The Near-Net-Shape Manufacturing of Affordable Titanium Components for the M777 Lightweight Howitzer

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The U.S. Marines' and U.S. Army's next-generation, titanium-intensive M777 howitzer offers reduced weight, increased mobility, and improved survivability over its aging, M198 steel-based predecessor. The National Center for Excellence in Metalworking Technology (NCEMT), operated by Concurrent Technologies Corporation, is helping to meet M777 program goals for cost, performance, and production schedule by developing near-net-shape manufacturing routes for traditionally machined and welded components. Under two projects sponsored by the Navy Manufacturing Technology Program, the NCEMT has developed investment cast spade and saddle components as well as flowformed tubes and forged bell housings. This paper summarizes the results of the two ongoing projects.

INTRODUCTION

A joint U.S. Marines and U.S. Army initiative is overseeing production of the M777 lightweight howitzer (LWH), a towed, 155 mm weapon system that incorporates approximately 1,450 kg of titanium alloy (Figure 1).[1,2] The use of titanium and reduced overall size of the M777 make it 2,800+ kg lighter than its aging, steel-intensive M198 predecessor. The weight savings will allow greater transportability of the gun, enabling a quicker response to strategic needs. Furthermore, the decreased weight and smaller footprint of the M777 (compared to the M198) help to reduce the time necessary for both emplacement and displacement, thereby enhancing survivability.

BAE Systems, the prime contractor for the M777, produced eight howitzers during engineering and manufacturing demonstration (EMD), the first of three successive production phases. Those developmental units incorporated multiple Ti-6Al-4V components that had been produced by bending and welding plate stock to form; additional EMD parts were machined directly from solid billet or thick-walled tube. Such manufacturing methods are material inefficient, labor intensive, and expensive. For higher-rate production of the M777, significant changes needed to be made to increase the manufacturability of the major components while simultaneously reducing cost.

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Titanium is a relatively expensive material due to its high melting point, affinity for oxygen, and complexity of processing. During the last decade, the U.S. Department of Defense has attempted to reduce the cost of titanium alloys, especially Ti-6Al-4V, to take advantage of their high specific strength and excellent corrosion resistance. All stages of titanium-component production, including extraction, melting, and secondary processing, have been targeted as areas of potential cost savings.[3,4] Advances in raw material extraction include the recently developed Fray-Farthing-Chen Cambridge[5] and MER[6] processes, which remove titanium from titanium dioxide using electrochemical methods, as well as the ITP-Armstrong process,[7] Industrial Technology of New York's (ITNY's) plasma reduction approach,[8] SRI International's fluidized bed chemical vapor deposition (CVD) method,[9] Ono Suzuki's calciothermic reduction,[10] and Okabe's oxide reduction by calcium vapor approach.[9,10] Research is also being conducted to increase the use of non-virgin alloy. Melting techniques such as single-step electron beam melting (EBM) and plasma arc melting (PAM) that allow the use of large amounts of revert and machine turnings in melt stock are opening the door to lower-cost raw material processing, as are direct slab casting, and improvement of ingot/slab surface quality.[6,11–13] Improving the ingot/slab surface eliminates the need for costly surface machining prior to upset-forging and permits direct rolling of slabs to plates without an intermediate forging step. The reduction in thermomechanical processing further reduces cost.[12]

Near-net-shape (NNS) processing offers cost reduction by minimizing machining, reducing part count, and avoiding part distortion from welding. Near-net-shape technologies such as flowforming,[14] casting, forging, powder metallurgy methods, three-dimensional laser deposition,[15] and plasma arc deposition[16] have been explored for

Figure 1. The M777 lightweight howitzer and crew.

