Multi-Metal Composite Gear/Shaft Technology

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Abstract

A research program, conducted in conjunction with a U.S. Army contract, has resulted in the development of manufacturing technology to produce a multi-metal composite gear/shaft representing a substantial weight savings compared to a solid steel component. Inertia welding is used to join a steel outer ring to a lightweight titanium alloy web and/or shaft through the use of a suitable interlayer material such as aluminum.

Fabrication is accomplished in a two-step inertia welding operation first joining steel to aluminum and then joining titanium to the aluminum side of the steel/aluminum weldment. The development program, carried out over a five-year period, included testing and metallurgical evaluation of torsion components, small fatigue test gears and prototype demonstration sun gears for the Allison 250-B17F gearbox. In addition to development of fabrication techniques, criteria were established to allow design of a new or retrofit component using the multi-metal welding technology.

A prototype multi-metal composite sun gear performed without incident when subjected to a 160-hour simulated flight endurance test in a gearbox test rig.

Introduction

Gears used in high-performance aerospace applications are typically forged from a single piece of alloy steel. Gear components for certain applications are then selectively or totally surface-hardened by techniques such as carburizing, nitriding or carbo-nitriding. This procedure imparts to the tooth contact surfaces the useful properties of high hardness, strength and wear resistance. The remainder of the gear component very often only transmits torsional loads and does not require the hardness and strength properties characteristic of the alloy steel contact surfaces. In a program begun in 1987 for the U.S. Army, a technology for producing lightweight gears and gear shafts has been developed that allows the use of hardened steel in the power transmission contact surfaces and lighter-weight titanium alloy in the non-contact areas of the web, hub and/or shaft. Since the density of titanium is 43% less than that of steel, significant weight savings are offered by the concept, provided the gear component geometry and contact surface configurations allow a significant titanium-for-steel substitution.

The use of lightweight, high-strength alloys for engine components is naturally an attractive proposition. Case-hardened steel alloys enjoy a well-established position of proven reliability and represent the very core of gearbox design technology. The objective of the program begun in 1987 was to develop a method for using surface-hardened steel where it was required and lighter weight titanium in other locations within the gear component. Metallurgical incompatibilities, however, have to date prevented titanium from being welded or otherwise metallurgically bonded directly to steel. This program developed a method for joining steel and titanium alloys by the solid-state inertia welding process using aluminum as a mutually compatible interlayer material between the two. The initial project was conducted over a period of five years by Materials Analysis, Inc., with its primary subcontractor, Interface Welding, under the auspices of U.S. Army AVSCOM, Ft. Eustis, VA. Additional contract assistance in the design, manufacture and test of flight-quality hardware was provided by Allison Engine Company (formerly Allison Gas Turbine Div. GMC).

Manufacturing Process Development

The five-year program to develop the multi-metal gear technology involved the design and fabrication by inertia welding of test specimens for the following purposes:

1. To develop the feasibility of the multi-metal approach,
2. To evaluate the metallurgical integrity of the multi-metal joint,
3. To generate the mechanical properties to be used in the design of test and prototype components.

The inertia welding machine which was employed by Interface Welding for fabrication of the majority of the test coupons, mechanical torsion test specimens and fatigue test gears is pictured in Fig. 1. A typical alloy steel test coupon ring is pictured in Fig. 2. In general these rings were 3.75" O.D. and 2.2" I.D. with a conical bevel machined in the I.D. on one side of the ring. The entrance diameter of the conical bevel on the face of the ring was maintained at 2.90". The conical bevel machined in the ring pictured in Fig. 2 was configured such that the beveled surface was inclined at an angle of 45° from the rotational axis of the ring. For the evaluation of joint geometry effects, which are discussed subsequently, the conical bevel on the weld surface was inclined at angles of both 45° and 30° from the axis of rotational symmetry. Although weld parameters and machine settings differed somewhat for the two different weld configurations, the technique employed for development of the weld procedures was similar.

