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REINFORCED METAL STRUCTURAL JACKETS FOR ADVANCED GUN BARRELS

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High performance reinforced metals are being developed that have a series of desirable properties for gun barrel structural jacket applications. The two materials of interest are reinforced aluminum and reinforced titanium. Both of these materials possess very high strength, high fatigue resistance, high temperature resistance, and low density. Ongoing work to apply these promising materials to high performance gun barrels includes diffusion bonding to specified liners, material characterization, development of appropriate gun modeling tools, autofrettage/prestressing parameter development, and dynamic analysis of performance in the composite structure. This paper discusses ongoing work to integrate these materials into large caliber gun barrels.

1. Introduction

The Naval Surface Fire Support (NSFS) and Surface Strike community has identified a need for an extended length barrel for a 5 in./MK 45 weapon system upgrade and a need for an Advanced Gun System (AGS) that is based on the 155mm crusader barrel. These advanced gun barrels are being developed to provide fire support to troops in near-shore and far-inland battle scenarios. The new mission requirements include extended range, increased rates of fire, the use of rocket-assisted projectiles, and high impetus, high temperature propellants. This enhanced Naval Surface Fire Support Mission has placed additional demands on gun barrel materials and designs, requiring them to be stronger and longer, without significant increases in mass moment of inertia. High specific strength, high specific stiffness barrel materials that can be integrated into the manufacture of these large caliber weapon systems are required to achieve the expanding NSFS mission requirements.

Fiber reinforced titanium and fiber reinforced aluminum have been under development for aerospace applications and appear to be eminently suitable for the NSFS mission requirements for gun barrel applications. These metal matrix composites have outstanding tensile, fatigue, and thermal properties [1,2,3,4,5,6] and are currently under development for integration into gun barrels. As shown in FIGURE 1, these materials are being integrated as a structural jacket over a steel liner in large caliber gun barrels. Fabricating these structural jackets with *steel* liners was chosen as the first logical step to gun integration to minimize the development effort required prior to initial qualification and testing. New revolutionary liner technologies not using steel as a base can be integrated into these structural jacket materials after the parallel efforts are completed. Integration technologies are currently under investigation from the perspective of the liner technology. This approach separates the technology efforts so that an efficient transition to existing weapons systems can take place without making the new (liner and structural jacket) materials systems co-dependent.

The titanium and aluminum matrix composites are both high specific strength materials, but due to the great difference in their thermal properties and performance, are being targeted at two different gun systems.

The titanium matrix composite (TMC) is being primarily developed as the muzzle

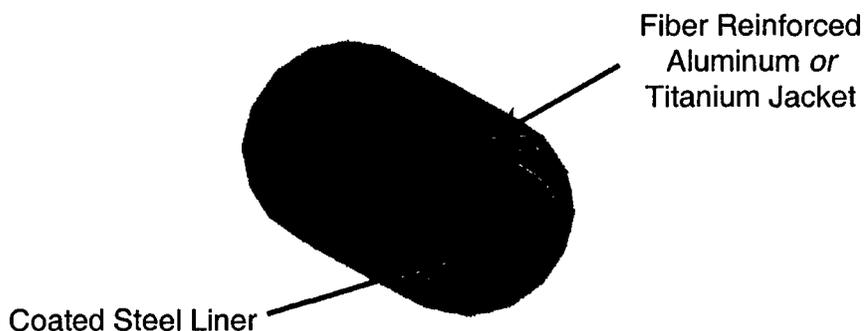


FIGURE 1 Schematic of reinforced metal gun barrel cross section.

extension for the MK 45 due to its very high strength and high temperature fatigue performance. In this application, the TMC will be used to reinforce a significant portion of the gun barrel near the muzzle to extend the length of the 5 in./Mk45 barrel from 62 caliber to at least 70 caliber without increasing the mass-moment-of-inertia of the barrel. Due to the very high specific strength of this material, the mass of the barrel can be allowed to increase while maintaining the current mass moment of inertia. This allows the new extended caliber barrel to be used with the existing MK45 mount.

The aluminum matrix composite (AMC) material is being developed to support the Advanced Gun System effort by developing the nextel fiber reinforced aluminum material for application along the entire length of the AGS barrel. The reinforced aluminum has a high specific strength and high thermal conductivity. The high thermal conductivity of the AMC significantly reduces the thermally induced stress across the barrel below that of a monoblock steel barrel allowing the barrel thickness and autofrettage levels to be increased.