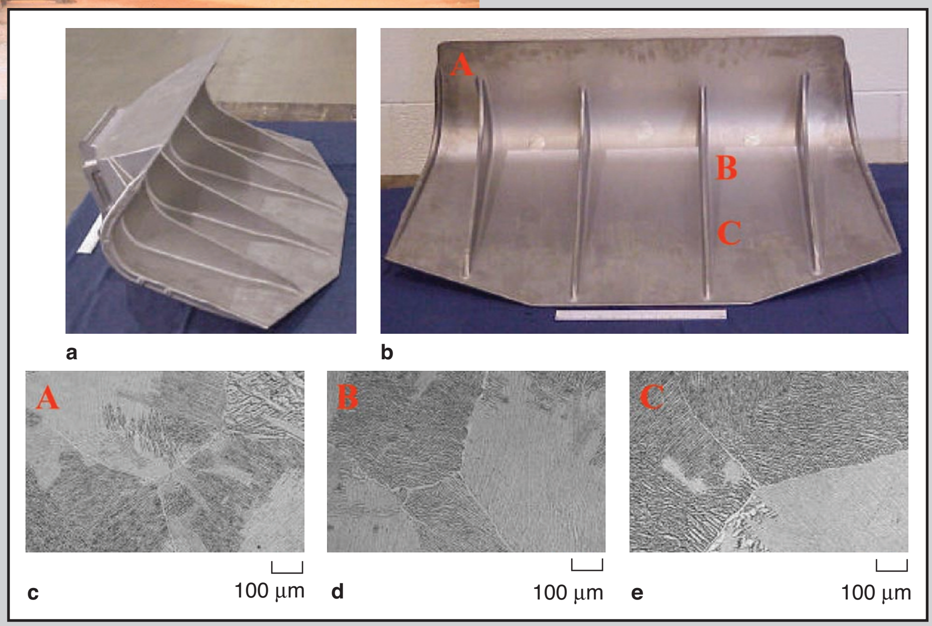

Figure 2. (a) Side and (b) front views of the spade, and (c), (d), and (e) are micrographs from select locations. Capital letters on the micrograph indicate locations on the spade.

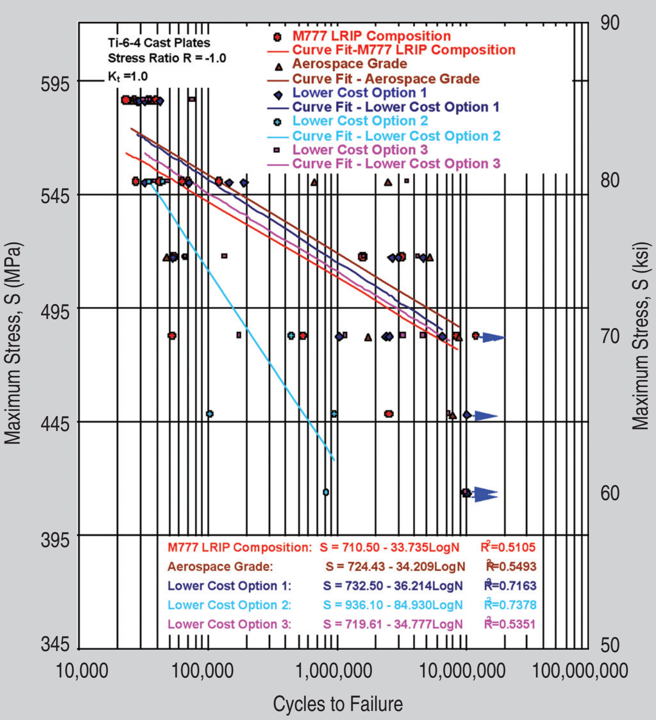

Figure 3. The fatigue properties of lower-cost feedstocks compared to current M777 material and baseline aerospace metal (all specimens extracted from 1.27-cm-thick Ti-6Al-4V plates—HIP 900°C, 103 MPa argon, 2 h; chemical milled; vacuum annealed 840°C, 2 h).

Figure 4. A three-piece investment cast saddle assembly.

potential use in tubular geometries and other shapes of varying complexity. It appears that the reduction in cost of a given titanium product will be maximized by achieving improvements in all of the manufacturing steps, from extraction to finishing.

Given that new titanium extraction technologies are not yet at the commercial stage, the National Center for Excellence in Metalworking Technology (NCEMT) has focused primarily on the replacement of labor-intensive manufacturing processes with NNS techniques to lower the cost and increase the manufacturability of the M777. Four LWH components, the spade, saddle, cradle tubes, and bell housing, were selected as components for which modifications in manufacturing technique would reduce component distortion, lower cost, and enable delivery schedule compliance. (See the sidebar for technical details.)

NEAR-NET-SHAPE COMPONENT DEVELOPMENT

Cast Components

The investment cast spade was developed in two phases. Initial spades were made using stereolithography (SLA) patterns for rapid prototyping. Those spades satisfied expectations, thereby validating the cast spade design. Consequently, hard tooling was created to produce wax patterns in support of higher-volume spade production.

