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(54) **PROCESSING OF RIFLED GUN BARRELS FROM ADVANCED MATERIALS**

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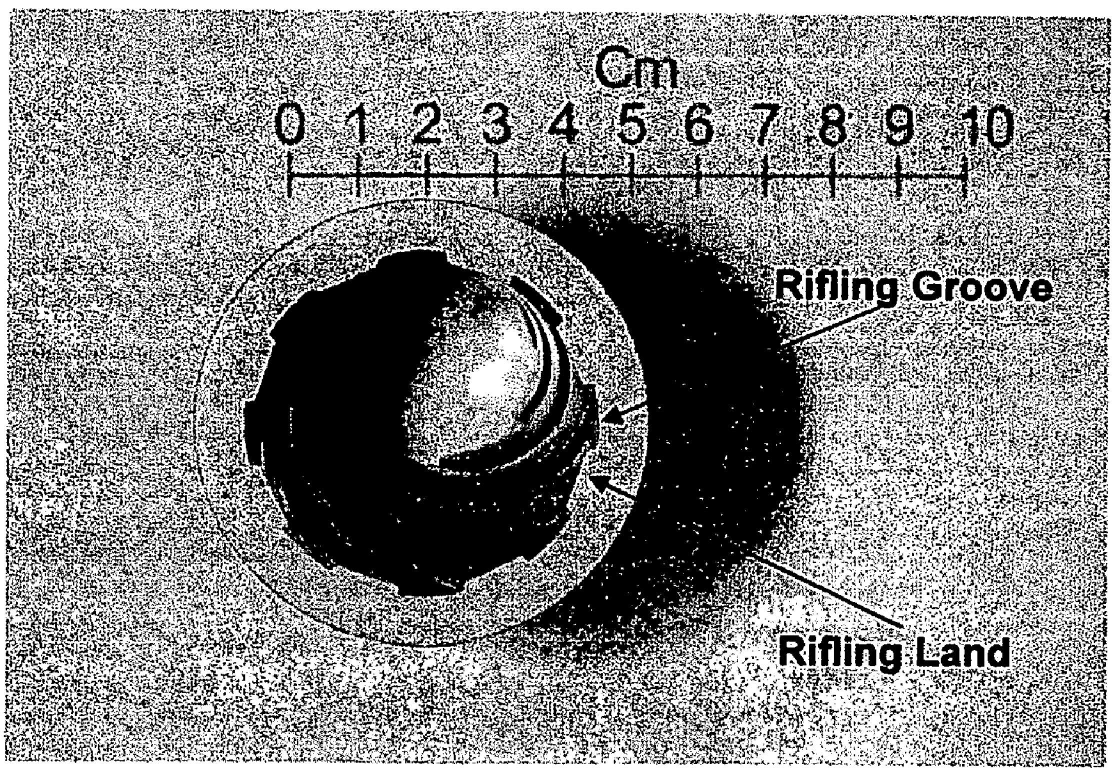
(57) **ABSTRACT**

Gun barrels made from advanced materials have the potential to provide a significant increase in barrel life as well as a reduction in weight (for advanced ceramic materials) for small caliber systems. The potential use of advanced materials as gun barrels is severely limited due to the difficulty in introducing the rifling pattern on the inner diameter. Most projectiles coming out of the guns are spin stabilized (for aerodynamic flight stability). This spin is imparted by a rifling pattern (lands and grooves) in the inner surface of the gun barrel. The processing of gun barrels made from advanced materials with internal rifling pattern poses a tremendous processing challenge to the materials community. The rifling lands and grooves and desired twist rate coupled with the difficulty of machining some of the advanced materials (ceramics, cermets, hardmetals, etc.) makes the economic manufacturing of such gun barrels extremely difficult. Currently, this form of rifling is achieved by machining in case of metallic gun barrels.

The limitation in producing the rifled pattern lies with the conventional processing of complex shaped advanced materials such as ceramics, cermets, or hardmetals. Shaping of these typically requires careful diamond grinding. This grinding process is not only very expensive but it also introduces flaws in case of the brittle ceramics (microcracks). These flaws are detrimental to the performance of these advanced materials as rifled gun barrels. Thus, there is an opportunity and challenge to the materials community to come up with a processing solution that will allow advanced materials such as silicon nitride (Si_3N_4), SiAlON, hardmetals, etc. to be used as gun barrels that have the rifled pattern in the inner diameter.

Herein are provided methods and compositions useful to form the rifled gun barrel tubes from advanced materials using little or no machining of the internal rifled geometry.