The important aspects related to material properties, material processing, gun fabrication integration (including full scale gun fabrication), and initial gun design are being developed for both the TMC and AMC material systems.

2. Titanium Matrix Composite Structural Jackets

The titanium matrix composite is a continuous fiber reinforced monotape consisting of continuous SCS-6 silicon carbide fibers in a Ti-6Al-2Sn-4Zr-2Mo-0.08Si (Ti-6242) matrix.[7] The silicon carbide fibers have tensile strengths ranging from 600 ksi for the SCS-6 fibers to 1,000 ksi for the Ultra-SiC fibers. Both fibers have a modulus of 60 Msi. The SiC filaments have a diameter of 0.0056 inches and the composite volume fraction ranges between 0.35 and 0.40. A typical microstructure of the titanium matrix composite material is shown in Figure 2. The dark core at the center of the filaments is the carbon core used in the chemical vapor deposition process during fiber fabrication. The dark outer layer of the filament is a carbon rich coating that aids adhesion between the Ti-6242 matrix and the fiber. [8,9,10]

The TMC material was chosen for its high strength, high temperature resistance, low density and excellent fatigue properties. The material properties of the TMC are shown in TABLE 1. The gun steel data is 4340 steel tempered to a tensile strength between 160 and 180

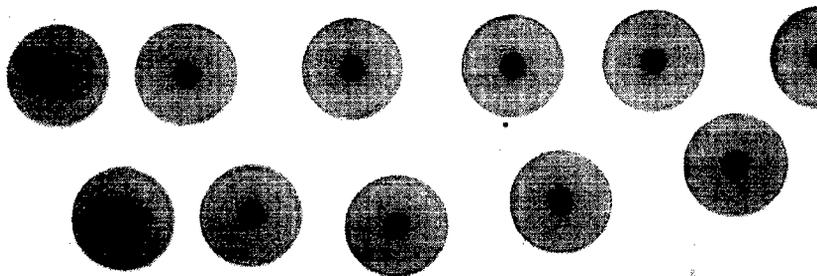


Figure 2 Cross Section of Consolidated TMC

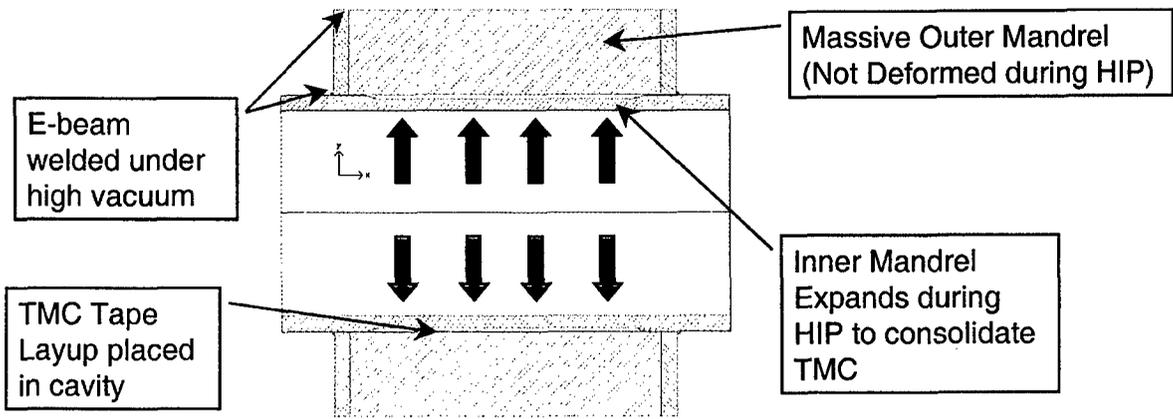
TABLE 1 Material properties of TMC material

Material	Density (lb/ft) ³	Tensile Yield Strength (ksi)		Elastic Modulus (MSI)		Coefficient of Thermal Expansion (PPM/°C)	
		72°F	800°F	72°F	800°F	72°F	800°F
Gun Steel	489	Tempere d to 160-180	<140 <60 @ 1000°F	29	24	11.2	13.5
Ti 6242 SCS-6 (35% by volume)	252	190	145	29	26.5	≅ 4.5-5	≅ 3.5-4
Ti 6-4 Ultra SCS (29% by vol)	252	321	245	29	26.5	≅ 4.5-5	≅ 3.5-4

ksi. As indicated by the table, the specific strength of the SCS-6 based TMC is more than two times that of the 4340 steel and the Ultra SiC based TMC is over three times the specific strength of 4340 steel. This high specific strength makes the TMC materials ideal candidates for the structural jacket muzzle extension for the MK 45. The low density, combined with high strength allows the design of a muzzle extension that does not increase the mass moment of inertia of the extended barrel, allowing the use of existing mounts. In addition to high strength, the TMC material will withstand over 100,000 cycles at stress levels over 100 ksi at a temperature of 1,000°F. The 4340 steel has a tensile strength of less than 60 ksi at 1000°F. [11]

