are presented in Fig. 18.

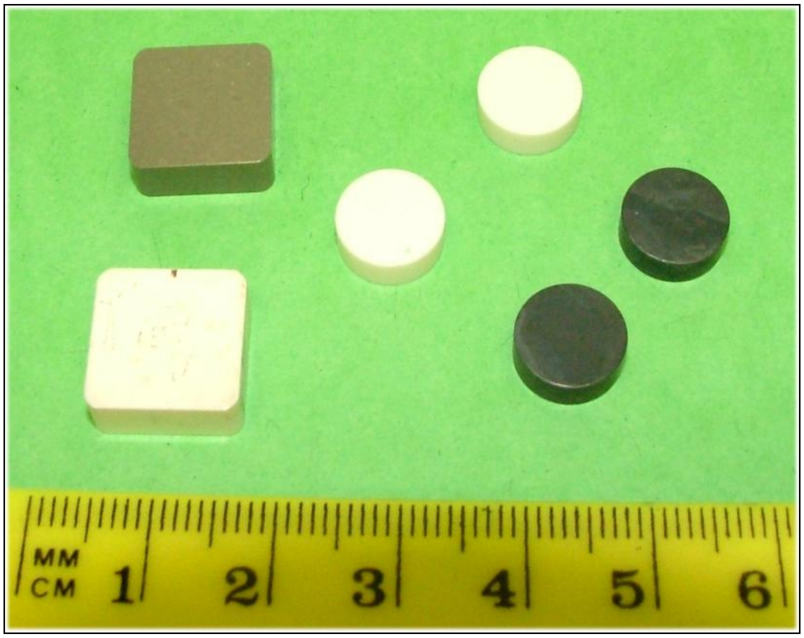
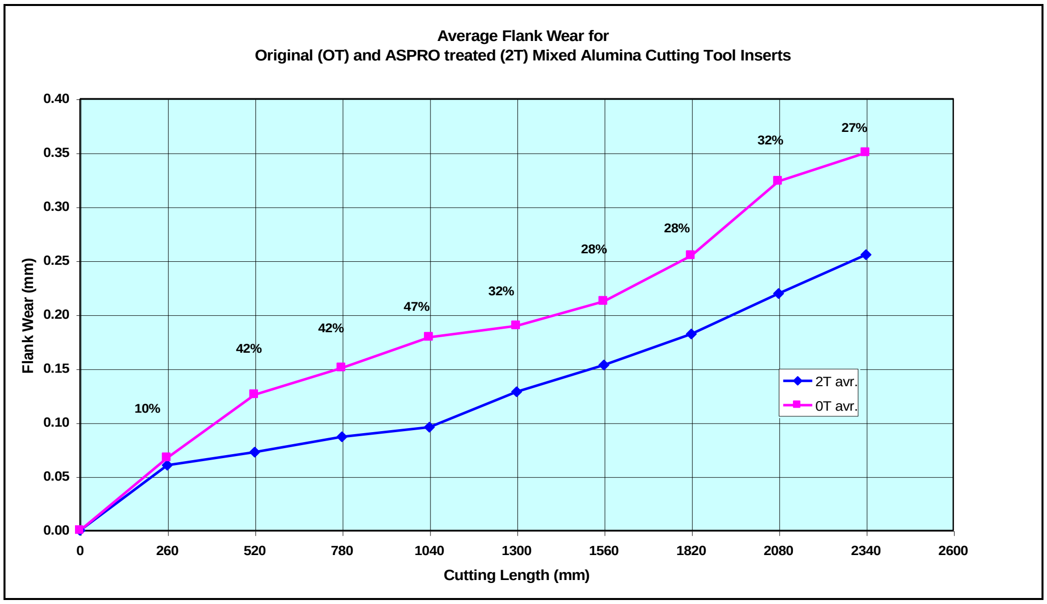


Fig. 18. The ceramic cutting tool inserts.