Fig. 3 pictures a typical alloy steel ring chucked in the spindle collet of the inertia welding machine at Location 1. The steel mass

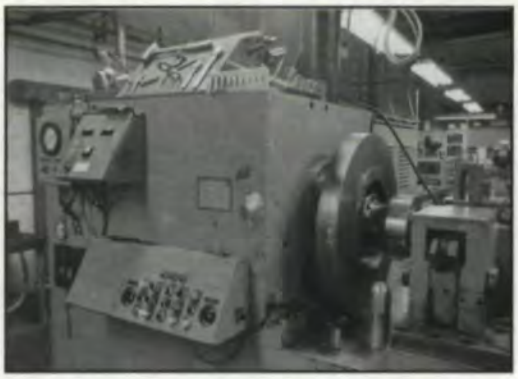

Fig. 1 — Inertia welding machine used in majority of welding trials.

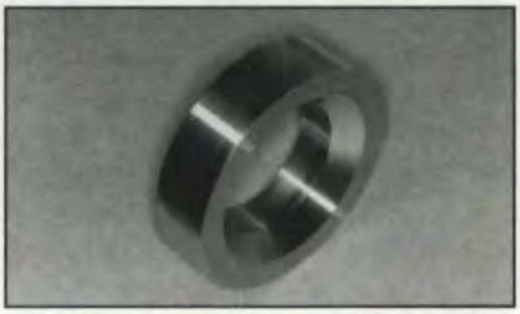

Fig. 2 — Alloy steel ring prepared for inertia welding with 45° conical bevel.

Fig. 3 — Inertia welding machine setup for welding aluminum bar to alloy steel ring.

surrounding the steel ring at Location 1 in the inertia welding machine is commonly referred to as the flywheel mass. Pictured at Location 2 in Fig. 3 is a section of 3.5". diameter 6061-T6 aluminum alloy round bar with a conical male bevel machined on one end. For the particular weld procedure pictured in Fig. 3, the mating surfaces of both the aluminum conical male bevel and the steel conical female bevel were inclined 45° from the axis of rotational symmetry of the parts.

After the two components to be inertia welded are properly machined, cleaned and chucked in the inertia welding machine, the spindle, containing the collet and attached to the flywheel pictured toward the left side of Fig. 3, begins to rotate. The rotational speed of

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the spindle assembly is a variable parameter that is selected for the individual weld. After the spindle and flywheel assembly reaches a preset rotational speed (rpm), the spindle assembly is disconnected from the drive mechanism in the inertia welder and allowed to freewheel with only the precise kinetic energy (inertia) provided by the rotating mass of the flywheel assembly. The flywheel mass itself is variable and is selected during machine setup based on the material and configuration of the components to be welded. While the spindle and flywheel assembly are rotating freely, the tailstock, containing the premachined aluminum bar pictured toward the right of Fig. 3, is stationary. The rotating component is thrust against the stationary component by hydraulic pressure provided by the inertia welding machine. The freely rotating alloy steel ring, pictured at Location 1 in Fig. 3, surrounded by the spindle and flywheel mass, is thrust against the non-rotating component, pictured at Location 2 of Fig. 3. The resulting friction between the mating surface materials of the two components, D6ac steel and 6061-T6 aluminum, generates enough heat to raise the temperature of the aluminum component to

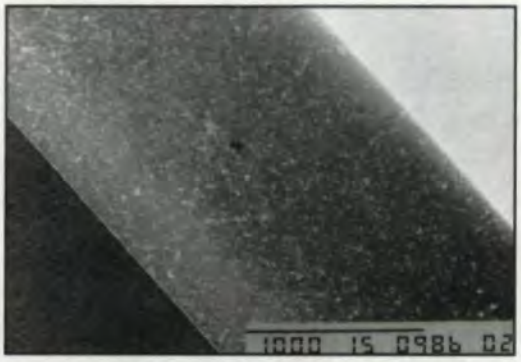

Fig. 4 — Electron micrograph of multi-metal weld cross section showing Ti 6Al-4V, 6061Al, D6ac steel components, lower left to upper right.