The TMC is fabricated using a two-step process. First, the silicon carbide fiber is wound on a stainless steel drum and plasma sprayed with titanium alloy. This forms a tape with uniaxially oriented fibers placed accurately on center to form a consolidated tape with a 0.375 volume fraction and a thickness of 0.014 inches. Initially, the plasma sprayed tape is 70% dense. To form a fully consolidated component, the multiple layers of plasma sprayed tape are placed in a hot isostatic pressing (HIP) tool. The HIP tool is evacuated down to 1×10^{-5} torr and welded closed using E-Beam welding. The HIP tool is placed in the HIP vessel and subjected to a temperature between 1650°F and 1750°F and a pressure between 15,000 and 30,000 psi. Consolidation takes place when the HIP tool deforms to compress the TMC layup. As the HIP tool deforms, the titanium tape layers are diffusion bonded together to form a fully dense composite. Dimensional control over the HIPped component is achieved through the design of the HIP tool itself. The HIP tool design for the structural jacket is shown in FIGURE 3.

In the structural jacket application on the Mk 45 gun muzzle, the primary orientation of the fibers is in the hoop direction to maximize the hoop strength of the composite jacket. The HIP tool was designed with a substantial outer mandrel and a much thinner inner mandrel, forcing the inner mandrel to expand into the composite layup against the relatively stable outer mandrel. This was desired so that the fibers would be loaded in tension rather than compression during consolidation and ensured that the fiber orientation remained normal to the cylinder axis.

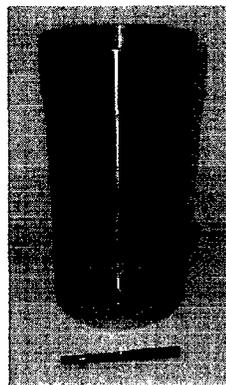


During HIP: pressure and temperature are applied over time to achieve solid state diffusion bonding of the Titanium composite

FIGURE 3 HIP tool design

A series of photographs showing the assembly of a 6-in-diameter cylinder is shown in FIGURE 4. After HIPping, the fully dense TMC jacket is excised from the HIP tool by machining.

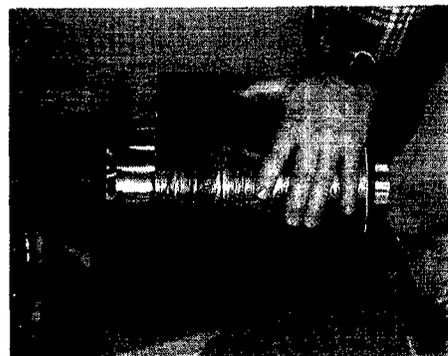
The TMC structural jacket must be integrated onto the muzzle of the gun barrel while maintaining the steel liner and TMC heat treatments. The options for joining the jacket to the liner include shrink fitting and autofrettaging the jacket into place. This allows the TMC and the steel liner to be fabricated and heat treated separately, prior to joining. This prevents the problems associated with press fitting the jacket over the steel. The longest HIP vessel available governs the length limit for the muzzle extension jacket, currently measuring 119-inches-long. This is long enough to extend the Mk 45 mod 2 from 54 to 77 calibers and the mod 4 from 62 to 85 calibers.



Inner Mandrel



TMC Tape wrapping



Final HIP tool assembly

FIGURE 4 Processing steps for TMC fabrication

3. Aluminum Matrix Composite Structural Jackets

The aluminum matrix composite structural jacket is pressure infiltration cast alumina fiber reinforced aluminum. The fiber reinforcement is Nextel™ 610 high purity alumina at a volume fraction of approximately 0.65. The alloy is high purity aluminum. This material was chosen for its high strength, high fatigue resistance, and high thermal conductivity. FIGURE 5 shows a micrograph cross section of the composite material. The material properties are shown in TABLE 2.