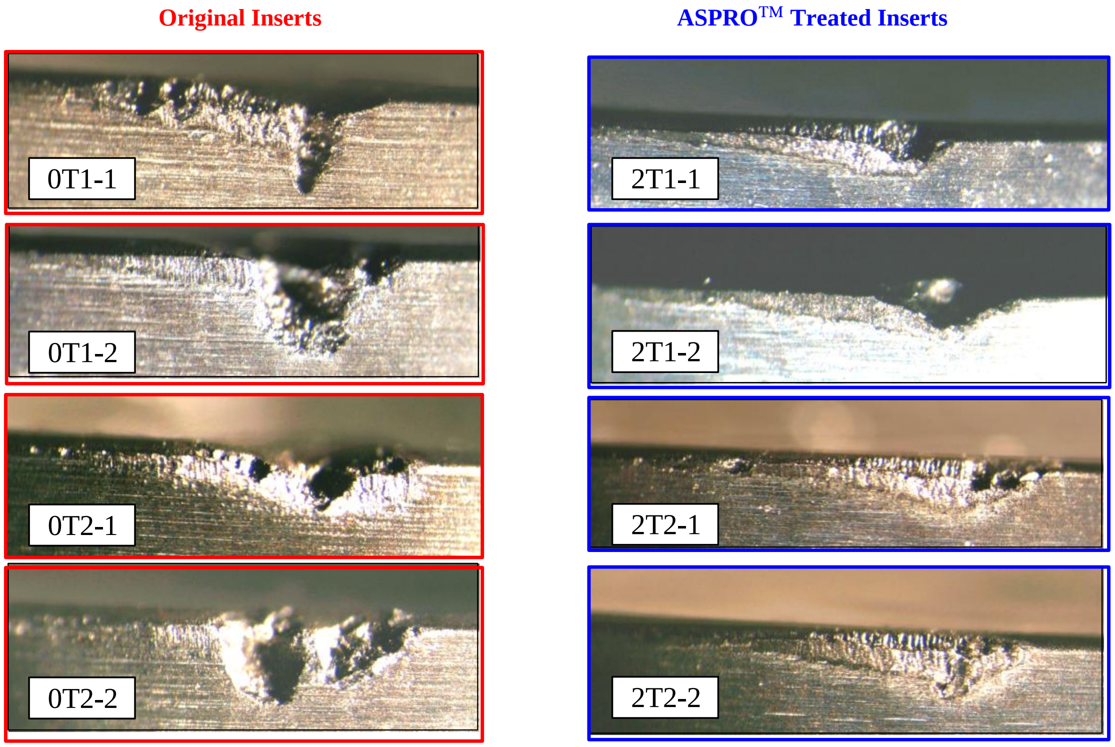
The machining tests for Original and ASPRO™ treated ceramic cutting tool inserts are presented in Fig. 19. The following cutting conditions have been applied: cutting speed – 600 m/min, feed rate - 0.12 mm/tooth, depth of cut – 0.2 mm, work material – H13 steel, inserts – Mixed Alumina (Al_2O_3+TiC).



Remarks: *Percentages indicate overall improvement in Flank wears of ASPRO ™ treated inserts vs. original inserts at corresponding cutting length.*

Fig. 19. Average Flank wears for Original (OT) and ASPRO™ treated (2T) mixed alumina ceramic cutting tool inserts.

The test indicates an average overall improvement in Flank wears of 32% using ASPRO™ treated inserts vs. original inserts. Flank wears for Original and ASPRO™ treated Mixed Alumina cutting tool inserts after 2340 mm cutting length are presented in Fig. 20.



Remarks: *Original inserts are marked as 0T1-1, 0T1-2, 0T2-1, 0T2-2 and ASPRO ™ treated inserts are 2T1-1, 2T1-2, 2T2-1, 2T2-2.*

Fig.20. Flank wears for Original and ASPRO™ treated Mixed Alumina cutting tool inserts

These test results indicate that the ASPRO™ Conversion Technology can be applied to enhance the required properties for ceramic cutting tools, and as a result the ASPRO™ treated ceramic cutting tool inserts can offer significant advantages in machining hard materials and distinguish them from traditional steel, tungsten-carbide and ceramic cutting materials:

- Higher corrosion and oxidation resistance
- Higher abrasive wear resistance
- Higher hardness
- Increased thermal shock resistance
- Increased heat dispersal

Together, these properties permit to increase the rate of metal removal while obtaining longer tool life. Reduced operating time to produce a finished part, and reduced machine downtime through less frequent insert indexing and replacement result in an overall improvement in productivity and part cost reduction. It is deemed that the ASPRO™ treated ceramic inserts, on account of their increased thermal shock resistance, could therefore potentially capture a significant share of the market, by providing a cost-effective solution. The further development of improved ceramic cutting tool inserts will pave the way for laying the foundation towards developing an innovative technology for machining hard materials.

9.6 Chemical, Mineral, and Metal Processing

Chemical, Mineral, and Metal Processing applications are largely based on the combination of thermal stability, wear, hardness, and corrosion resistance. Potentially, the main application areas of ASPRO™ treated ceramics are:

- Chutes
- Pipelines
- Hydrocyclones
- Pumps and valves
- Crucibles
- Bearings
- Metal casting

9.7 Medical Applications

Biomedical applications include:

- Dental and orthopedic implants
- Dental restoratives
- Knee and hip replacements

The key to using advanced ceramics in these applications to be inert, biologically compatible with body fluids, provide a visual appearance, which matches the natural system (for teeth), and resist fatigue. They must have good specific strength, stiffness and heat resistance (for teeth). The candidate materials for medical applications include, for example, aluminum oxide, hydroxyapatites, borosilicate glasses, and glass-ceramics. In biomedical applications alumina has considerable advantages over other materials because of its inertness, which results in excellent biocompatibility. Potentially, the ASPRO™ Conversion Technology can be applied to enhance strength and heat distribution in materials used for medical applications.