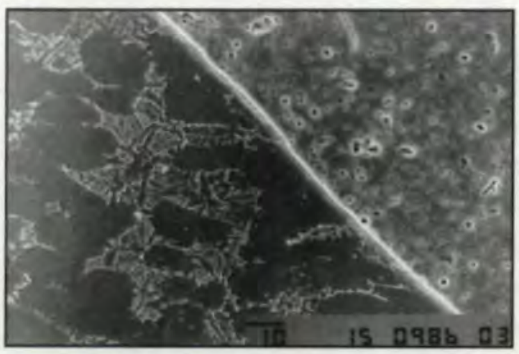

Fig. 5 — Electron micrograph of weld interface between Ti 6Al-4V, lower left, and 6061Al, upper right. (750X)

the forging temperature range, but not into the melting temperature range. In addition to creating heat and providing deformation, or flash, of the two components at their interface, the friction between the two components also brings the flywheel and spindle assembly to a stop. Thus the rotating (kinetic) energy of the spindle and flywheel assembly is transformed into thermal and strain energy, which causes the two components to be welded together without either component changing to the liquid phase during the process. The resulting weldment is then removed from the inertia welding machine, and the aluminum bar is cut off adjacent to the completed weld.

After completion of the first inertia weld, the aluminum center (interlayer) in the intermediate weld coupon was machined to create a conical female bevel on the inside surface of the steel/aluminum subassembly. At the conclusion of machining, the intermediate weld coupon with a newly machined aluminum surface was chucked in the inertia welding machine in a manner similar to that previously described for the steel ring component. Inertia welding of the titanium alloy bar to the aluminum interlayer was accomplished in a manner similar to that described for the aluminum-interlayer-to-steel weld, although different weld parameters were employed. This two-step inertia welding technique was employed with several variations to produce test coupons and components required in the R&D program.

For the coupon configurations described above, the inertia welding process generally produces welds of rotational symmetry. Machine settings, or weld parameters, which can be varied in the process, are flywheel mass, spindle rpm (weld speed) and weld pressure (the force with which the rotating weld component is thrust against the non-rotating weld component during the welding process). The length of total upset, or axial length loss, is a useful parameter to monitor; however, it is a variable resulting from the three machine setting parameters, the weld configuration and the properties of the materials being welded. All of these parameters are typically determined through a weld development program.

After development of the welding process parameters suitable for multi-metal weldment fabrication, metallurgical microsections were taken through the composite joints of each of the alloy combinations evaluated. Fig. 4 pictures at 35X magnification an electron micrograph showing the overall appearance of a joint profile of weldment materials Ti 6Al-4V, 6061Al and D6ac steel; lower left, center and upper right, respectively. The titanium/aluminum inertia weld profile is pictured at 750X magnification in Fig. 5 with the Ti 6Al-4V and 6061Al materials pictured lower left and upper right, respectively. Similarly, the steel/aluminum profile is pictured at 750X magnification in Fig. 6 with the 6061Al and D6ac steel alloys pictured lower left and upper right, respectively.

Mechanical Characterization

Mechanical characterization conducted on the multi-metal composite weldments consisted of microhardness surveys and static torsion testing. Microhardness surveys conducted on polished cross sections, such as the one pictured in Fig. 4, revealed that the heat treated properties of the titanium and steel alloy components were virtually unaffected by the inertia welding process. The aluminum alloy interlayer, however, being the lowest melting and the most sensitive to heat of the three materials in the stackup, was briefly subjected, during the inertia welding process, to temperatures which were at or near the solution treatment temperature for the alloy. Consequently, the 6061-T6 aluminum bar stock, which was the primary interlayer material used, experienced over-aging and thermal softening at locations immediately adjacent to the bond lines. Metallographic examination of these thermally softened regions did not reveal the presence of any defective condition, such as eutectic melting.

Specimens for mechanical torsion testing were designed and fabricated using the multi-metal inertia welding process. An example of one such torsion specimen is pictured in Fig. 7. Evident in the picture are the two inch-square drives machined into the titanium component to the right and the steel component to the left side of the photo. Specimens were made with interlayer thicknesses in the range of 0.020–0.050". A further joint geometry variable was evaluated by fabricating torsion specimens with the conical, aluminum interlayer oriented at 30° and 45° from the rotational axis of the specimen.