The primary reason for integrating this material as a structural jacket in the AGS barrel is its high thermal conductivity, maximizing the heat transfer from the bore surface, keeping the bore cool, and minimizing the thermal stress across the barrel wall. Reduction in bore temperatures increases bore life while reduction in thermal stress increases fatigue life, thus effectively increasing both major factors governing barrel life.

Active cooling of the AGS barrel is required to minimize bore temperatures and the bore erosion caused by the high firing rate NSFS mission. Active cooling allows the bore surface temperature to be kept low, increasing bore life. Although active cooling significantly increases bore life, it dramatically increases the heat flux through the barrel, causing a significant increase

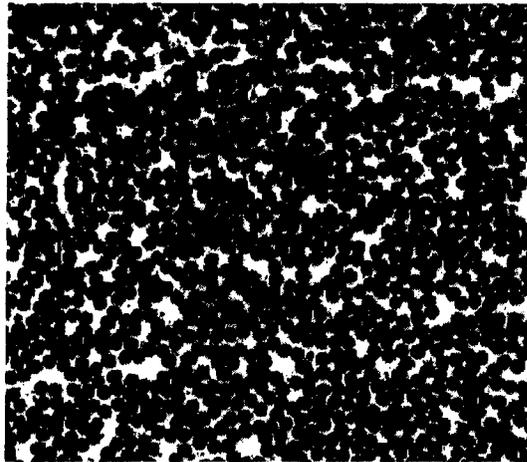


FIGURE 5. Typical cross-section of Triton Systems' Al/Nextel 610/60f composite.

TABLE 2 Material properties of AMC material

Tensile Strength	240 ksi
Compressive Strength	500 ksi
Density	3.4 g/cc
Modulus	35 msi
Biaxial Composite Fatigue (0-90)	30+ ksi runout 10 ⁷ cycles -same at 700 F
Thermal conductivity	120 W/mK
Specific stiffness	3 times greater than 4340 steel
Specific strength	3.85 times greater than 4340 steel

in thermally induced stress.

Heat flux in conventional barrels is limited by free convection in air, while actively liquid cooled barrels have a much higher heat flux due to the higher heat transfer coefficient of forced liquid systems. This high heat flux generates a high ΔT across the barrel wall due to the limited thermal conductivity of steel. The temperature drop through a thick wall tube is related to the thermal conductivity of the material and the ratio of the inner to outer radii. For comparison purposes, FIGURE 6 shows the temperature profile of the barrel cross section using a steady state heat transfer analysis. For comparative purposes, the curve indicating the lowest bore surface temperature is for an all reinforced aluminum barrel and the upper curve is for an all steel barrel. The intermediate curves represent a jacketed barrel with a .5-in-thick steel liner and a 2.25-in-thick steel liner. For these calculations the heat flux and the cold wall temperature were held constant for comparison purposes. The shallower slope of the aluminum curve is directly related to the difference in thermal conductivity between the steel liner and the reinforced aluminum jacket.

In addition to lowering the bore temperature, the high ΔT across the all-steel barrel wall induces a high compressive stress at the bore and a high tensile stress at the outer surface. The expansion of the relatively hot inner elements is constrained by the cool outer elements. At the steady state heat flux levels of the AGS, the compressive stress developed at the bore surface can approach 100 ksi. This high thermally induced stress places limits on the autofrettage levels attainable if bore collapse is to be prevented. This limit on autofrettage levels causes the prestress to be less than desired during cold fire situations.

The thermally induced stress in all-steel actively cooled barrels is high due to the low thermal conductivity of steel. This thermal stress can be minimized, and the bore surface temperatures further reduced through the use of a high thermal conductivity reinforced aluminum structural jacket. As indicated in FIGURE 6, the high thermal conductivity AMC material significantly reduces the ΔT across the barrel wall resulting in a nearly 50% reduction in thermally induced stress. The reduction in thermally induced stress allows the autofrettage levels

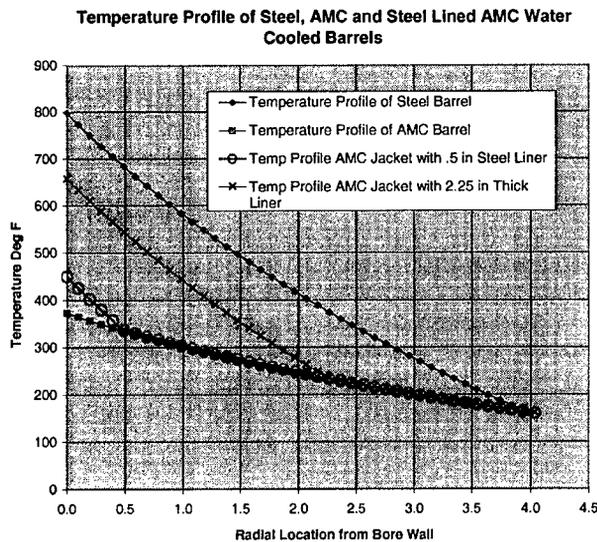


FIGURE 6 Actively Cooled Barrel Temperatures

with the AMC jacketed barrel to be increased, thereby allowing an increase in autofrettage levels and a concomitant improvement in fatigue life for the barrel.