To compare spades cast from the different pattern types, wall thickness measurements and coordinate measurement machine (CMM) measurements were taken from a pair each of the SLA spades and the hard-tooled spades. Thickness measurements were taken at 119 locations per spade by a combination of micrometers and ultrasound. The difference between each measurement and the target spade thickness at that location (plus mill stock for anticipated losses during subsequent processing) was determined. The average difference for the as-cast SLA components was only 0.06 mm greater than that of the hard-tooled spades. Coordinate measurement machine data, which are used to evaluate the three-dimensional conformity of a component to its design,

TECHNICAL APPROACH

The manufacturability of each of the four selected M777 lightweight howitzer components—the spade, saddle, cradle tubes, and bell housing—has been, or is being, improved through a similar series of steps. Working closely with the M777 Joint Program Management Office (JPMO), BAE Systems, and the most appropriate industrial manufacturer(s) for a given component, the National Center for Excellence in Metalworking Technology (NCEMT) employed its computer-aided design and process modeling expertise to explore the potential redesign of a given part as well as the viability of alternative manufacturing techniques. The NCEMT then contracts and works closely with the identified industrial supplier(s) to develop first article components from the newly adopted or modified manufacturing process. The first articles are subjected to dimensional inspection and destructive mechanical test evaluation to verify that the component geometry and mechanical properties are within specification. When possible, the developed parts are incorporated into an existing M777 unit and subjected to live-fire testing under the JPMO's watch.

Each M777 unit utilizes two spade components and a single saddle. The spades are located at the back of the howitzer and dig into the ground to stabilize the gun upon firing. The saddle provides the interface between the howitzer base and the cradle structure, which supports the barrel and absorbs recoil loads. During the engineering and manufacturing demonstration, both components were manufactured by shaping and welding Ti-6Al-4V plate. Assembling each 60-piece spade and 120-piece saddle required a considerable amount of labor and resulted in part-to-part variability and distortion due to welding.

The NCEMT, JPMO, BAE Systems, and industrial titanium companies recognized that investment casting offers great potential to increase the manufacturability and lower the cost of M777 components. That belief was founded in prior work performed by Concurrent Technologies Corporation under the Combat Vehicle Research Program sponsored by the U.S. Army Tank-Automotive Research Development & Engineering Center. In 2001, two large M777 stabilizer arms (Figure A) were successfully investment cast from stereolithography (SLA) patterns by PCC Structurals of Portland, Oregon. The use of investment castings, which replaced 35-piece, dimensionally noncompliant,

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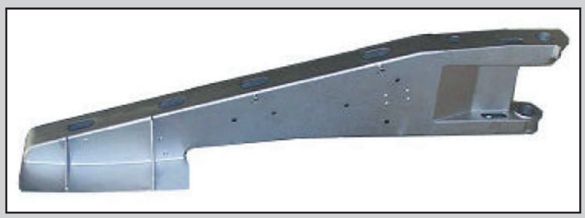

Figure A. An investment cast Ti-6Al-4V stabilizer arm (approximately 39.9 cm wide, 194.6 cm long, and 45 kg).

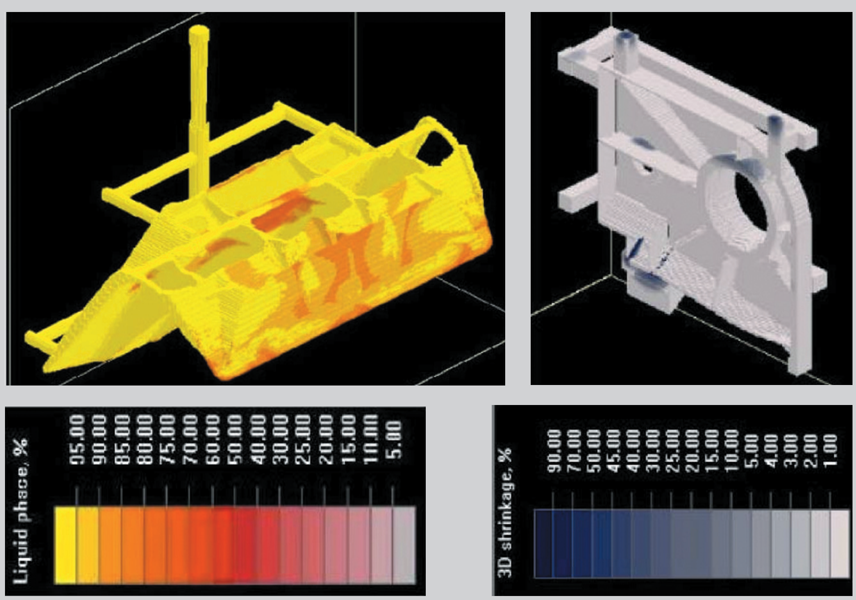

Figure B. Simulation results of the (a) spade and (b) saddle investment castings. (a) shows the mold-filling and solidification pattern after 7.2 s for the spade casting and (b) is a two-dimensional view (cut through the two back right risers) of the shrinkage map for a portion of the saddle.