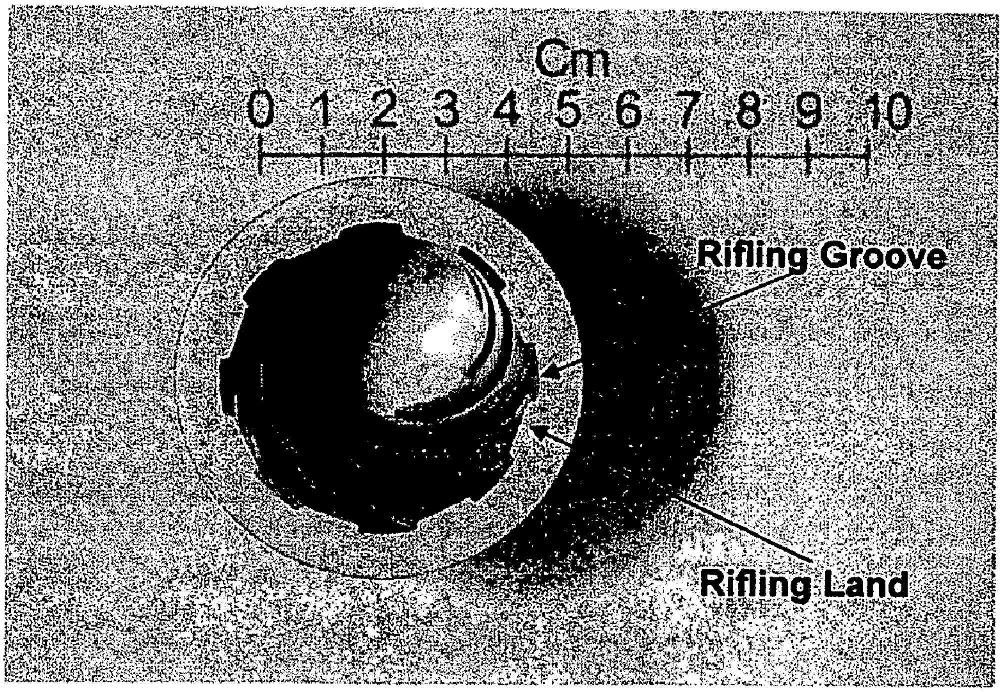


Figure 1: ~~End view of molded rifling tube showing lands and grooves~~

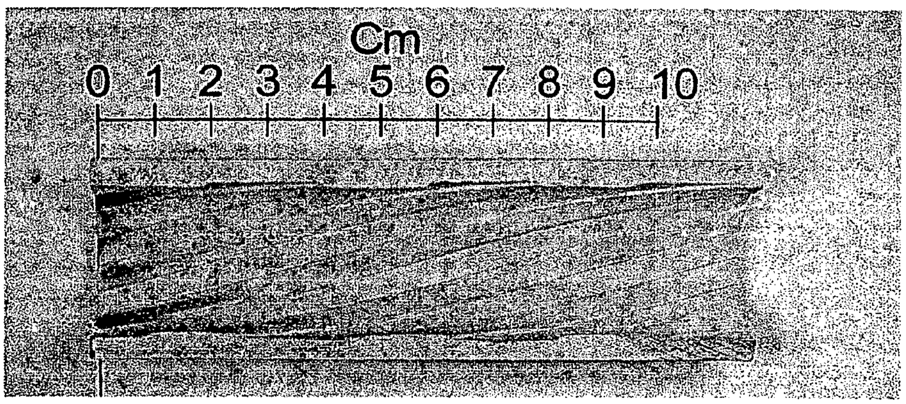


Figure 2: A view of a sintered Si3N4 rifling tube that had been sectioned in half in the as-molded state.

PROCESSING OF RIFLED GUN BARRELS FROM ADVANCED MATERIALS

PRIORITY

[0001] Priority is claimed on the basis of Provisional Application Number 60/697,183, Filed on Jul. 7, 2005.

STATEMENT CONCERNING FEDERAL SUPPORT

[0002] This patent application is based to a large extent on the research work carried out in connection with contract W911QX-05-C-0029 with the US Army Research Laboratory. Accordingly, the federal government retains certain rights in the invention disclosed herein.

FIELD OF THE INVENTION

[0003] The invention relates to the processing of rifled gun barrels from advanced materials.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1**: End view of a molded Si_3N_4 tube with internal rifling pattern showing lands and grooves.

[0005] FIG. **2**: View of a sintered Si_3N_4 rifling tube sectioned in half to show the rifled geometry in the internal diameter of the tube.

PROBLEM

[0006] With the emergence of new propellants, the bore surface erosion in gun barrels has become a major problem that has to be tackled in the very near future. This need is forcing the gun barrel designers to try and develop various techniques to try and improve the life of the current steel gun barrels as well as look at new liner materials.

[0007] The other need of great importance to gun barrel materials is to try and reduce the weight for improved mobility. These requirements are challenging the designers and manufacturers of gun barrel liners. The current state-of-the-art gun barrels use chrome plating in their large caliber weapons to improve the bore life. The problem is that the failure of the current coated gun barrels frequently occurs after only about 250 rounds (compared to earlier 500 rounds). The failure occurs as the chromium coating is prone to cracks which allow the hot propellant gases to reach the steel substrate and eventually resulting in the coating layer spalling off. Also, the chrome plating process itself has major environmental concerns associated with the process itself and its compliance cost is also very high. Thus, there is the need for a change in the gun barrel material, and advanced materials such as ceramics, cermets, or in some cases even hardmetals (though they have higher densities) offer the best promise. However, the machining of these materials to produce the complex shape of the rifling pattern in the inner diameter of a tube is a major problem that has not until now been solved.

SOLUTION

[0008] As the advanced materials are extremely difficult to shape (through conventional machining or casting route), it was necessary to come up with alternate processing techniques that can be used to form these materials into near net shaped components. The process of powder injection molding (PIM) is a relatively new technology (its true commercialization started in mid to late 1980's) that is used for the processing of complex shaped parts from advanced materials (metals, ceramics, cermets, etc.). The processing of PIM has not been exploited to manufacture rifled gun barrel tubes from advanced materials. Other than PIM, processes that will produce net shape or near net shape parts include gel casting of powdered materials or slurry casting of advanced material on a shaped core that can later be removed by a number of means such as machining, leaching, or simple mechanical extraction, etc. All the above processes use a shaped core rod to impart the internal geometry of a rifled gun barrel tube. The invention provides a processing method that can be used to form the net shaped or near net shaped rifled gun barrel tubes.

BACKGROUND

[0009] Powder Injection molding (PIM) is a materials processing technique that has the unique capability of producing complex shapes from numerous high performance materials. This is a relatively new technology that has come of age over the last 15 years. PIM uses the shaping advantages of traditional plastic injection molding but expands the applications to numerous advanced materials such as metals, alloys, ceramics, intermetallic compounds, and composites. A number of these advanced materials have dual use potential. Most of the development and applications of PIM have been in the commercial sector. However, PIM is an ideal dual use technology that has applications both in the military as well as in the commercial arena.

[0010] Advanced materials, especially advanced ceramics such as silicon nitride and SiAlON are extremely attractive due to their unique property combination of high strength, oxidation resistance, elevated temperature strength, and moderate toughness. They will have numerous dual use applications if they can be manufactured into complex shapes in a cost effective manner. Several cermets can also provide extremely attractive properties that will be suitable for rifled gun barrel applications. Another material known as hardmetal (tungsten carbide), though having a higher density compared to steel, could be useful as a short segment of a large caliber gun barrel, especially in the breech area where the pressure, temperature and erosion is maximum. The small addition in weight may be worth it for large caliber systems if the erosion can be significantly reduced. While for the low caliber gun barrel tubes, the stress will be not on just a more high temperature erosion resistant material but also on lowered weight. In the latter case, the advanced ceramics will provide an ideal solution.

