

Chapter 12

Metal-to-Composite Structural Joining for Drivetrain Applications

Peter J. Fritz, Kelly A. Williams, and Javed A. Mapkar

Abstract Dissimilar material components in structural applications require advanced joining geometries and processes that permit the interface of these components to have mechanical behavior equivalent to the lesser of the base metal material behavior and the base composite material behavior. In volume-constrained applications, such as drivetrain parts, the interface must have the strength of the base materials, and the envelope of space of the current drivetrain componentry. The interface surfaces of the composite and metal are demonstrated here to achieve base material capability for the thickness, width, and length directions, resulting in conservation of mechanical properties throughout the interfaces, for all loading and deformation at material transitions. The method of material forming, modification, combining, and product operation is explained here, for optimization of materials usage and for processing equipment.

In designs to date, the metal to composite interface has been the weak link of the assembly, and product performance has been limited to this characteristic. This new method of interface build, and theory of base-to-joint equivalent strength, results in a new capability for drivetrain component design, and will start a new era of dissimilar materials combinations to offer the consumer improved product functionality with enhanced interface design, manufacture, envelope, and operational improvements.

Keywords Drivetrain • Joining • Dissimilar • Structural • Composite

12.1 Introduction

Metal parts in vehicle drivetrains dominate the materials selection for cars and trucks. The mostly steel, cast iron, and aluminum parts of the drivetrain are reliable, and are low-cost, but these metal parts result in drivetrain components that are heavy. As drivetrain components are generally very heavily loaded, composite material substitutions require the higher-strength composite selections, and joining between metal and composite must be sufficient to equal the strength of the base materials. To achieve such high interfacial strength capabilities, metal-to-composite interfaces need to be tailored by composite-fiber orientation, loading, geometry, and metal surface preparation.

Basic research has been completed here, to characterize joining between dissimilar materials, such as metal and composite, to determine the capability of standard joining within the framework of application requirements, and the special geometries necessary to attach metals to composites in drivetrains. Fundamental interfacial shear strengths for rotational component interfaces will be demonstrated here, and compared to the minimal necessary shear strengths of the base materials. Basic information on metal surface preparation, cylindrical interfaces, classical analysis, and thermal limitations will be verified here, so that the metal-to-composite interface capability of drivetrain applications can be compared to the base material of component metal shear capability and component composite interlaminar capability, leading to the design of joints that are stronger than the base materials.

The Eaton Vehicle Group provides automotive, aerospace, and commercial vehicle manufacturers worldwide with products and systems that are designed to improve vehicle efficiency, performance and power—such as emission control components, engine valves, valve-train systems and superchargers—as well as offering driveline expertise through its transmission, clutch and torque management products and systems. The testing and verification in this report was done for Eaton on driveline parts including transmission, differential, supercharger, and clutch.

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12.2 Shear Strength

12.2.1 Shear Strength Samples

To determine the effect of the metal surface preparation, the metal surface of coupon parts for bonding attachment were prepared as plain, textured (grit blasted), dimpled, and holes (penetrated). These preparations were all cleaned by acetone wipe, and then adhesively bonded or overmolded to a polymer, such as a thermoplastic, and cooled to strength. In tensile testing, the shear coupons were subjected to the highest loading to lead to failure, and that load was divided by the contact area, such as both sides summed, leading to the average shear stress of the interface at failure. In general, these coupons were loaded with an increasing load until debond occurred. At coupon debond, the peak load was recorded, and the interface area with the thermoplastic polymer was recorded, to calculate the peak shear stress. The schematic of Fig. 12.1 shows a standard lap-shear coupon indicating two green areas where the composite base material (d_1) on the left is bonded by overmolding to the metal component on the right (d_0). The bond area A_b then, is

$$A_b = 4lz_0 \quad (12.1)$$

where z_0 is the width of the metal specimen near the green area, but in a direction z that is not shown, but is the direction perpendicular to both directions x and y . This geometry is useful for symmetrical loading of the bonded area so that the shear strength can be measured with reduced peeling of the bond area.