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distortion-prone welded fabrications, was selected in lieu of rammed graphite castings due to the complexity and size of the stabilizer arms. Based on the success of those original units, investment cast stabilizer arms are now used in M777 production. Those early interactions also assisted the JPMO and BAE Systems with the development of a casting specification for the M777; that specification allows slightly relaxed Ti-6Al-4V alloy composition and mechanical properties (relative to aerospace material specifications), single-melt heats, and weld repair. The specification also limits the requirement for full inspection to critical areas only, further reducing cost for this land-based application.

The NCEMT is working with PCC Structurals and Howmet Castings (Hampton, Virginia) to extend the role of castings in the howitzer by introducing single-piece, investment-cast spades and saddles, respectively. Some of those efforts involved using computer modeling to probe the effects of casting parameters on mold filling, part cooling, and resultant component microstructure and properties. A spade modeling image is displayed in Figure Ba; by monitoring metal flow and cooling patterns for a series of process conditions and part orientations, mold filling is assured and casting defects such as shrinkage and porosity can be minimized. Figure Bb shows a shrinkage and porosity map for a portion of the single-piece saddle casting. Similar to the spade study, there are a number of areas with a high potential to form shrinkage voids and porosity.

In addition to pursuing the cost savings afforded by near-net shape processing, the NCEMT is exploring the possibility of using lower-cost, alternative raw material feedstocks to further reduce the cost of cast components. Using a high level of revert and/or accepting high-oxygen content scrap for investment casting has previously been shown to be a viable option to reduce the cost of titanium while meeting or exceeding property requirements.[17] In the present work, three potential inputs, each incorporating different percentages of machining chips, forging scrap, titanium sponge, and master alloy compacts, have been used to cast 12.7-mm- and 25.4-mm-thick plates for subsequent mechanical testing. On the basis of those plate studies, one of the lower-cost options has been selected for casting two additional spades for further evaluation.

The NCEMT is also leading the development of two non-cast M777 components: cradle tubes and the bell housing. Cradle tubes, along with cast Ti-6Al-4V bridges, form the cradle structure that supports the howitzer recoil loads during firing. Each howitzer requires a total of 14 m of approximately 15-cm diameter, thin-walled tubing. During EMD, those tubes were produced by machining solid billet or thick-walled, extruded tube. Both approaches require an extensive amount of time and are material inefficient, which results in high associated costs.

To minimize waste, lower cost, and increase throughput during the manufacture of cradle tubes, the NCEMT is currently exploring a matrix of extruded and rotary pierced tube suppliers as well as a flowforming vendor (see Table A). The targeted approach to achieve the stated goals would begin with thick-walled extruded or rotary pierced tube. The inner and outer diameters of that tube would then be machined to improve surface finish and remove oxide scale. The clean, still relatively thick-walled tube would then be used as the input for material-efficient single or multiple-pass flowforming. During flowforming, the tube would be fitted around a rotating mandrel and plastically deformed (radially compressed and axially elongated) to size by a set of three rollers. Flowformed tube has inherently tight dimensional tolerances and an excellent surface finish.

To evaluate the tubes, plasma arc welding will be used to test their weldability; the inner diameter, outer diameter, wall thickness, concentricity, straightness, and length of each tube will be measured; and tensile and fatigue specimens will be extracted from each tube for mechanical evaluation.

The NCEMT and Arcturus Inc. have developed a forged bell housing to replace the previously machined version of that component. Bell housings were manufactured by near-net-shape forging using low-cost single melt plasma arc melted (SM PAM) material that contained machine turnings. To determine the maximum allowable oxygen content for acceptable mechanical properties while lowering billet cost, forgings were produced from SM PAM billets at three oxygen levels: 0.16 wt.%, 0.20 wt.%, and 0.24 wt.%. Forgings using standard, double vacuum arc remelted billet were also made to allow a baseline comparison with the SM PAM material.