[0011] It is, therefore, necessary to develop a PIM process that will be able to incorporate the processing of fine silicon nitride powder, fine alumina powder and a hardmetal (WC—Co), to form the desired rifled shapes. Collectively, the use of these materials shows the generality of the disclosed process. The ultimate goal is to develop a PIM process that is capable of producing complex shaped advanced material gun barrels with internal rifling pattern, in an affordable manner.

[0012] Other alternate processes capable of forming the rifled gun barrel tubes include gel casting and slurry casting. All these processes involve the use of a core or mandrel that has the land and groove and the rifled pattern already machined into it around which the advanced material that will be used is molded or cast. In all cases, the advanced material is in a powder form and is mixed with other organic compounds and/or water to form suitable slurry or a feedstock that can then be molded or poured around the pre-shaped core rod which already has the desired lands and grooves and the rifling pattern all formed into it.

PROCESS BACKGROUND

[0013] In general, the process of powder injection molding (PIM) consists of four major steps: feedstock formation, molding, debinding and consolidation. The process begins with the mixing of a small amount of organic binder with a desired inorganic powder (metal, alloy, intermetallic compound, ceramic, etc.). The mixture is granulated (pelletized) to form a "Feedstock." The feedstock is introduced into the hopper of a powder injection-molding machine, where it is re-melted in the barrel and moves up to the front section near a nozzle through which it is pushed into an oversized die cavity. This molded "green" shape which is usually an oversized replica of the final product is subjected to a step known as debinding where the organic portion of the green part is removed. The purpose of debinding is the gradual and complete removal of the organic phase without leaving behind any residual contamination. After the removal of the binder, the part is subjected to a thermal treatment known as sintering which results in the consolidation or densification of the part to the desired level. Post sinter heat treatments and additional hot consolidation steps (Hot Isostatic Pressing, HIP) can be used to attain the desired properties.

[0014] The PIM process is extremely suitable for moderate volume of parts that are relatively small (golf ball being on the upper size range of "conventional" PIM process). Thus, it provides the designers and engineers with a powerful shaping technique that can shape materials like plastics but does not confine them to the plain engineering plastic materials (thermoplastic or thermosetting type). It should be realized that the process has numerous variants that is a reflection of the different combinations of powders, organic binders, mixing and molding techniques, numerous debinding routes (which are dependent on the initial binder choice), and widely varied sintering practices (batch or continuous; vacuum or atmosphere which can vary from air to hydrogen to dissociated ammonia to inert gases). Some of the typical post sinter processes includes coining (for metallic parts), HIP'ing, grinding, polishing, etc.

[0015] The conventional PIM process is carried out in high pressure plastic injection molding machines. As the size of the part increases, the machine capacity typically has to be increased due to the larger clamping force that is necessary. Thus, a different molding approach can also be considered when trying to PIM process moderately large parts using fine powders of advanced materials. Some of these approaches include the use of a low or medium pressure injection molding techniques.

[0016] At this point it would be worthwhile discussing some of the characteristics of PIM Feedstock that forms the starting point of the process. The ideal feedstock will have relatively high amount of the inorganic powder loading (minimum 50 volume percent); can be molded into relatively large components without molding defects; the organic binder phase can be removed in an environmentally friendly manner without debinding defects and distortion; and the material can be sintered to the desired density without the loss of shape (distortion). Unfortunately, PIM processing of fine materials (cermets, ceramics, hardmetals, etc.) have contradictory property requirements that complicate the process. For example, as the relative solids loading of the powder is increased, the viscosity of the feedstock increases rapidly and it becomes more difficult to mold large parts free of defects. Alternately, if we go with lower solids loading for the ease of mold filling in large parts, subsequent processing will result in large shrinkage, which usually results in problems with distortion and the part precision. Similarly, for filling out a large size mold free of defects, it would normally be necessary to use large injection molding pressures. With the high pressures in the conventional PIM process, there is the need for large clamping pressures to keep the molds together so as to prevent parting line defects such as burrs, which are difficult to remove. The other problem associated with high-pressure injection molding is also the extensive wear and tear on the tooling, which has to be made from the expensive high quality steel. Also, the tooling in this case is extremely complex and it will be cost prohibitive to build a new tooling only after the fabrication of a relatively low number of parts due to excessive tool wear. However, for making short sized tubes for use in only the breech area of the gun barrel tubes (where the erosion and temperature is at its peak), it may still be cost effective to use conventional high pressure injection molding process. The automation, experience, and the availability of these injection molding machines are the major advantages of this process.

[0017] The other alternative is to make larger sized parts in a cost effective manner. In this case it may be possible to use low cost tooling made from aluminum or brass or some less expensive steels. Such low cost tooling for larger parts is only possible when we use a low pressure or medium pressure injection-molding machine. It should be realized that the tooling cost difference increases (between a tool steel mold and a mold made of aluminum, bronze, or low cost steel) significantly as the part size becomes larger. Thus, for larger parts, the tooling cost can be significantly lower if the mold material can be made from aluminum, bronze, or low cost steels instead of the relatively expensive tool or die steels. In the overall economics of producing large size PIM parts in small volume, the factors that start to play an important role are the powder price, tool cost, and production cost. For economic viability, it is vital to use relatively inexpensive tooling, and have a lower operating cost. For making moderately large sized ceramic parts in fairly moderate numbers (around 10,000 parts a year), it is best to make dies from conventional tool or die steel materials and use low or medium pressure injection molding machine. In this case, using a low pressure injection molding will result in a tool life that will be around 70 to 100% more due to the lowered wear on the die as the pressure used is significantly lower.

[0018] The desired powder of the advanced material has to be mixed together with the organic binder system. There are a host of available organic binder systems to choose from. Some of the organics that can be and have been used in powder injection molding process are: a variety of different waxes such as paraffin wax, microcrystalline wax, Carnauba wax, bees wax, etc.; variety of different polymers such as polyethylene, polypropylene, polystyrene, methyl ethyl ketone, butyl stearate, aniline, polyethylene glycol, polyvinyl butyryl, dibutyl phthalate, polymethyl methacrylate, ethylene vinyl acetate copolymer, methacrylic acid ester copolymer, polyvinyl chloride, etc.; oils and acids such as stearic acid, oleic acid, vegetable oil, palm oil, fish oil, peanut oil, etc. Typically, the organic binder system is a combination of waxes, polymers, oils and acids. The viscosities of the typical binder systems can vary significantly depending on the individual binder components and their combinations. The temperature of the mixing and molding can be quite high, which necessitates the use of high pressure injection molding machines, or quite low which can allow the use of low pressure injection molding machine.