The specimens used a composite thermoplastic, as shown on the left in Fig. 12.2, where the reinforced thermoplastic was overmolded on steel half-dogbone-shaped base material. Unlike Fig. 12.1, the reinforced thermoplastic was bonded on five sides of the steel. As the “end” of the steel was small and the end area offered only tensile bonding in all specimens, its area was ignored. But the other four sides did provide shear strength so all were utilized in the measurement of the shear area A_s as

$$A_s = 4l(z_0 + d_0) \quad (12.2)$$

This geometry of testing follows the method of ASTM D3528 [1], and uses symmetrical loading to prevent wrenches (force couples) in the interlaminar bond area. This deviates from the method of Watson in AFWAL-TR-82-4013 where steel plates are used on both ends of the coupon [2], but allows for symmetrical overmolding of the composite component.

Fig. 12.1 Schematic of composite material surrounding metal sheet specimens for shear loading

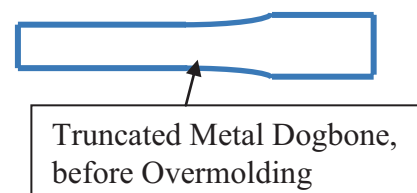
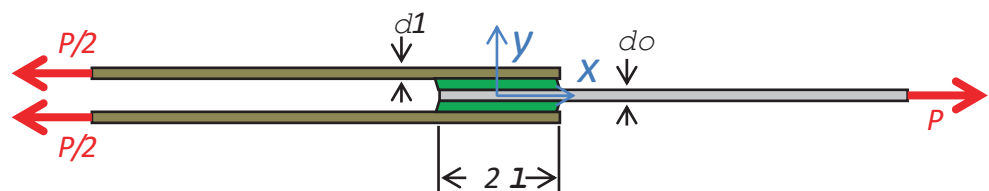
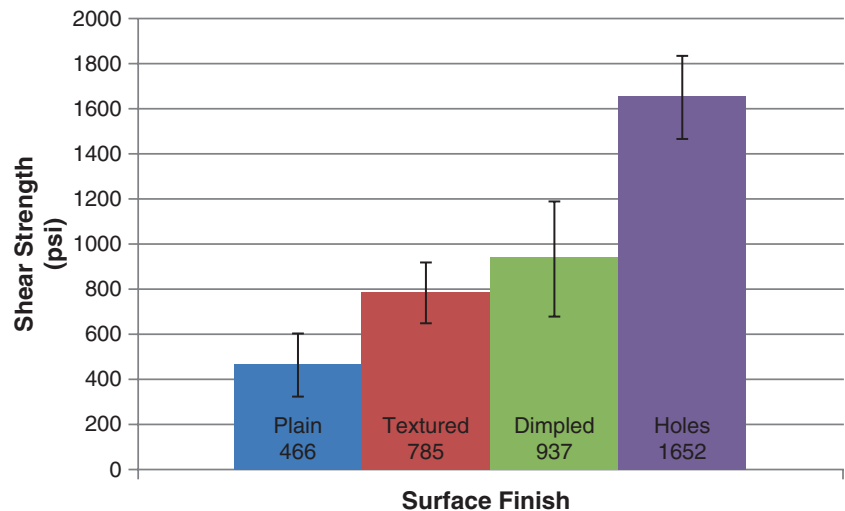


Fig. 12.2 Photograph of composite material bonded to truncated metal dogbone specimens for shear loading

Fig. 12.3 Shear strength of metal-to-composite interfaces with application of metal surface preparation, and overmolding of the composite coupons, with the metal as an insert