Table A. Ti-6Al-4V Tube Processes

Process	Post Process
β extrusion	Annealing/ machining
$\alpha + \beta$ extrusion	Annealing/ machining
Rotary piercing	Annealing/ machining
Flowforming	Minimal or no machining

were collected at 205 locations for each spade. The average spatial location deviation from nominal for the as-cast SLA spades was only 0.20 mm greater than that of the as-cast hard-tooled spades. These minor differences suggest that components cast from SLA and hard-tooled patterns may be expected to possess similar wall thicknesses and geometry. Accordingly, the decision to use SLA or hard-tooled patterns should be based on issues of production quantity, schedule requirements, and budget, rather than on issues of geometrical compliance.

A hard-tooled spade is shown in Figure 2, along with micrographs from three different regions of that spade. The spade was hot isostatically pressed (HIPed) for 2 h under 103 MPa argon at 900°C, chemical milled, and vacuum annealed at 840°C. The morphology is consistent throughout the spade and reflects a typical cast Ti-6Al-4V microstructure of mixed α/β within prior β grains. Further investigations, aimed at quantifying prior β grain size, α plate width, and areal fraction of α and β phases as a function of cast section thickness, are ongoing.

Transitioning from the weldment to the cast component has significantly increased the part-to-part uniformity of the spades; the only non-repair welding required of the NNS casting is the attachment of wrought Ti-6Al-4V plates to cover casting support holes in non-critical areas. An M777 unit with cast spades has also passed live-fire testing in both hot-weather and cold-weather conditions. As a result, the single-piece investment cast spade has been implemented in low-rate initial production, the current and second production phase for the M777.

The exploration of alternative casting material feedstocks has shown promise for reducing component cost without compromising performance. 12.7-mm-thick and 25.4-mm-thick plates were cast for each of three lower-cost feedstock options and then HIPed (900°C, 103 MPa argon, 2 h), chemical milled, and vacuum annealed (840°C, 2 h). The three options exhibited tensile properties (875.6–910.1 MPa tensile strength; 779.1–827.4 MPa yield strength; 6–7% elongation) that are comparable to both the relaxed composition Ti-6Al-4V used for current M777 castings and triple vacuum arc remelted, aerospace-quality material. Figure 3 shows that two of the techniques (Option 1 and Option 3) also displayed fatigue properties that are comparable to the M777 and aerospace heats. Based on those results, the NCEMT has commissioned production of two spades from the lower-cost Option 1. If those spades perform well under live-fire conditions, they may pave the way for the use of lower-cost material inputs for additional M777 cast components.

Prior to the NCEMT's involvement, the Joint Program Management Office, BAE Systems, and Howmet Castings developed a three-piece investment cast saddle (Figure 4). The two vertical "arms" of the saddle were individually cast and then welded to the base of the component. While the three-piece design represented a significant improvement over welding 120 individual pieces of formed plate, the three-piece, low-rate initial production (LRIP) configuration leaves open the possibility of distortion from welding and significant part-to-part variability. The NCEMT is currently working with JPMO, BAE Systems, and Howmet Castings to transition from a three-piece saddle to a single-piece component. This is being accomplished through a redesign of the arm-to-base transition and assembly of the individual wax patterns into a composite structure before commencing mold formation and casting. A single-piece saddle has already been cast successfully and is undergoing post-casting processes. The component will be finish machined, checked for agreement with dimensional tolerances, and then destructively tested to verify that the target mechanical properties have been achieved. Production and live-fire testing of a second cast piece are planned to evaluate the single-piece saddle design under firing conditions.

Tubular Components

In executing the test matrix outlined in Table A, multiple Ti-6Al-4V tube production paths have been investigated. The NCEMT is currently evaluating the product from each manufacturing process according to several dimensional criteria: inner diameter, outer diameter, wall thickness, concentricity, roundness, straightness, length, and surface finish.