The torsion testing machine itself consisted of a drive shaft mounted in a sturdy set of bearings and operated through a 16-in. crank arm by a servohydraulic cylinder fitted with an LVDT and a 50,000 lb. load cell. The digital control system and hydraulic power supply were comparable to those that would be employed on a servohydraulic mechanical testing machine. Nine each of the 30° and 45° specimens were successfully torsion tested to failure in this program. The average maximum torque for the 45° weld specimens was 9,409 ft-lbs., while the corresponding value for the 30° specimens was 13,302 ft-lbs. Geometrical analysis of the surface area of the conical weldment in each of the two weld angle configurations revealed total weld areas of 3.96 square inches and 5.6 square inchs for the 45° and 30° configurations respectively. When the maximum torque values were calculated on a unit area basis, it was discovered that for both the 30° and 45° conical weldment configurations, the maximum torque values reduced to 2,375 ft-lbs. per square inch of interlayer material. This torsional strength consistency would prove useful during subsequent stress analysis and design activities associated with the manufacture of flight-quality demonstration gears.

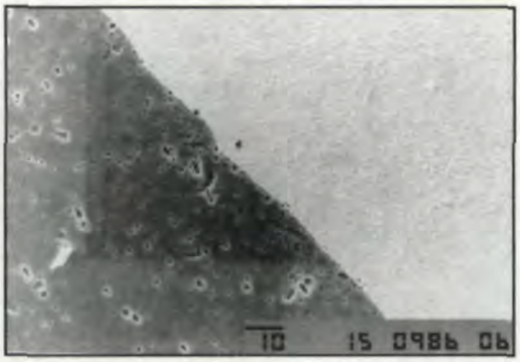

Fig. 6 — Electron micrograph of weld interface between 6061Al, lower left, and D6ac steel, upper right. (750X)

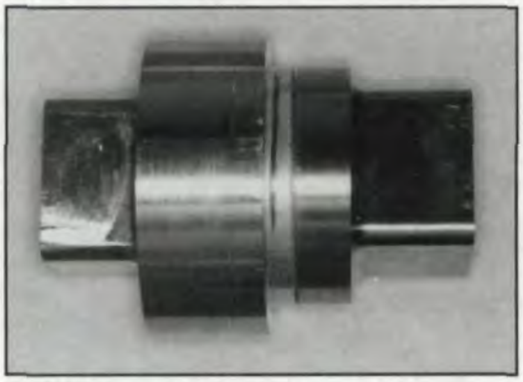

Fig. 7 — Typical composite torsion specimen prior to testing.

The 30° interlayer torsion test specimen, pictured in Fig. 7, is shown after torsion testing to failure in Fig. 8. The interlayer fracture surface was carefully examined on all torsion specimens to verify that fracture had occurred entirely through the aluminum interlayer, and that no de-bonding of the various components had occurred during the testing sequence. Fig. 9 is an electron fractograph, taken at 1000X magnification, showing the typical shear dimple microfeatures associated with the shear overload fracture mode in the aluminum interlayer material.

The fracture path through the interlayer material on specimens subjected to static torsional overload bore certain characteristics worthy of note. The shear fracture path in a thick-walled tube composed of a homogeneous and isotropic material would be predicted to occur on a transverse radial plane; however, in the case of the composite weldment, fracture through the aluminum is forced to occur along a line defined by the configuration of the conical interlayer. The longer the path of the fracture, the greater the strain energy required to create new surface during the fracture process. In appreciably thick interlayers, the fracture path occurred from one side of the interlayer on the O.D. to the opposite side of the interlayer on the I.D. in such a manner as to minimize the cross sectional area of the fracture. The fracture was simply passing through the path of least resistance, minimum area. In the eighteen torsion test weldments used for mechanical behavior characterization, an effort was made to maintain the interlayer below 0.050" in thickness. Once the interlayer was reduced to a thickness on the order of 0.050", and below, the tendency to fracture from one side of the interlayer at the O.D. to the opposite side of the interlayer at the I.D. was not as predictably observed. At the small interlayer thicknesses, other factors, such as local thermal softening of the aluminum alloy, probably exerted an influence on fracture path. This ameliorating effect of a thin interlayer configuration is consistent with the fact that the thinner the interlayer, the less difference in strain energy requirements for the very small angle of optional fracture paths through the interlayer. For this thin interlayer condition, other factors influencing fracture stress are probably of the same order of magnitude as the variations possible from available fracture paths. As the interlayer becomes thicker, the optional fracture path band increases, as does the percentage difference in strain energy required for separation along the various possible fracture paths.