[0019] The next important step in PIM is injection molding. In this step, the desired feedstock is fed into the hopper of an injection-molding machine, where a screw advances the feedstock to the front of the barrel while also heating the feedstock to the molding temperature. The molten feedstock is then pushed into an oversized die cavity at high pressures. This type of injection molding machine is used by more than 95% of the PIM industry. The pressures used in these conventional PIM machines are high (typically around 4000 to 5000 psi) and the tool material for the dies are usually tool or die steels. The clamping force of a conventional reciprocating screw type machine must exceed the peak injection pressure times the projected cross sectional area of the die cavity and the runner system. Thus, as the size of the part increases, the clamping force of the machine also increases greatly when the injection pressure is high. The fabrication of complex dies from tool steels is quite expensive especially when the number of parts is low (1000 parts/year). If a larger number of parts is required, it makes sense to use a hardened steel die. For larger parts, it may be reasonable to use a low pressure injection molding machine as it would produce a larger number of parts compared to high pressure molding machine due to the lower wear of the tools. For large parts, dies made of softer metals would not work with the conventional high-pressure injection molding machines. To combat this, a low or medium pressure injection-molding machine may be useful. In this type of machine the feedstock is fed into the die cavity at low pressures, resulting in low tooling cost and tool wear. Large size parts are possible with this type of low-pressure machine. Gun barrel tubes with the rifling pattern have been successfully molded using the low/medium pressure injection molding machine. The tooling was made from conventional steel with a pre-designed core rod that could be extracted. An alternate to the elevated temperature injection molding process is a low temperature injection molding where the feedstock is made from a water-based binder system. The feedstock is molded at low pressures into the die cavity where the feedstock is subjected to a low temperature where the part freezes. The part is then extracted from the mold and subjected to a process similar to freeze drying which removes a significant part of the water which is a part of the feedstock.

[0020] After a PIM part has been molded and extracted, the parts known as "green parts" are subjected to a step known as debinding. A variety of different debinding schemes are available based on some of the different binder combinations. Some of the debinding techniques include solvent extraction, thermal debinding, catalytic debinding, freeze drying, etc. The purpose here is to remove the binder and yet retain the shape of the part itself. This process is a very delicate step in the manufacturing cycle and needs to be carefully controlled as numerous defects can result during this step. Typically, a major part of the organic binder is removed during this step, leaving behind a small amount of binder that holds the shape of the part.

[0021] The final step in the PIM process is the consolidation step. Typically, in this step, the debound part is heated to a temperature where the parts undergo sintering. The sintering process is responsible for the consolidation of the part, where due to the temperature driven atomic motion, the pores are gradually eliminated. The sintering process may be carried out in solid state (where all material remains in the solid state throughout the sintering cycle) or with the help of a liquid phase (known as liquid phase sintering where a small volume of the material is in the liquid state) that forms during the sintering cycle. The aim in this case is the attainment of near full density of the advanced material. It is conceivable that in some cases, complete densification of the part may not be possible through pressureless sintering techniques. In that case, pressureless sintering will be used to densify the parts to a level where all the pores will be closed pores. Once that is achieved, an additional step of containerless hot isostatic pressing may be used to fully densify the part. It should be noted that the final part is a miniature version of the green part. Thus, it is important to know the exact shrinkage of the part before the tooling is designed. Unless the proper shrinkage is used to design the tooling, the part will not be to final print. The process of PIM has good repeatability and if the conditions of feedstock formation, molding, debinding and sintering are kept unchanged, the parts are quite repeatable. This can be used to a great advantage in the formation of the rifled gun barrel tubes.

[0022] Other similar processing concepts can also be used to form these rifled gun barrel tubes without the use of extensive machining to form the intricate inner diameter lands and grooves with the rifling pattern. Two of the techniques that can be used are gel casting and slurry casting. In these processes, the powder of the desired advanced material (ceramics, cermet, hardmetal, etc.) is formed into slurry using water or solvents that have small amounts of gel forming material. In this case, a machined core rod is used as in case of PIM to form the internal diameter of the rifled gun barrel tube. In this case, the slurry will be poured into a mold that has the machined core rod. The material then can gel and form a solid. The core rod can be made from a variety of different materials such as machined ceramics, high temperature wax, rigid plastics, gypsum, etc. The key purpose of the core rod is to impart the desired shape to the internal diameter of the gun barrel tube and then it should be easily extractable. The core rod may be mechanically removed, may be thermally extracted, or may be extracted chemically or through its dissolution in a solvent. The gel cast or the slurry cast material will harden and take up the shape of the mold and the core rod. Once the core rod is removed, the process will include the removal of the gel or the small amount of organic binder. The remaining step will be the same as the PIM process where the part will be consolidated though the sintering step, which is the high temperature exposure of the part.

EXAMPLE 1

[0023] This example describes the processing of a rifled alumina gun barrel tube that was around 100 mm long having eight lands and eight grooves. Over and above the lands and grooves in the ID, the barrel had a 10:1 twist (1 complete twist in 250 mm) incorporated into it.

[0024] The powder chosen for this investigation was an alumina powder that had an average particle size of around 0.61 micrometer with a D20 of 0.42 micrometer and a D90 of 1.39 micrometer. The BET specific surface area of the powder was 5.1 m^2/g. The powder had a small amount of (515 ppm) MgO milled in as a sintering aid. Other impurities in the powder are 37 ppm of K, 12 ppm of Na, and 19 ppm of Si. The powder had a density of 3.97 g/cc.

[0025] The powder was mixed with an organic binder using a double planetary mixer. Initially the critical solids loading of the powder was determined using a torque rheometer. It can be said that this powder will have a critical solids loading of around 56 v/o. Based on the loading curve and MPI's experience with the powder injection molding process using the low/medium pressure molding, the final loading of the material used was 53.4 volume percent. The green density of the feedstock was measured by the pycnometer to be around 2.38 g/cc.