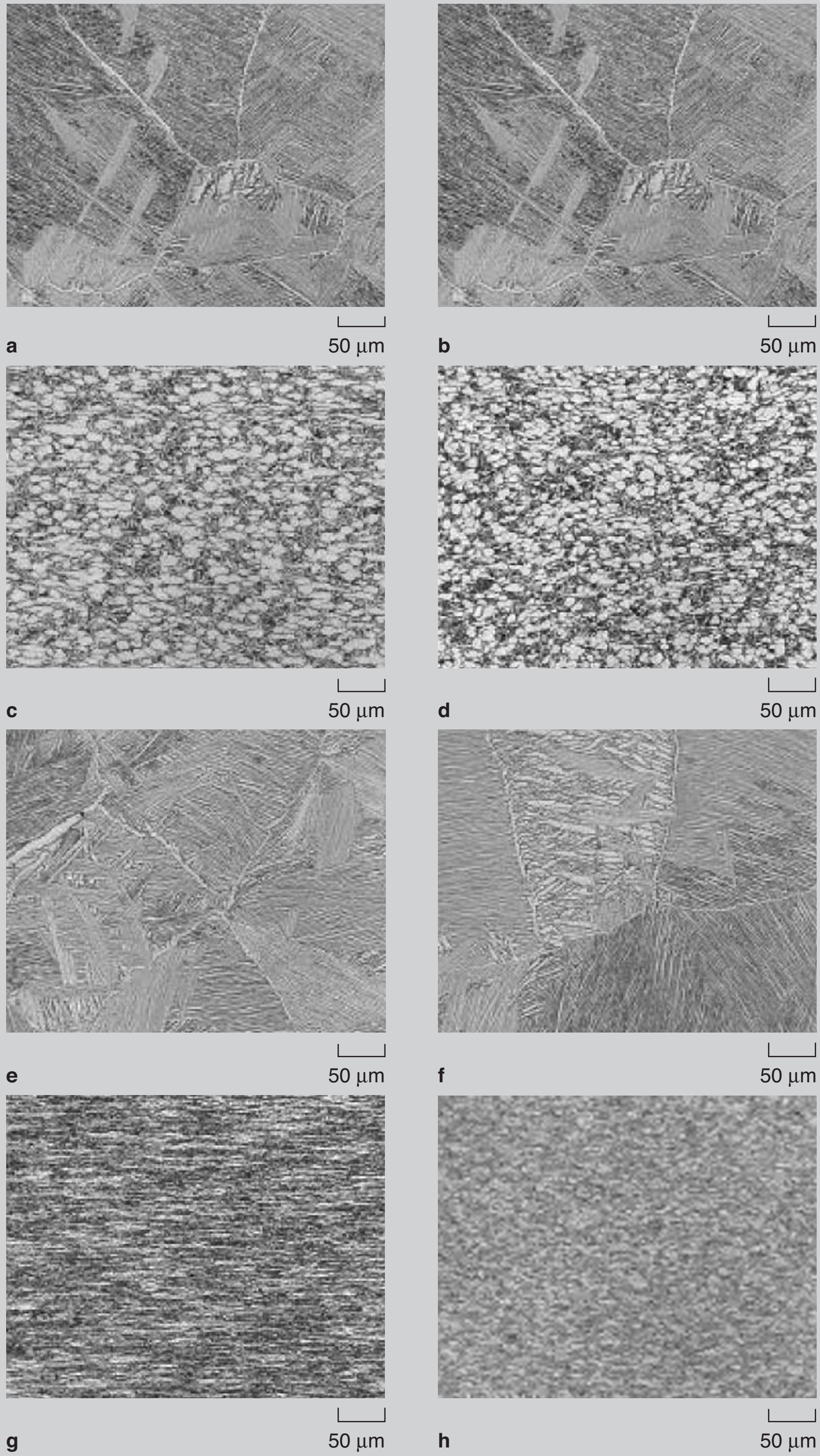

Figure 5. Micrographs and tensile properties (longitudinal direction) of various candidate, standard grade Ti-6Al-4V tubes; all properties met M777 specifications. (a), (c), (e), and (g) are longitudinal and (b), (d), (f), and (h) are transverse views. (a,b) β extrusion—865 $\pm$ 5 MPa YS, 959 $\pm$ 5 MPA UTS, 13.2 $\pm$ 0.4% El, 26 $\pm$ 1% RA; (c,d) $\alpha + \beta$ extrusion—909 $\pm$ 11 MPa YS, 980 $\pm$ 5 MPa UTS, 17.3 $\pm$ 0.5% El, 39 $\pm$ 1% RA; (e,f) rotary pierced—883 $\pm$ 6 MPa YS, 998 $\pm$ 6 MPa UTS, 12.8 $\pm$ 0.7% El, 27 $\pm$ 2% RA; (g,h) flowformed—968 $\pm$ 11 MPa YS, 1,245 $\pm$ 8 MPa UTS, 11.8 $\pm$ 1.9% El, 28 $\pm$ 9% RA.