Fig. 8 — Fracture surfaces of 30° interlayer torsion specimen after testing.

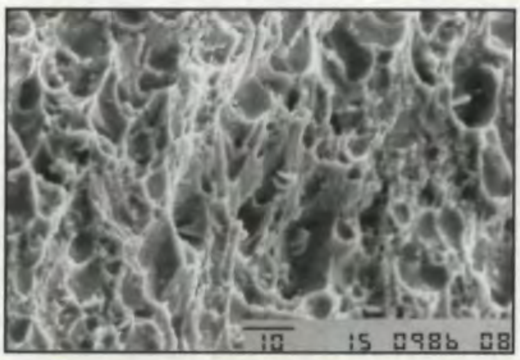

Fig. 9 — Electron micrograph of sheared aluminum interlayer from torsion specimen fracture surface. (1000X)

Fig. 10 — Pair of multi-metal fatigue test gears.

In summary, joint geometry exerted a substantial influence on the static torsion strength of a composite weldment. This influence appears to be directly related to the cross sectional area of surface that the fracture separation is forced to create. For thicker interlayers there is a distinct tendency for the fracture to pass through the path of least resistance from one side of the interlayer at the O.D. of the weld to the opposite side of the interlayer at the I.D. of the weld. The tendency observed was for the fracture path to pass through the weaker interlayer material, but at the same time to cut corners and pass through the shortest, most nearly radial path possible. As the interlayer material becomes thinner, the strain energy difference between the optional fracture paths becomes less, as does the tendency of the fracture to predictably follow a given path.

Small Fatigue Test Gear Fabrication and Evaluation

One of the major goals of this project was to evaluate the performance of the multi-metal gear manufacturing concept in a gearbox environment. Simulation of such a gearbox environment had been successfully achieved by Allison using a four-square gear fatigue test machine. This machine, reportedly developed by Allison, was similar in design to rigs used at NASA Lewis Research Center. A standard gear configuration has been established for evaluation in the four-square test rig. The multi-metal inertia welding concept was incorporated into this standard gear configuration while maintaining all exterior dimensions of the gear. The multi-metal inertia welding process was employed to fabricate gear blanks suitable for subsequent machining of the test gear configuration. Several pairs of small fatigue test gears were manufactured with a pitch diameter of approximately 3.3". Fig. 10 pictures a typical set of these test gears with a titanium alloy hub, aluminum alloy interlayer and hardened alloy steel teeth. The small fatigue test gears were tested in the four-square rig under the following conditions:

1. Speed	10,000 rpm
2. Torque	400 in-lb.
3. Oil Inlet Temperature	119°F
4. Oil Type	MIL-L-23699C
5. Duration	50 hrs.
6. Max. Contact Stress	261 ksi

These test conditions were selected to be similar to those employed routinely by Allison to test steel gears. Employing this standard test gear design and test protocol did not subject the tri-metal weld joint to either temperature or torsional stress that would be considered severe. The test did, however, subject the tri-metal weld to vibratory loading similar to that experienced in an aircraft gearbox.

It is well-established that in most aircraft gearbox applications, oil supply temperatures of 175–250°F are normal. In this test, the oil supply temperature was maintained at 119°F to provide a thick lubricant film and prevent scuffing or scoring of the gear teeth. The actual surface temperature of the gears is usually somewhat higher than that of the oil supply. The web of the test gear is over-designed to provide rigidity and ease of manufacturing. Because of this, the maximum stress in the weld interlayer during the test was calculated to be 0.168 ksi. For comparison, the torsional design allowable stress utilized in the demonstration gear was 27.2 ksi.