Autofrettage of Steel Lined AMC Jacketed Barrels

The separate fabrication of the AMC structural jacket and the steel liner will be used to fabricate the gun barrel. In this process, the heat treatments of both the steel and the structural jacket are performed separately, and joined using either heat shrinking or autofrettage. This concept solves a number of issues associated with the fabrication of a large-scale gun barrel, including:

- Inspection of the liner and jacket separately
- Provides greater control over autofrettage stresses on the liner
 - OD of steel machined
 - ID of AMC jacket machined
 - ID of steel liner independently machined
- Allows greater strains on outer elements of steel

Analysis

Thick wall cylinders are able to sustain an internal pressure that is no greater than the yield strength of the material used. As the wall thickness approaches infinity, the hoop stress on the bore becomes equal to the internal applied pressure. This is due to the uneven stress distribution across the thick wall, causing inner elements to carry more tensile stress than outer elements. It is desired to redistribute these stresses across the barrel wall section so that the tensile load is carried more evenly, causing an increase in the fatigue limit and strength of gun barrels. Stress redistribution is accomplished by placing the bore surface into a state of residual compression and the outer elements into a state of residual tension. This reduces the maximum hoop stress on the inner elements of the gun barrel and increases the allowable internal pressure along with the fatigue limit for the structure. In the gun barrel application, bore surface compression also aids in the prevention of cracks that develop under harsh service conditions. Bore surface compression is attained in monoblock steel barrels through autofrettage. In the autofrettage process, the inner elements at the bore surface are overstrained into the plastic regime by swaging, leaving the bore in a state of high residual compression.

It is desired to use the swage autofrettage process to generate these internal compressive stresses in the AMC jacketed gun barrel to attain the advantage of prestressing the bore. The important factors to be considered when establishing a method to achieve autofrettage in this structure are:

- Strains required for the attainment of suitable autofrettage
- Strain at plastic deformation of the steel liner
- Strain to failure of the composite structural jacket
- Stress state at the steel/jacket interface

When the swage passes through the layered barrel composite the bore is strained into the plastic range and the interface is strained to a somewhat lesser extent. The extent of the strain at the interface is dependent upon the bore strain and the liner thickness. Interface strain decreases with increasing liner thickness.

The gun barrel consists of a steel cylinder directly wrapped in an all-hoop direction with MMC. During autofrettage, stress applied to the bore of the steel liner causes the material to plastically deform. Once the applied stress equals the yield stress of the steel, plastic deformation begins. With increase in stress, the depth of plastically deformed material moves further into the material. This “front” of plastically deformed material is called the elastic-plastic interface. Subsequent removal of the applied stress results in residual stresses produced by the elastic spring-back of the material.

The system is modeled as an internally pressurized cylinder. Calculating the bore deflection at a particular pressure makes the translation to the autofrettage process. This deflection represents the radial interference created during the swaging process.

The analysis breaks down into three parts; elastic-plastic, fully plastic, and unloading analysis. Elastic-plastic refers to analysis where the elastic-plastic interface has not moved completely through the steel liner. Fully plastic refers to analysis of a fully yielded steel liner. Unloading analysis predicts the residual stresses produced by the elastic spring-back. The maximum shear stress yield criterion is utilized and linear strain hardening is assumed.

The analysis will look specifically at the 6.1 inch gun and the bulk of the equations used in this exercise were obtained from Chen [12]. The variable definitions are shown in FIGURE 7.

Elastic-Plastic Analysis

The independent variable is the radial location of the elastic-plastic interface. All other parameters are functions of this depth of plastic deformation. The required internal pressure for a given depth of plastic deformation is determined. The effect of the metal matrix composite (MMC) jacket on the behavior of the steel liner is characterized by calculating an interface pressure. This is the pressure on the outer diameter of the steel liner and inner diameter of the MMC jacket, created by stressing the MMC jacket. Once the internal pressure and interface pressure are known, all the stresses, deflections and strains can be determined as functions of the depth of plastic deformation.