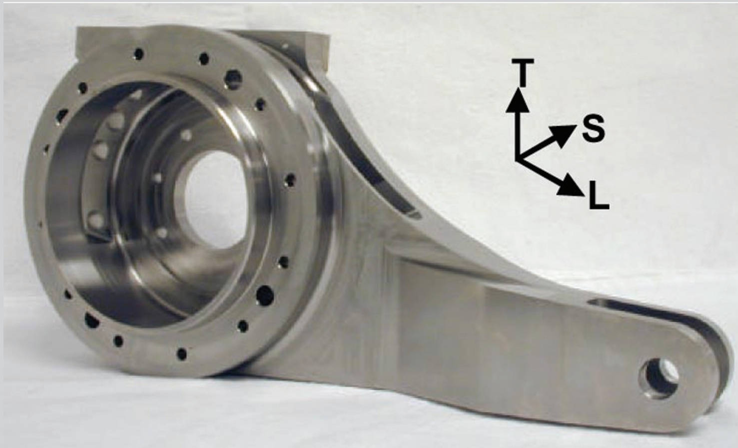

Figure 6. A forged M777 Ti-6Al-4V bell housing with sample orientation convention.

Of significance is the fact that the NCEMT and Dynamic Machine Works Inc. have successfully produced what are believed to be the longest standard grade (~183 cm long) and extra-low interstitial grade (~188 cm long) Ti-6Al-4V tubes ever flowformed. Those lengths satisfy the requirement for the longest tube segment length in the M777 cradle structure. Pending the results of mechanical testing and welding trials, it should therefore be possible to fabricate an M777 cradle using tubes that are all flowformed, thereby maximizing material efficiency and minimizing production cost.

Representative micrographs of standard-grade Ti-6Al-4V tubes from each of the Table A vendors are displayed in Figure 5, along with the averaged tensile properties measured for each respective tube. The axis of each tensile sample was parallel to the longitudinal axis of the tube from which it was extracted. The first tube, which was extruded above the β transus temperature, displays a transformed structure with alpha at the relatively large prior β grains, acicular α, and intergranular β. The tube extruded below the transus temperature, in the mixed α/β phase field, exhibits a much finer structure consisting of primary α, acicular α, and some intergranular β. The smaller grains of this tube may be better suited for flowforming than those of the tube extruded above the transus temperature. The microstructure of the rotary-pierced tube closely resembles that of the β-extruded tube, while the flowformed tube consists of fine primary α and intergranular β grains that are highly elongated in the primary working direction. The tensile properties of all tube varieties meet the requirements for implementation on the M777; the longitudinal yield strength and ultimate tensile strength of the β-processed tubes are slightly lower than those of the α/β-processed tube, which in turn are surpassed by the highly deformed flowformed tube. Fatigue tests are also being conducted and will be evaluated with the described microstructures and tensile properties described to better determine the processing/microstructure/properties relationship that exists for each type of tube.

In addition to the dimensional, metallurgical, and mechanical analysis of the tubes, the NCEMT has begun exploring the welding behavior of each tube variety. Trials will determine how each type of tube responds to plasma arc welding. Of particular concern is the possibility that residual stresses in the extruded, rotary-pierced, or flowformed tubes may lead to distortion in a welded structure. If such problems are detected, the NCEMT will take the lead in redesigning fixtures or prescribing supplementary heat treatments to minimize distortion effects.

Forged Components

Bell housings, shown in Figure 6, have been successfully forged from low-cost single melt plasma arc melted (SM PAM) Ti-6Al-4V billets containing 0.16 wt.%, 0.20 wt.%, and 0.24 wt.% oxygen. The mechanical properties and microstructure of those bell housings and the initial billet were characterized and compared with those of both standard double vacuum arc remelted billet (2XVAR) and baseline bell housing forgings with a nominal 0.17 wt.% oxygen level. All bell housing forgings were subjected to a mill-anneal heat treatment at 732°C for 3 h followed by furnace cooling below 538°C and then cooling in air to ambient temperature. The low-cost SM PAM bell housing forgings exhibited tensile strengths (average of six specimens) of 965 MPa and 1,034 MPa, yield strengths between 910 MPa and 972 MPa, elongations between 14.9% and 15.9%, and reductions of area between 36.2% and 40.9%. All tensile properties of SM PAM forgings were above the requirements of AMS 4928 and ASTM B 381, which are accepted standards for Ti-6Al-4V forgings and standard 2XVAR forgings. The strengths increased with increasing oxygen content with a gradual decrease in elongation and reduction of area values.