[0026] Special tooling was designed for fabricating the injection molded rifled gun barrel liners from alumina. The tooling consisted of the mold cavity and a core rod. The molding conditions used for molding the gun barrel tubes were determined and used to mold several gun barrel tubes. The gate was removed from the main mold body by cutting away the gate section. The as-molded samples of the ceramic rifled gun barrel tube were debound using a thermal debinding process. The debinding program was around 32 hours long. After the parts had cooled to room temperature, they were weighed to determine the amount of binder extracted. After an adequate amount of binder is removed (typically greater than 50% of the binder) the samples are taken to a different furnace for sintering. The sintering was carried out at a temperature of around 1600° C. with a hold of 2 hour at the peak temperature. The sintering cycle consisted of a number of slow ramps in the early stages to remove the remaining binder without creating debinding defects in the part. After sintering, the rifled gun barrel tubes were visually observed, followed by observations under a stereo-microscope. The samples were dimensioned to determine the shrinkage and the densities of the parts were also measured using the water immersion technique. The densities of the parts were determined to be around 3.7 g/cc which is almost close to full density. Thus, the process of PIM is suitable for fabricating an advanced ceramic gun barrel liner based on alumina that had 8 grooves and 8 lands which had a uniform twist of 1:10.

EXAMPLE 2

[0027] This example describes the processing of a rifled hardmetal (WC—Co) gun barrel tube that was around 100 mm long with a 25 mm inner diameter, a 33 mm outer diameter, having eight lands and eight grooves. Over and above the lands and grooves in the ID, the barrel had a 10:1 twist (1 complete twist in 250 mm) incorporated into it.

[0028] The powder chosen for this investigation was a hardmetal based on WC—Co. The desired WC—Co powder was mixed with an organic binder using a double planetary mixer. The feedstock was then molded into a special tooling that had an extractable core rod that was machined to have the desired lands and grooves and the uniform twist needed for the injection molded rifled gun barrel liners to be fabricated from the hardmetal. The molding conditions used for molding the gun barrel tubes were determined and used to mold several hardmetal gun barrel tubes. The gate was removed from the main mold body by cutting away the gate section. (As is known to one skilled in the art, the feedstock during injection molding flows through the runner and then through the gate into the actual cavity of the mold.)

[0029] The as-molded WC—Co rifled gun barrel tubes were debound using a thermal debinding process. After the parts had cooled to room temperature, they were weighed to determine the amount of binder extracted. After an adequate amount of binder was removed (typically greater than 50% of the binder) the samples were taken to a different furnace for sintering. The sintering was carried out at a temperature of around 1450° C. with a hold of 1 hour at the peak temperature. The sintering cycle consisted of a number of slow ramps in the early stages to remove the remaining binder without creating debinding defects in the part. After sintering, the rifled gun barrel tubes were visually observed, followed by observations under a stereo-microscope. The samples were dimensioned to determine the shrinkage and the densities of the parts were also measured using the water immersion technique. The densities of the parts were determined and found to be close to full density. Thus, the process of PIM is suitable for fabricating a hardmetal gun barrel liner based on alumina that had 8 grooves and 8 lands which had a uniform twist of 1:10.

EXAMPLE 3

[0030] This example describes the processing of a rifled silicon nitride (Si_3N_4) gun barrel tube that was greater than 100 mm long with around 25 mm inner diameter, a 33 mm outer diameter, having eight lands and eight grooves. Over and above the lands and grooves in the ID, the barrel had a 10:1 twist (1 complete twist in 250 mm) incorporated into it.

[0031] The powder chosen for this investigation was a silicon nitride powder with some sintering additives consisting of alumina and yttrium oxide. The combined powder had a measured density of 3.3 g/cc.

[0032] For preparing the actual feedstock, a loading lower than the critical loading was needed. The critical solid loading was determined to be around 62 volume percent. A final feedstock solid loading of 56.7 volume percent was chosen. After weighing the desired amount of organic binder, the binder constituents were placed into the pot of a double planetary mixer and it was allowed to heat until all the binder was melted. The powder was then added (silicon nitride powder with the additives) to the melted organic binder. The powder and the organic binder were then mixed for 12 hours. The binder and powder mix was allowed to cool and then it was removed. This feedstock was introduced into the hopper of a low/medium pressure injection molding machine. Several gun barrel tubes were molded using a tooling that had an extractable core rod that was machined to have the desired lands and grooves and the uniform twist needed for the injection molded rifled gun barrel liners to be fabricated from the silicon nitride. With respect to the tooling, it should be noted that there is a core that has the desired rifling patter built in and after the molding the core can be removed by manual extraction or by a motor. The core has to turn slowly and the lands and grooves have to follow the twist for proper extraction, analogous to a bolt being removed from a threaded hole. The molding conditions used for molding the gun barrel tubes were determined and used to mold several silicon nitride based gun barrel tubes.

[0033] The spiral samples were molded to provide an idea about the molding parameters that can be used to provide good mold filling as the mold to be filled is quite complex and moderately large in size (relative to injection molded parts). The longer the spiral length that is filled, the better is the mold filling. Spiral samples were first molded using a constant pressure of 80 psi and varying the molding temperature. The next set of spiral samples were molded using a constant temperature but varying the molding pressure. The results of the spiral tests provided an idea about the molding parameters to be used for molding the gun barrel tubes. It was observed that keeping the molding pressure constant, the length of the molded spiral increases with increasing molding temperature. This is to be expected as the viscosity of the feedstock is expected to decrease with temperature, thus causing the material to fill the die to greater lengths. It can also be seen that keeping the molding temperature constant, the length of the molded spiral increases with increasing molding pressure. This is also natural as with increasing pressure, more feedstock tends to be pushed into the die, thereby increasing the length of the mold fill.

[0034] Even though the spiral molding provided an idea about the mold filling parameters to be used, multiple molding trials were necessary to obtain the conditions necessary for proper molding of the gun barrel tubes. Majority of the molded samples would crack during the core rod extraction. After the samples were molded, green weights and green dimensional measurements were obtained. Using a stereomicroscope, each sample was inspected thoroughly for any molding defects. Some samples showed signs of cracking along the spiral edge where the groove meets the land. These samples were reverted into the injection molding tank to be recycled. However, a few good samples were eventually molded. One skilled in the art can, without undue experimentation, likewise determine the proper molding parameters needed in each instance to practice a process according to the present invention.