Post-test inspection of the fatigue test gears after the scheduled teardown indicated a teardrop-shaped contact patch on the gear faces. This contact pattern, pictured on the visible faces of the right hand gear in Fig. 11, was uniform in size, shape and location. The gears showed no sign of pitting or other distress that would have prohibited continued testing. The tested gears passed magnetic particle inspection according to EIS 1169, Method D, and fluororescent particle inspection according to Method AMS 2640.

Aircraft gears are generally designed with contact stresses kept below 160 ksi. Using the American Gear Manufacturers Association Method 2001, the successful operation of this gear for 50 hours at 261 ksi is equivalent to 300,000 hours operation at 160 ksi. Although not statistically significant, the success of this test verified the soundness of the approach to a multi-metal composite gear and paved the way for design and manufacture of a full-scale, flight-quality, demonstration gear.

Demonstration Gear Design, Fabrication and Test

One of the primary goals of the project was to produce a sample quantity of flight-quality demonstration gears using the multi-metal inertia welding process. Selection of the gear to be manufactured included fabrication and

Fig. 11 — Contact surfaces of multi-metal fatigue test gears after testing.

application considerations. The completed part would be subjected to high frequency dynamic testing and simulated flight endurance testing.

It is necessary to consider several important criteria when designing a multi-metal gear or gearshaft, some of which can only be evaluated through testing of a prototype part. A few of these criteria follow.

1. Weight savings must be realized sufficient to justify increased manufacturing cost associated with the multi-metal process.

2. Weld geometry and strength must be considered. The lower-strength aluminum interlayer material may necessitate a larger shafting cross section at the location of the inertia welds.

3. *The difference in modulus of elasticity* between steel and titanium introduces inherent stiffness differences between the multi-metal gear and an all-steel gear. Design modifications may be required to maintain satisfactory gear web or shaft dynamics when designing a composite component.

4. In some cases special tooling is required to control weld component concentricity during the fabrication process. Excess runout from eccentricities introduced during welding can lead to poor spline and gear loading and detrimental vibration.

5. The complexity of the component to be produced may simply require so many two-step inertia welds or so much specialized tooling that it may be impractical to replace in its current configuration with a multi-metal gear.

The demonstration gear was selected by a team from Materials Analysis, Interface Welding and Allison. The major consideration of the team in its final selection process was to select a gear that, when manufactured using the multi-metal inertia welding process, would subject the weld locations to relatively high loads and at the same time would be a relatively simple gear shape to fabricate. The intent was to select a gear shaft that was not overly complicated to fabricate, but that would challenge the ultimate performance of the welds by providing a high service load application. After careful consideration the sun gearshaft, P/N 23033882 from the Allison 250-B17F gearbox, was selected as the demonstration gear to be *fabricated using the multi-metal technology.* Prototypes would be subjected to a performance evaluation and comparison to the incumbent, all-steel sun gear shaft.

In order to evaluate the applicability of several manufacturing techniques, it was decided to produce a small quantity of flight-quality, demonstration sun gears using two parallel manufacturing approaches to produce the hardened steel portions of the gear shafts. On one set of demonstration gears, dual pulse induction hardening (DPIH), an Allison proprietary process, would be employed to induction surface harden the gear and spline teeth as the final step in the multi-metal sun gear manufacturing process. A second set of demonstration sun gears would be manufactured employing conventional gas carburizing to