12.2.2 Shear Strength Verification

The base metal surface preparation, per the test plan, resulted in significant variations in interfacial shear strength. For these samples, all of the composite was overmolded onto the metal extended half-dogbones, so that results would only indicate the relative performance of the surface preparation. The weakest was the metal with flat faces, and no preparation. When texturing (grit blasted) was added, the interfacial shear strength increased with the additional geometry and increase in surface area, because of the texturing. The dimpling was a more severe case of geometry alteration, so more surface area was generated, and more shear strength was measured. Finally, with “holes,” an additional material interlock of the metal and composite was introduced, so significant additional shear strength was obtained, because all of the bonded surface was loaded and the composite material that extruded into the holes formed a base material mechanical “interlock,” increasing the maximum strength of the interface. The interlock was independently about as strong as the overmold (flat surfaces van der Waals) bond, so that strength of the “holes” samples was about double that of the other textured and dimpled attachment methods. Unfortunately, the holes interface strength also only achieve under 10% of that of the shear-strength of the steel base material (Fig. 12.3).

12.2.3 Shear Strength with Metal Surface Preparation

For metal preparation, the more severe the treatment is, and as the additional surface area is created by disturbing the metal surface, the higher the apparent shear-bond strength is attained. Where mechanical interlocks (holes) are used in the preparation of the base material, strength, beyond that of the chemical bonding, whether van der Waals or covalent, can be readily achieved.

12.3 Adhesive Bonding

12.3.1 Adhesive Bond Samples

To determine the interfacial strength of a rotational-part subassembly-interface, a set of two metal components were made with a cylindrical interface. The components were fitted to allow a 0.25 mm gap, as recommended by the adhesive manufacturer, between the metal parts for the joining. The bonding surfaces were all cleaned with an acetone wipe to remove grease and oil residue. Two-part epoxy adhesive was mixed by hand and applied to all surfaces on both the metal parts where adhesion was desired, as shown in Fig. 12.4, on a cylindrical interface. The parts were slid together on a fixture that assured concentricity. Excess adhesive flowed on both sides of the cylindrical interface during assembly, assuring complete coverage. After green strength was achieved in an hour, the bonded part was removed from the fixture. The adhesively bonded parts were cured by manufacturer specification, and then inspected for tolerance stack. All parts were found to be within 0.025-mm of

Fig. 12.4 Rotational parts slathered with cyan-colored adhesive, before assembly



Fig. 12.5 Rotational parts assembled together with cylinder-shaped adhesive dollops



circumferential and radial dimensioned positions, well within tolerance of rotational equipment. One assembled part is shown in Fig. 12.5, where the cyan-colored band is the thermoset adhesive.

12.3.2 Adhesive Bond Verification

The bonded parts were subjected to rotational loading as pure torsion, and torqued to failure. The smooth surface adhesive-bonded area failed by a combination of cohesive and adhesive failure. All of the 57 square centimeters of adhesive bond failed simultaneously, and the failure occurred at a load of 2400 Nm. For design purposes, this corresponds to a shear load on the specimen of 15 MPa, that is average for a structural epoxy adhesive. Compared to a flat interface, such as with a symmetrical shear-load coupon, this cylindrical shaped strength is slightly more than can be achieved by the same adhesive in a flat area. This shear strength of the adhesive bond is less than 10% of that of the base material steel, so is significantly low for joining.

12.3.3 *Adhesive Bond of Rotational Parts*

In the situation of a cylindrical shaped adhesive bond interface (rotational part), the shear loading is uniform, and not dependent on a symmetrical and flat surface (e.g. lap-shear coupon), that has stress concentrations at the ends of the bonded intervals. For a symmetrical shear flat-adhesive coupon, the ends are subject to stress concentration, lowering the measured strength of the complete adhesive dollop. So, although the strength of the adhesive may be the same at all sites, in practice, the stresses will appear higher where there are starts and ends to the bond area, as is the situation for a lap-shear coupon. For the situation of a cylindrical bond shape, the strength will be slightly higher, as the load is distributed evenly.