10. Electrical/electronic applications

The electronic ceramic industry constitutes the largest market segment using advanced ceramic materials and is characterized by rapid innovation and technological changes, which require the use of novel materials with new desired properties. Electronic ceramics provide basic components in the support for a variety of electronic products including computers, industrial control equipment, consumer automotive devices, and digital switches. The ceramic properties, which are important for electronic applications, result from a variety of mechanisms that depend on the bulk material, grain boundary properties, and surface effects. Important properties include electrical: dielectric constant, dielectric strength, electrical conductivity, dielectric loss and power loss; thermophysical: thermal shock resistance, heat capacity, thermal expansion and conductivity; and mechanical strength.

Preliminary investigations of electrical properties for transformed alumina suggest that the change occur due to an increase in the concentration of defects (e.g., dislocations and charge carriers) and a change in the grain and grain boundary structures [3, 15]. Dielectric properties showed unusual behavior at different frequencies especially the loss factor (Fig 21). The impedance of alumina samples showed also the change in values after the treatment.

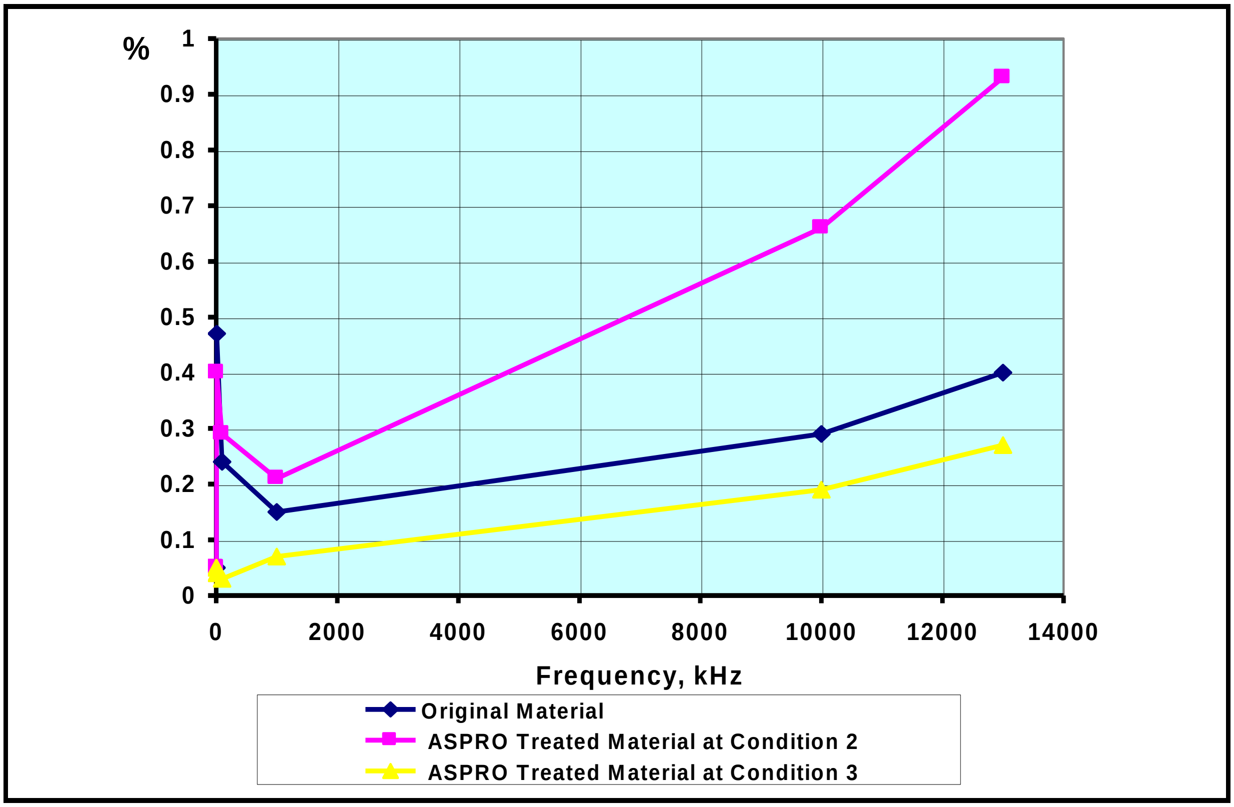


Fig. 21. Dielectric loss of alumina ceramics.