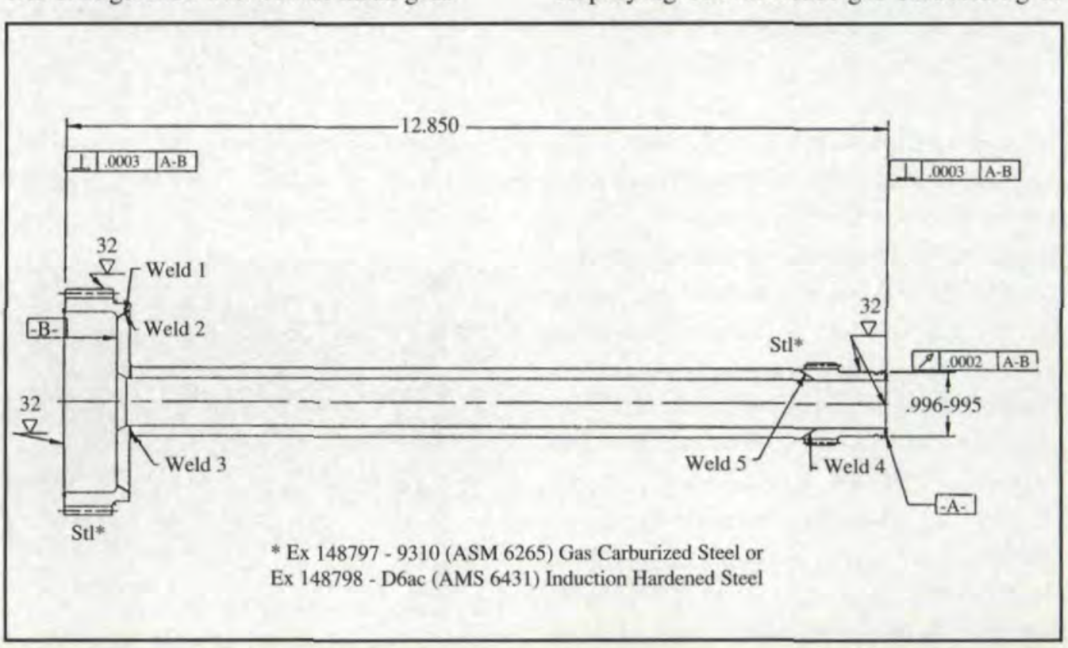

Fig. 12 — Allison 250-B17F multi-metal sun gear shaft weld locations.

prefabricated 9310 alloy steel gear and spline components prior to the inertia welding fabrication process and finish grinding of the sun gear component.

Weld locations were selected within the gear shaft so as to maximize the amount of steel replaced with titanium and thus maximize weight savings. These weld locations are presented in the schematic gear shaft cross section of Fig. 12. The welds involving aluminum interlayers (welds 1 and 2 and welds 4 and 5), were designed as conical welds with the interlayer oriented at an angle of 30° from the rotational axis of the gear shaft. Weld 3, identified in Fig. 12, was simply a Ti 6Al-4V butt weld employed in the fabrication process to reduce machining costs and material waste.

The torsion test information previously described was used to determine the allowable torsional shear stress for the weld joints in the multi-metal sun gear. The failure torques for the 30° torsion specimens were compiled, and resulting torsional shear stresses were calculated. The resulting torsion design allowable stress within the interlayer was found to be 27.2 ksi. Analysis of the sun gear shaft predicted torsional stress in the shaft at the spline end to be 26.3 ksi. Since this was below the 27.2 ksi design allowable, no modification to the shaft section thickness was required. Since the service stresses at the location of the shaft spline were considerably greater than those in the region of the spur gear, the tri-metal weld in the spur gear web was also expected to be of sufficient strength without increasing the web thickness at the weld location.

A lateral and torsional dynamic analysis was performed at Allison. These dynamic studies were conducted to verify that the torsional and lateral natural frequencies were located well away from the frequencies associated with normal operation. Sufficient margin between the operating speed and both torsional and lateral natural frequencies assured no excessive engine vibration or dynamic loading of engine components.

Once the design analysis for the 250 sun gear was complete, manufacturing procedures were conducted in parallel for the D6ac and 9310 multi-metal gear shafts. The inertia welding process parameters were developed for each of the five welds cited in the gear shaft schematic of Fig. 12.

Two of the completed demonstration gears are pictured in Fig. 13. In that photo the gear shaft with 9310 alloy steel and gas carburized teeth is shown at the top of the photo and the gear shaft containing induction hardened, D6ac gear teeth is shown at the bottom of the photo. The geometry of the two gears is identical. Physical weighing of one of the finished composite sun gear shafts showed it to weigh 1.75 lbs., a weight savings of 28% over the 2.45-lb. weight of the incumbent all-steel component. The gear shaft with the 9310 alloy steel teeth was inertia welded into the tri-metal gear form using previously manufactured gas carburized steel parts. The gear shaft with the

Fig. 13 — Multi-metal demonstration sun gears with gear and spline portions composed of 9310, top, and D6ac, bottom.