Fully Plastic Analysis

The next level of the analysis is fully plastic. In this range, the elastic-plastic interface has moved through the entire section of the steel. The controlling variable in this case is internal

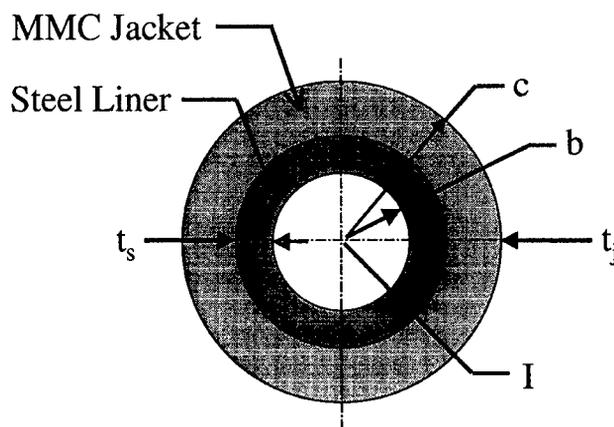


FIGURE 7 Variable definitions used for analysis

pressure. The interface pressure is determined and all stresses, deflections and strains are found subsequently.

Unloading Analysis

The residual stresses, strains and final geometry of the barrel are determined by this analysis. The unloading pressure is simply the negative value of the internal pressure, and this is used to determine the unloading interface pressure. Unloading stresses, deflections and strains are calculated, and added to the initial deformation values to determine the residual magnitudes.

155mm Gun Analysis

A critical relationship to be determined is what level of autofrettage will the barrel accept without fracturing the AMC jacket. The strain at failure of the AMC jacket loaded uniaxially in the fiber direction is 0.6%. For the hoop orientation of the gun jacket application, this translates into a maximum hoop strain at the steel jacket interface of no more than 0.6%. The following illustrates the relationship between radial interference and the strain at the steel liner-MMC jacket interface.

FIGURE 8 demonstrates the ability of the steel liner to be fully plastically deformed without fracturing the AMC jacket. Thinner sections of steel yield higher interface strains for a given radial interference during swaging. For example, the 0.5-inch-thick liner can sustain just over a radial interference of 0.025 inches. The 2-inch-thick liner can sustain a radial interference of over 0.05 before overstraining the composite jacket. The associated residual stresses obtained at the bore are illustrated in FIGURE 9.

FIGURE 9 plots interface strain against hoop stress at the bore for three liner thicknesses. All curves are cut off at the maximum interface strain of 0.6%. The curves show that compressive hoop stress from zero to over 150,000 psi can be attained without failing the jacket for all liner thicknesses. The design space for autofrettage of the AGS barrel is wide open, and sufficient levels of autofrettage stress are obtainable with the thinnest sample analyzed.