[0035] The debinding of the rifled silicon nitride tubes was carried out till the binder extracted was greater than 75%. This precaution was taken since the silicon nitride powder was quite fine and it was felt necessary that a major part of the binder be removed before the part was subjected to pre-sintering and sintering. Once this was achieved, the debound samples were taken for pre-sintering and sintering.

[0036] The debound rifled tubes were first presintered. The purposes of presintering the samples were a) Remove the binder prior to sintering; and b) Increase strength for better handling. The parts were presinterted in a Lindburg Box Furnace. The presintering was carried out using a flowing nitrogen atmosphere of 5 cfm. The box furnace runs were carried out at 800° C. It was observed that all the rifled tubes that were presintered in the larger box furnace had a slightly darker color. After presintering, the samples still exhibited enough strength for handling which was important as the sintering of these parts had to be carried out in a different high temperature furnace. The Si_3N_4 samples were sintered in a graphite furnace that had the capability to go to 2000° C. Two sintering temperatures were used. The first sintering was carried out at 1800° C. and the hold-time at the peak temperature was around 120 minutes. A nitrogen pressure of 3 psig was maintained in the furnace throughout the run. The sintered density of the samples was measured by water immersion technique. The average of the densities of the parts was around 2.8 g/cc. This was lower than what was desired. Next the higher sintering temperature of 1900° C. was tried with a hold time at peak temperature of 180 minutes. This resulted in rifled gun barrels with sintered density of around 2.92 g/cc. Some of the rifled gun barrels were then containerless hot isostatically pressed at a temperature of 1750° C., using a nitrogen gas pressure of 15 ksi (kg per square inch) for 2 hours. The densities of the rifled tubes were increased to 3.0 g/cc.

EXAMPLE 4

[0037] This example describes the processing of a rifled silicon nitride (Si_3N_4) gun barrel tube that is greater than 100 mm long with around 25 mm inner diameter, a 33 mm outer diameter, having eight lands and eight grooves. Over and above the lands and grooves in the ID, the barrel has a 10:1 twist (1 complete twist in 250 mm) incorporated into it.

[0038] The powder chosen for this is a silicon nitride powder with some sintering additives consisting of alumina and yttrium oxide. The combined powder has a measured density of 3.3 g/cc. The powders are mixed with a gel forming material and then poured into the cavity of the die with the shaped core rod. Time is allowed for the gel to dry and then the core rod is extracted. The part is then heated to burn off the gel and then sintered to obtain high sintered density of the part.

Silicon Nitride Rifling Tubes

[0039] The silicon nitride powder with alumina and yttrium oxide was mixed in a double planetary mixer using an organic binder. The mixed feedstock was granulated and then transferred to a molding machine.

[0040] Various molding iterations were carried out. In some cases going to high temperature resulted in sinkholes and lower temperatures resulted in poor fill. The final parameters used on the injection molding machine for molding the Si_3N_4 rifling tubes can be seen in Table SN1. These parameters were used to successfully mold nine of the rifling tube samples. The molded dimensions and weights are shown in Table SN2.

TABLE SN1

Molding parameters used for the tapered Si_3N_4 rifling tubes

Part Description	Tank Temp.	Pipe Temp.	Orifice Temp.	Fill Time	Mold Temp.
Rifling Tube Si_3N_4 Samples	182	177	177	12	Ambient

TABLE SN2

Green weights and green measurements for rifling tubes with a slight taper.

Sample Number	Weight (g)	Length (mm)	O.D. (mm)	I.D. (mm)
1-T	173.7384	125.45	42.05	30.33
2-T	172.8143	125.50	42.07	30.32
3-T	173.6280	125.45	42.07	30.31
4-T	171.3400	124.08	42.06	30.31
5-T	172.0314	125.25	42.02	30.32
6-T	173.2958	125.10	42.01	30.28
7-T	173.3372	125.48	42.02	30.32
8-T	172.4473	125.45	42.05	30.25
9-T	144.1747	104.85	42.07	30.32

[0041] The samples were debound using the same debinding cycle twice. The detail of the preferred debinding cycle is shown in Table SN3. The samples were allowed to cool to room temperature before they were removed from the furnace.

TABLE SN3

Debinding cycle.			
Dewax Cycle ° C.			
Ramp Time (hours)	Ramp Rate (°/hr)	Set Point ° C.	Soak Time (hours)
1.45	34	75.0	6
1.00	28	102.8	8
5.50	3	121.1	10
3.03	18	176.7	10
Dewax Cycle ° F.			
Ramp Time (hours)	Ramp Rate (°/hr)	Set Point ° F.	Soak Time (hours)
1.45	60	167.0	6
1.00	50	217.0	8
5.50	6	250.0	10
3.03	33	350.0	10

[0042] These samples were then weighed to determine the amount of binder extracted. The binder extraction values can be seen in Table SN4 for both dewax cycles.

TABLE SN4

Binder extracted from 1st and 2nd dewax cycles.			
Sample Number	Binder Extracted From 1st Dewax	Binder Extracted From 2nd Dewax	Total binder Extracted
1-T	53.62%	22.38%	76.00%
2-T	54.12%	21.03%	75.15%
3-T	53.36%	22.88%	76.25%
4-T	54.43%	23.10%	77.53%
5-T	55.97%	22.66%	78.63%
6-T	56.65%	21.29%	77.94%
7-T	57.06%	21.55%	78.61%
8-T	57.65%	19.71%	77.36%
9-T	51.63%	21.83%	73.46%
Average	54.94%	21.83%	76.77%

[0043] These debound samples were presintered in flowing nitrogen atmosphere (5 cfm) using a temperature of 900° C. The samples were then sintered using the following sintering cycle:

[0044] Room Temperature to 1000° C. in 500 min (overnight heating)

[0045] 1000° C. to 1750° C. at 10° C./min

[0046] Hold at 1750° C. for 15 min

[0047] 1750° C. to 1900° C. at 3° C./min

[0048] Hold at 1900° C. for 180 min

[0049] Cool from 1900° C. to 1000° C. in 200 minutes

[0050] Furnace Shut Off

[0051] The sintered sampled were subjected to containerless hot isostatic pressing (HIP). The hot isostatic pressing was carried out at a temperature of 1750° C., using a gas pressure of 15 ksi for 2 hours. The resultant density was in the range of 3 g/cc. The samples had 8 lands and 8 grooves and a uniform twist of 1:10. The typical dimensions (nominal) of the rifled tubes are:

[0052] Outer diameter: 38 mm

[0053] Inner diameter: 27.5 mm

[0054] Length: 111 mm

Alumina Rifling Tubes

[0055] Many molding attempts were made. Table Al below shows the molding conditions for a incomplete mold fill and a complete mold fill.