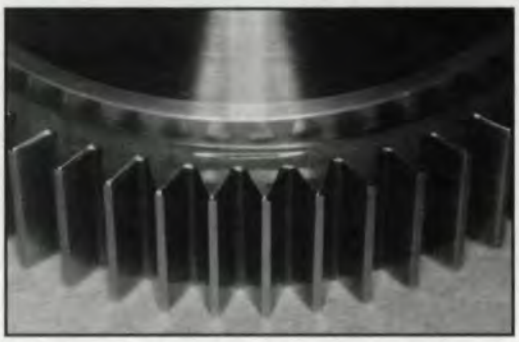

Fig. 14 — Spur gear end of 9310 multi-metal demonstration sun gear.

Fig. 15 — Spline end of 9310 multi-metal demonstration sun gear.

D6ac alloy steel components was fabricated by inertia welding and completely machined prior to induction hardening of the steel portions of the part. Close-up views of the spur and spline ends of the 9310 demonstration gear are pictured in Figs. 14 and 15, respectively. Figs. 16 and 17 picture the internal profile of the multi-metal weldments on the spur and spline ends of a demonstration sun gear.

One of the 9310 multi-metal sun gear shafts was subjected to dynamic stress characterization at Allison. This work complemented the analytical torsional and lateral dynamic analysis previously described. The physical testing associated with dynamic characterization was designed to further verify that the natural frequencies of the sun gear were located far enough from the operating speed frequencies so that no excessive engine vibration or dynamic loading of engine components would likely occur. Physical test results indicated the composite gear shaft exhibited natural frequencies very close to those observed in the all-steel production gear shaft. Since both the tri-metal gear shaft and the incumbent all-steel gear shaft exhibited very similar high frequency vibrational behavior, and since no problem has been observed in the long history of operation of the all-steel sun gear shaft, it seemed safe to conclude that no vibrational difficulties would be expected with the dynamically similar composite sun gear shaft.

Fig. 16 — Segment removed from spur gear end of D6ac multi-metal sun gear for metallographic evaluation.

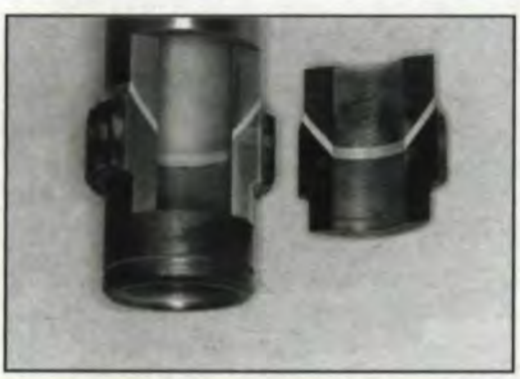

Fig. 17 — Segment removed from spline end of D6ac multi-metal sun gear for metallurgical evaluation.

The high frequency vibrational behavior similarities between the multi-metal composite sun gear shaft and the all-steel version of that component was an unexpected finding in light of the significant difference in weight, 2.45 lbs. versus 1.75 lbs. for the all-steel and multi-metal sun gears, respectively. One possible explanation for this observed vibrational behavior similarity is that, although the density of titanium is considerably less than that of steel (0.160 lb/in.^{3} versus 0.282 lb/in.^{3}), the difference in the elastic modulus of the two materials (16.5 x 10^6 psi for titanium versus 30 x 10^6 psi for steel) results in a ratio of elastic modulus/density which is virtually identical for the two materials.

Finally, one of the 9310 alloy multi-metal sun gears was subjected to a 160-hour simulated flight endurance test by Allison in a B17F gearbox test rig. This test consisted of approximately 500 duty cycles, each consisting of idle, take-off, cruise and landing service segments. The multi-metal composite sun gear shaft performed without incident and was undamaged during the test. Successful completion of the simulated flight endurance test verified that the multi-metal composite gear technology is sufficiently mature for incorporation into a full-scale engine development program and is a viable candidate for retrofit, where feasible, into existing power transmission and accessory gearbox applications. ○

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