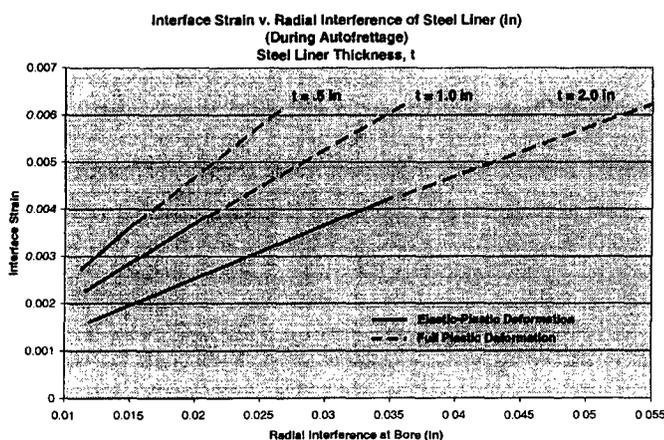


FIGURE 8 Interface Strain during Autofrettage

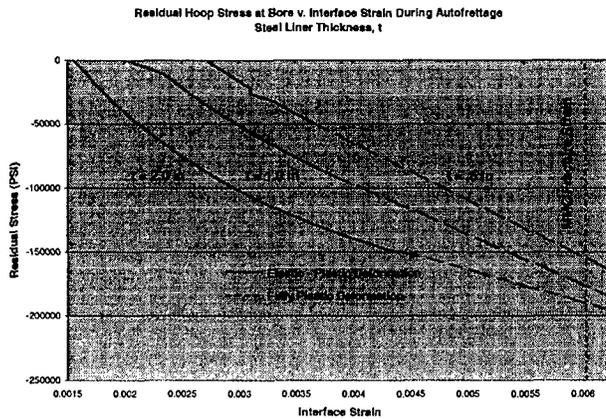


FIGURE 9 Residual Stress at Bore

The associated residual stresses at the steel liner-MMC jacket interface are shown in FIGURE 10. This figure shows that full plastic deformation is necessary to obtain any residual compressive stresses at the interface. Thinner sections of steel yield larger residual compressive stresses for a given interface strain during autofrettage. It is not clear at this writing if it is necessary to generate compressive hoop stress in the steel to achieve long barrel fatigue life.

Residual radial stresses do not occur at the bore, but the associated residual stresses at the interface are shown FIGURE 11. The major feature of this graph is the large shift in radial interfacial stress that occurs when the deformation transforms from elastic to plastic. It is necessary to generate radial stress at the interface to ensure sufficient load transfer between the liner and jacket material. As this graph shows, the design space is there at well below the strain limit of the jacket material to preload this interface in radial compression.

This analysis shows that significant residual compressive radial stresses are obtained for small interface strains during autofrettage. These stresses diminish by an approximate factor of 10 when full plastic deformation is reached. The magnitudes of the stresses for the three samples are very close, differing by only about 15,000 psi throughout the entire range of strain. The

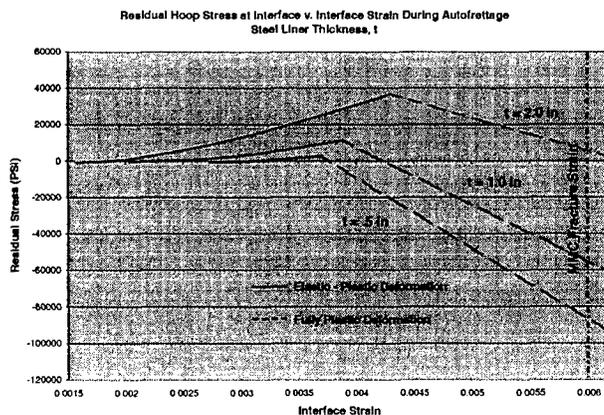


FIGURE 10 Residual Hoop Stress in Steel at Interface.

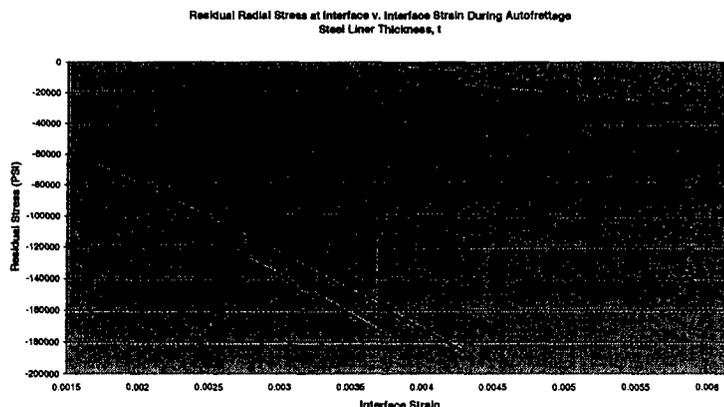


FIGURE 11 Residual Radial Stress at Interface

thinner sections provide slightly higher residual radial stresses prior to full plastic deformation, but yield lower levels after the liner becomes fully plastic.

The preceding analysis indicates that there is considerable design space for optimizing the autofrettage of the AGS barrel to desired levels.

Subscale Sample Fabrication

In a recently completed program, small-scale samples of AMC jacketed cylinders were pressure infiltration cast and then successfully autofrettaged. This was demonstrated by the fabrication of two-layer composite cylinders, as shown in **FIGURE 12**, followed by machining and swage autofrettage in a press. Results showed that the steel liners took on a permanent set (plastically deformed) as desired, and that the reinforced aluminum jackets remained in the elastic regime, as desired. All samples were fabricated on steel liners with a 1.5-in-outside diameter and a reinforced aluminum jacket with a 1.9-in-outside diameter. Sample sizes were kept small to keep tooling costs down.

3.2 Autofrettage Of Reinforced Aluminum Jacketed Samples

To keep tooling costs down, one swage was machined and hardened. It was designed with a lead diameter slightly less than the composite samples, a 2-degree taper and a smaller top section that allowed the swage to fall through the sample at the completion of the swaging stroke.