TABLE A1

Molding conditions for ceramic rifling tube						
Part Description	Tank Temp	Pipe Temp	Orifice Temp	Pressure	Fill Time	Comments
Ceramic Rifling Tube	165° F.	155° F.	150° F.	65 psi	20 sec	Incomplete
Ceramic Rifling Tube	165° F.	155° F.	150° F.	80 Psi	20 sec	Good

[0056] Several rifled tubes were molded out of the alumina feedstock. The as molded samples were characterized and then debound. The wick debinding is carried out at 350 F. After cooling, the samples were cleaned and the percent binder extracted is calculated. The binder removal in all the samples was over 80% which is considered adequate. Sintering was carried out at various temperatures. The sintering is carried out at peak temperatures that varied between 1550 to 1600 C.

[0057] The sintered densities of the samples were measured by water displacement. The two different sintering cycles showed different densities. The lower temperature (1550 C) sintered material showed a density of 3.5 g/cc while the higher temperature (1600 C) sintered sample showed a density of 3.7 g/cc.

OTHER EXAMPLES

Example OE1

[0058] Processing a rifled gun barrel tube using another ceramic capable of withstanding high temperatures and with good erosion resistance. The ceramic is AlON (aluminum oxynitride).

Example OE2

[0059] Processing of rifled gun barrel with a larger diameter to fit the larger caliber guns such as 155 mm.

Example OE3

[0060] Processing of rifled gun barrel tubes with different land and groove arrangements such as the lands and grooves being sinusoidal in nature or like a saw-tooth in nature.

Example OE4

[0061] Very long tubes cannot be made as one piece by PIM. The way to overcome this difficulty is to fabricate tubes with shorter segments and join them together using a very high temperature ceramic joining pastes (having lower melt temperatures than the tube material). The small segments are designed in such a way that a V-groove is created when the parts are butted up against each other and the V-groove was filled with the ceramic joining paste. This ensures that the tube is gas sealed.

WC—Co Rifling Tubes

[0062] Rifled gun barrel tubes fabricated by the process of powder injection molding have been demonstrated with advanced ceramics. This section shows the generic nature of the PIM processing in fabricating the rifling tubes through the use of a hardmetal, commonly known as tungsten carbide. Tungsten carbides are a special class of ceramic-metal composite (sort of like a Cermet). There are different types of WC—Co with widely varying properties depending on the composition of the material. In this case, we have used simply the cobalt content to vary the material.

[0063] Table WC1 shows the molding conditions for the WC—Co rifling tubes with varying cobalt amounts. The WC-6Co alloy will be hard and have low toughness, while the WC-12Co will be relatively lower hardness (though it will have much higher hardness than most steels), but have high toughness. The hardmetals are much more dense compared to ceramics as well as compared to steels. So the purpose of rifled gun barrels made of hardmetals would not be useful for lightweight gun barrels that will be used by ground troop (for which the ceramic gun barrels will be ideal). However, the hardmetals are significantly tougher and impact resistant compared to ceramic-based materials. An ideal application for hardmetal gun barrels would be as a short segment, which can be placed in the breech area of a large caliber gun (155 mm). At the breech area, a slight pocket can be made by machining and then the short segment of the hardmetal rifled gun barrel can be fitted in place so as to match the rifling pattern with the rifling pattern of the remaining gun barrel. It has to be remembered that WC—Co-based hardmetals are much harder and erosion resistant as well as higher temperature resistant compared to steel. Thus, strategically placing a hardmetal segment at the breech area where the erosion, pressure and temperature is at its peak will provide major advantages. The slight additional weight will be negligible compared to the gains this hardmetal section will provide. This section shows the processing of two hardmetal compositions: WC-6Co and WC-12Co. The molding conditions for the two materials have been shown in Table WC1.

TABLE WC1

Molding parameters

Part Description	Tank Temp	Pipe Temp	Orifice Temp	Pressure Psi	Fill Time	Mold Temp
6% Rifling Tube	160° F.	150° F.	150° F.	43 psi	15 sec	Room Temp
12% Rifling Tube	170° F.	160° F.	160° F.	48 psi	15 sec	Room Temp

[0064] After the samples were molded they were weighed using an analytical scale and then measured with Mitutoyo calibers. Table WC2 shows the weights and measurements for each sample.

TABLE WC2

Green weights and measurements for molded rifling tube samples

Material Description	Sample Number	Weight grams	O.D. inches	Length inches
6% WC—Co	2	614.3000	1.6470	4.9270
	4	614.0000	1.6480	4.9270
	6	613.9000	1.6480	4.9250
12% WC—Co	1	596.8000	1.6520	4.9330
	2	260.9000	N/A	4.9340

[0065] When molding the 12% WC—Co, sample number 2 sample was sectioned in half (that is why the weight is low).

[0066] The debinding cycle for the WC-6Co and WC-12Co rifling tubes can be seen in Table WC3.

TABLE WC3

Debinding cycle for the WC-6Co and WC-12Co rifling tubes

Dewax Cycle ° C.			
Ramp Time (hours)	Ramp Rate (°/hr)	Set Point ° C.	Soak Time (hours)
1.45	34	75.0	6
1.00	28	102.8	8
5.50	3	121.1	10
3.03	18	176.7	10
Dewax Cycle ° F.			
Ramp Time (hours)	Ramp Rate (°/hr)	Set Point ° F.	Soak Time (hours)
1.45	60	167.0	6
1.00	50	217.0	8
5.50	6	250.0	10
3.03	33	350.0	10

[0067] The binder extracted from the 6% WC—Co rifling tubes is around 55%, while the binder removed from the WC-12Co rifled tube was around 53%.