The potential benefit of the ASPRO™ conversion technology is evident when viewed in the context of electronic applications. The ASPRO™ conversion technology alters the atomic structure and chemical bonds in the treated materials. This could result in enhanced critical properties for electronic applications. The measured changes in the thermal shock resistance, specific heat, thermal conductivity, thermal expansion, and dielectric properties are unexpected in traditional ceramic materials and serve as evidence that fundamental structural changes have occurred in the ASPRO™ transformed materials. The process could influence properties, which are important to enhance electrical and, especially, for example, the High-Tc Superconductor performance, such as transition temperature (Tc) and current density. This could occur as a result of changing the grain and grain boundary structure, concentration of defects, and grain contacts.

The ASPRO™ treated materials could be used as passive or active components for functional electronic devices. The enhanced performances of the ASPRO™ materials allow a new and extended range of applications in the highly complex and multi-functional regime of a microelectronic package. The ASPRO™ conversion technology can be applied in the areas electrical/electronic applications (Fig. 22), for example:

- Insulators
- Ceramic Packaging of Integrated Circuits
- Substrates
- Dielectric Capacitance
- Piezoelectric Devices
- Electro-optic Devices
- Ceramic Sensors
- Magnetic Ceramics
- Semiconductors
- Superconductors

Electronic Applications of ASPRO™ Treated Ceramic Materials

Electronic Ceramic Applications

The Substrate/Insulator

to

The Package

Insulators

Semiconductors/Ceramic Packages,
"Integrated Circuits"
Ceramic Sensors and Magnets
Superconductors

Fig. 22. Electronic applications of ASPRO™ treated materials

The ASPRO™ process can be integrated in the fabricating process while considering the requirements of the processing details and control of precursors, synthesis, and impurity level, and achieving improvement of components for electronic applications.

11. Conclusions

The patented novel ASPRO™ technology changes and significantly enhances the physical and thermal properties of ceramic materials, while maintaining near theoretical density levels and providing enhanced mechanical performances. The ASPRO™ treated ceramic materials exhibit unique combinations of properties relative to their untreated counterparts, which were revealed by a battery of advanced characterization tests, such as physical, thermo-physical, mechanical testing, and materials composition and microstructure analyses. Customized treated materials can be achieved by tuning the ASPRO™ conversion process and the composition of the original materials.

The test results indicate that the new ASPRO™ treated ceramics can be used for combustion engines, aluminum die-casting, chemical and metal processing, medical, and for electronic applications as insulators, substrates, and functional electronic materials. The value of ASPRO™ technology in the manufacture and operation of internal combustion engines was proven as a result of the successful installation and testing of the alumina ceramic cylinder liners into an engine. The inexpensive aluminum oxide based materials transformed by ASPRO™ process meet the major selection criteria for ceramics in internal combustion engines. The ASPRO™ treated alumina ceramic liners, incorporated into combustion engine, posses high thermal shock and oxidation/corrosion resistance, higher operational temperature capability and wear resistance, and lower mass density than metal components. Observation of ceramic components of engine with ASPRO™ treated ceramic liners indicates reduced friction, and improved wear and oxidation/corrosion resistance. The ASPRO™ conversion technology can improve efficiencies, enhance material properties, ease ecological problems, and provide cost savings by using the converted alumina instead of more expensive advanced ceramic alternatives.

The analyses of the Material – Process – Property – Application Relations using a new model of interactions in material systems is providing opportunities to gain further understanding into the phenomena created by ASPRO™ Conversion Technology and for extending the use of ASPRO™ treated ceramic materials.

The value-added component of the ASPRO™ Conversion Technology is a process that enhancing the performance, use, and life of existing components. Accordingly, it has opened the door to exciting new markets where traditional ceramics have had limited success. In many instances, the ASPRO™ treated ceramics, possessing desired properties, could lead to substitution of metals or traditional materials in a wide range of applications. The benefits to be gained include:

- Producing ceramics with enhanced mechanical, thermo-physical and electrical properties, including high thermal shock resistance for full dense ceramics.
- Providing alternative low-cost alumina ceramics and new ceramic materials to metal or expensive ceramic components for internal combustion engines.
- Easing ecological problems, reducing emissions of hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter emission, and fuel consumption in combustion engines.
- Increasing the reliability and longevity of specific applications and components.
- Enhancing the performance of applications.
- Cost savings arising from the use of lighter weight and better functioning ceramic components.
- Extending the use of advanced ceramic materials well beyond their traditional limits.

The ASPRO™ Conversion Technology exhibits the potential to extend the performance of advanced ceramic materials and subsequent products for structural and electronic applications in numerous industries while increasing efficiencies and achieving very favorable cost/benefit ratios.

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