The swage assembly is shown in **FIGURE 13**. The swage jig has a center hole slightly larger than the maximum swage diameter to allow the swage to fall through at the completion of the pressing stroke. It also has a 0.050-in-counterbore that just fits the outside diameter of the samples, so that the assembly is kept on center during the swage process.

All samples were fabricated from the same casting. The bore diameters were final machined

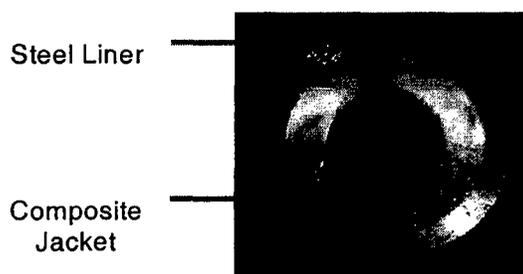


FIGURE 12 Pressure Infiltration Cast AMC Over Steel

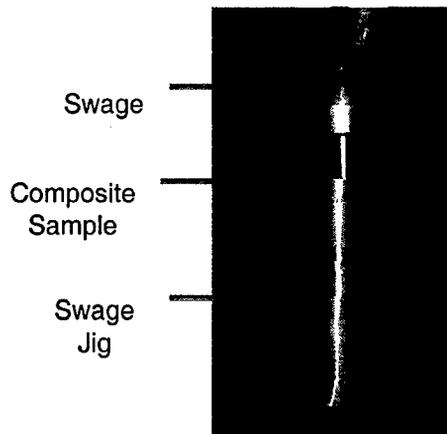


FIGURE 13 Swage Autofrettage Process

to tolerances of ± 0.0005 to ensure that the predicted strains would be achieved during autofrettage.

FIGURE 14 is a photograph of the jacketed samples after autofrettage. The sample on the left was strained to levels just below the strain limit of the jacket. The sample on the right was subjected to interface strains above 0.6%, the strain limit for the composite jacket and was expected to crack, as indicated.

4. Conclusions

The reinforced titanium is under development for a muzzle extension of the 5"62-caliber Navy gun to 70 calibers by fabricating a muzzle extension that provides a barrel with the same mass and moment of inertia as the 5" 54-caliber barrel. The processes to diffusion bond the reinforced titanium to the 4340 gun steel liner are being developed. Developments for the near future include the fabrication of full bore hoop specimens for impulse and high temperature fatigue testing.

The reinforced aluminum is under development as a structural jacket in the Advanced

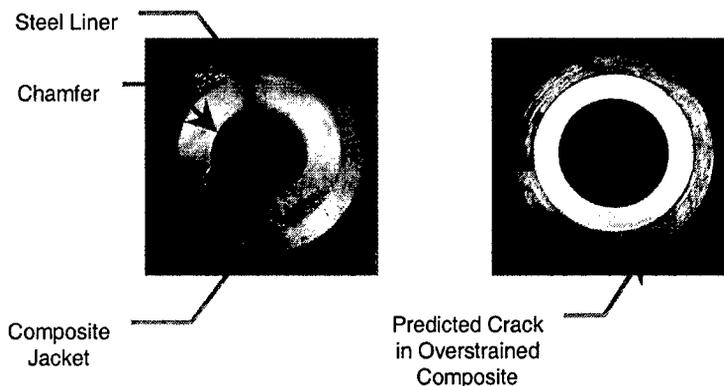


FIGURE 14 Autofrettage samples

Gun System (AGS) barrel. In this case, the high conductivity of the reinforced aluminum is being used to reduce thermally induced stress in this actively cooled barrel. By applying the high conductivity structural jacket to the AGS barrel, bore temperatures are reduced significantly and the delta T between the outer cold wall and the inner bore surface are reduced. The reduction in delta T between the outer and inner walls reduces thermally induced stress by as much as a factor of four. These factors open the design space in the autofrettage levels and in the cooling system for the AGS barrel. The ultimate effect is that the bore and fatigue life are both increased for this barrel. The work to date has successfully shown that the reinforced aluminum can be autofrettaged without overstraining, and can be used to successfully reduce bore temperature and thermal stress in the AGS barrel. Additional future effort includes the development of a large scale manufacturing approach, the verification of those approaches by fabrication of full section barrels, and development of computer design tools for behavior prediction in the AGS gun barrel environment.

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