[0068] Sintering was carried out in a sinter-HIP furnace. The sintering was carried out at a temperature in the range of 1375° C. for times between 30 to 60 minutes. The samples were almost fully dense.

ADDITIONAL EXAMPLES

[0069] A powder injection molding (PIM) process for the manufacture of a rifled gun barrel liner comprising an advanced material, said liner having a multiplicity of lands and grooves having a uniform twist, said process comprising feedstock formation to form a feedstock; molding of the feedstock to form a molded feedstock, wherein the molding imparts the multiplicity of lands and grooves; debinding the molded feedstock to form a brown part; and consolidation of the brown part to form the liner.

Example 1

[0070] The process wherein the advanced material comprises of alumina, hardmetal, silicon nitride, SiAlON, a cermet, zirconia, and/or a superalloy.

Example 2

[0071] The process wherein the feedstock comprises alumina, zirconia, SiAlON, silicon nitride, hardmetal, a cermet, a superalloy, silicon and/or carbon.

Example 3

[0072] The process wherein the lands and grooves have a sinusoidal pattern with a uniform twist.

Example 4

[0073] The process wherein the molding is effected through use of a high-pressure molding machine, a medium-pressure molding machine, and/or a low-pressure molding machine.

Example 5

[0074] The process wherein the molding is effected through use of a core rod.

Example 6

[0075] The process wherein the feedstock formation comprises of mixing a powder of an advanced material or an advanced material precursor with a composition comprising wax, polymer, oil, water, and/or acid.

Example 7

[0076] The process wherein the debinding comprises of solvent extraction, thermal extraction, wick debinding, catalytic debinding, freeze-drying, and/or supercritical fluid extraction.

Example 8

[0077] The process wherein the consolidation comprises of pressureless sintering, pressureless liquid-phase sintering, pressure-assisted sintering, and/or containerless hot isostatic processing.

Example 9

[0078] The process wherein the rifled gun barrel liner extends throughout the entirety of the length of the breech portion of, but extends less than the entirety of the length of, a gun barrel to which the liner is fitted.

Example 10

[0079] The process wherein the rifled gun barrel liner comprises a multiplicity of partial gun barrel liners, each of which said partial gun barrel liners lines the entirety of the inner diameter of a portion of, but less than the entirety of the length of, a gun barrel to which the liner is fitted.

Example 11

[0080] The gun barrel liners fabricated can be put under compressive loading by constraining the outer diameter of the gun barrel with a metal tube or a fiber reinforced epoxy winding.

Example 12

[0081] A process for the manufacture of a rifled gun barrel liner comprising an advanced material, said liner having a multiplicity of lands and grooves having a uniform twist, said process comprising feedstock formation; casting of a slurry or a gel, said slurry or gel comprising an advanced material or an advanced material precursor, wherein the casting imparts the multiplicity of lands and grooves; drying/debinding; and consolidation.

[0082] The foregoing disclosure is intended to teach the disclosed invention, not to enumerate each iteration of the infinite variety of ways in which the disclosed process can be practiced. The examples provided are accordingly illustrative. It will be understood by those skilled in the art that the invention can be practiced according to the disclosed process in ways equivalent to those herein disclosed. It should accordingly be understood that the rights of the inventors and any assignees of the invention will be bounded only according to the full scope accorded at law and in equity to the claims in any patent for which the present application serves as a priority document. The following sample claims represent an initial reckoning of aspects of such scope.

Each of the following is claimed:

1. A powder injection molding (PIM) process for the manufacture of a rifled gun barrel liner comprising an advanced material, said liner having a multiplicity of lands and grooves having a uniform twist, said process comprising feedstock formation to form a feedstock; molding of the feedstock to form a molded feedstock, wherein the molding imparts the multiplicity of lands and grooves; debinding the molded feedstock to form a brown part; and consolidation of the brown part to form the liner.

2. The process of claim **1**, wherein the advanced material comprises alumina, hardmetal, silicon nitride, SiAlON, a cermet, zirconia, and/or a superalloy.

3. The process of claim **1**, wherein the feedstock comprises alumina, zirconia, SiAlON, silicon nitride, hardmetal, a cermet, a superalloy, silicon and/or carbon.

4. The process of claim **1**, wherein the lands and grooves which have a sinusoidal pattern with a uniform and/or a square twist.

5. The process of claim **1**, wherein the molding is effected through use of a high-pressure molding machine, a medium-pressure molding machine, and/or a low-pressure molding machine.

6. The process of claim **1**, wherein the molding is effected through use of a core rod.

7. The process of claim **1**, wherein the feedstock formation comprises mixing a powder of an advanced material or an advanced material precursor with a composition comprising wax, polymer, oil, water, and/or acid.

8. The process of claim **1**, wherein the debinding comprises solvent extraction, thermal extraction, wick debinding, catalytic debinding, freeze-drying, and/or supercritical fluid extraction.

9. The process of claim **1**, wherein the consolidation comprises pressureless sintering, pressureless liquid-phase sintering, pressure-assisted sintering, and/or containerless hot isostatic processing.

10. The process of claim **1**, wherein the rifled gun barrel liner extends throughout the entirety of the length of the breech portion of, but extends less than the entirety of the length of, a gun barrel to which the liner is fitted

11. The process of claim **1**, wherein the rifled gun barrel liner comprises a multiplicity of partial gun barrel liners, each of which said partial gun barrel liners lines the entirety of the inner diameter of a portion of, but less than the entirety of the length of, a gun barrel to which the liner is fitted.

12. The process of claim **1**, further comprising imparting a compressive loading to the gun barrel liner by constraining the outer diameter of the gun barrel by constraining the outer diameter with a metal tube or a fiber reinforced epoxy winding.

13. A process for the manufacture of a rifled gun barrel liner comprising an advanced material, said liner having a multiplicity of lands and grooves having a uniform twist, said process comprising feedstock formation; casting of a slurry or a gel, said slurry or gel comprising an advanced material or an advanced material precursor, wherein the casting imparts the multiplicity of lands and grooves; drying/debinding; and consolidation.

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