The plane strain fracture toughness (K_{IC}) of the 0.16 wt.% oxygen SM PAM mill-annealed bell housing forging in the T-L orientation (see Figure 6), 66.5 $MPa \cdot m^{1/2}$, was superior to that of the 2XVAR forging (59.4 $MPa \cdot m^{1/2}$). Contrary to the trend observed for yield strength, fracture toughness (average of three samples) decreased from 66.5 $MPa \cdot m^{1/2}$ to 43.5 $MPa \cdot m^{1/2}$ among the SM PAM forgings as the oxygen content was increased from 0.16 wt.% to 0.24 wt.%. Smooth bar fatigue strengths (10^7 cycles, L orientation, $R = -1$) of 494.4 MPa, 464.7 MPa, and 439.2 MPa were observed for 0.16 wt.%, 0.20 wt.%, and 0.24 wt.% oxygen SM PAM bell housing forgings, respectively, compared to 422.0 MPa for the 2XVAR forging. Fatigue strengths were determined from best-fit S/N curves of at least ten specimens. The microstructures of SM PAM and 2XVAR forgings were quite similar to those of conventional α-β forgings, consisting of primary grains, intergranular β, and transformed β (lamellar α in a β matrix). Stereological measurements revealed that the total α volume fraction content increased from 85.4% for the 0.16 wt.% SM PAM forging to 88.5% in the case of the 0.24

wt.% SM PAM forging.

Based on test results obtained in this work, bell housing forgings made using SM PAM billet stock with an oxygen level up to 0.24 wt.% appear to be viable replacements for bell housings machined from wrought plate. Forging reduced material waste by about 50% compared to machining from wrought plate, and use of the SM PAM method should also significantly reduce the billet cost. Combined, these factors may reduce component cost by as much as 40%.

FURTHER REDUCTIONS IN THE COST OF TITANIUM PROCESSING

The discussions of NNS processes and alternative material feedstocks in this paper illustrate the utility of those techniques in delivering high-quality, lower-cost M777 components. Despite these improvements in manufacturability and cost reduction, additional opportunities exist for improvement. Potential areas for future work include: additional heat and fluid flow process modeling coupled with casting experience to avoid potential defects; low-cost rapid prototyping in conjunction with computer-aided design and manufacturing; development of large capacity, cold-wall induction melting that enables the charge to be super-heated, thereby filling thin wall sections, allowing high revert use and improving surface finish;[18–20] development of faster and/or low-cost heat-treatment process such as microwave atmospheric pressure technology to replace some of the current heat-treating processes with cheaper, faster microwave ovens that inherently offer better thermal control;[21] improvement of non-destructive inspection processes that allow faster processing; development of high-speed machining processes; and development of a user-friendly titanium property database that would provide the design engineering community with access to critical lower-cost titanium properties. The NCEMT has begun work in the latter area by establishing a web-based low-cost titanium database[22] and by hosting a low-cost titanium workshop.[23]

CONCLUSIONS

The NCEMT is increasing the affordability of the M777 lightweight howitzer through the application of appropriate manufacturing techniques such as investment casting, extrusion, rotary piercing, flowforming, and forging to produce M777 stabilizer arms, spades, saddles, cradle tubes, and bell housings. The investment cast spade and stabilizer arms have been successfully implemented in the LRIP phase of M777 production, and current research holds promise that the use of machine chip and revert-intensive feedstock may reduce costs further. The development of an SM PAM forged titanium bell housing is expected to lead to the adoption of this component in future M777 production after field testing in the first quarter of the 2005 fiscal year. The single-piece saddle, which has been cast and will soon be evaluated, is scheduled for implementation during full rate production, scheduled to begin in fiscal year 2006. Finally, ongoing work on the use of leaner cradle tube production methods is expected to yield lower-cost tubes with reliable tolerances and shorter lead times.

ACKNOWLEDGEMENTS

The authors wish to thank the following for their contributions to this work: Chris Hatch and Ming Chan from the M777 JPMO, Picatinny Arsenal, NJ; Ronald Lomas and Anthony Galloway of BAE Systems, Cumbria, United Kingdom; Bret Clayton, Rick Soll, Jim Ault, and Bob Spencer of PCC Structurals, Portland, OR; John Klepeisz of Howmet Castings, Hampton, VA; Matthew Fonte of Dynamic Machine Works, Billerica, MA; George Legate of Nu-Tech Precision Metals, Ontario, Canada; John Cash of Titanium Engineers, Stafford, TX; Daniel Fleming of RTI International Metals, Houston, TX; Kuang-O (Oscar) Yu of RMI Titanium Company, Niles, OH; Patrick Dugan of Arcturus, Oxnard, CA; and Christian M. Joest of Imperial Machine & Tool Company, Columbia, NJ.

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