12.4 Thermal Range

12.4.1 *Thermal Range Samples*

Rotational components need to operate at high and low temperatures. To determine the range of temperature that interface joining can survive, samples were constructed with cylindrical interfaces to represent rotational machinery. The samples were built with metal and composite parts, and these parts were attached by adhesive and by interference fit. To create a mechanical load, the subassemblies were shaken with an acceleration of up to 50 g's to represent a 10,000 N load, as rotational components encounter as their highest known loading. Simultaneously, the assemblies were subjected through a 24-h cycle to achieve a high dwell temperature of 175 °C and a low dwell temperature of -45 °C, repeatedly. Various combinations of base materials were tested, but all had a 0.25 mm adhesive gap, and were assembled with coaxial alignment. The temperatures and accelerations were ramped up with a slow gradient, so that if an intermediate failure occurred, the maximum achievable temperature and acceleration could be recorded as the joint capability. The shake was applied in the radial direction of the rotational component, the component was constrained to a central axis, and to prevent circumferential movement, the component was further constrained at a line near the outer radius. The shake was applied at a rate lower than one cycle per second, and hundreds of cycles were conducted at each temperature extreme, as traced in Fig. 12.7. To establish capability, these parts were disassembled from the fixture, visually inspected for cracks and disassembly, at every temperature extreme shown in Fig. 12.7. If no cracks or disassembly could be observed by visual, tactile, CMM, thermography, and NDE, then the assembly was labeled to be structurally intact, and capable of that loading at temperature.

12.4.2 *Thermal Range Verification*

The rotational components were subjected to ramped-up temperature extremes for exposed automotive driveline components, and ramped-up accelerations. All samples were inspected after shaking, for each temperature low extreme and each temperature high extreme, for microcracking, relative movement between parts, and catastrophic separation of parts. All parts passed this testing, showing no deterioration, during all of the temperature extremes, to the last cycle, with no microcracking, relative movement, or part separation. This is a significant observation, as both the base materials and the interfaces survived readily within the temperature bounds.

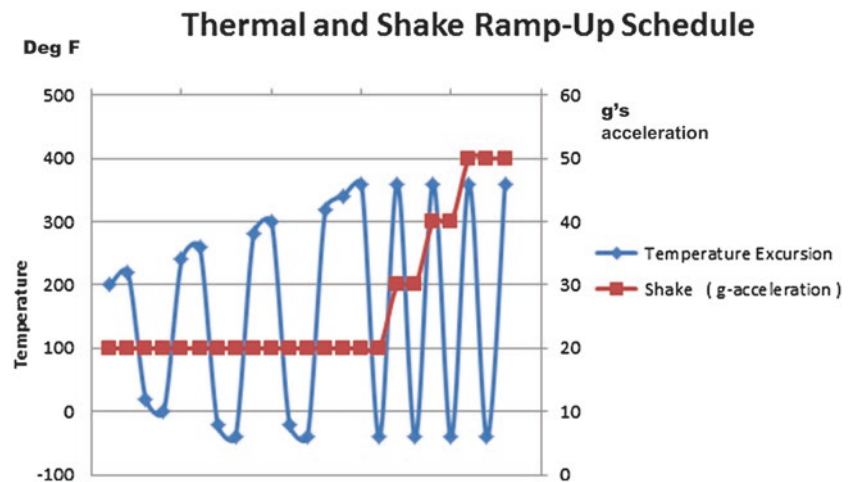
In Fig. 12.6, three drivetrain components (samples) that are each rotationally symmetric were tested simultaneously in the thermal chamber. At each temperature extreme, the components were disassembled from the fixture and inspected for survivability. All bonded components passed completely, with no visible damage. These parts were subjected to additional fatigue testing to indicate that there was no operational damage to all of these components.

In other testing of rotational components, a reinforced thermoplastic part was overmolded onto a metal part, and subjected to the thermal excursions of Fig. 12.7, without external loading. All of the adhesively-bonded parts passed this test, and when inspected by ultrasonic, tactile, and thermography methods, indicated that no opening occurred, and the bonding by van der Waals force of overmolding had no gapping.

Fig. 12.6 The hydraulic actuator is behind the step-ladder and the rotational components to be tested are in the thermal chamber. The rotational components are shaken in the stationary thermal chamber



Fig. 12.7 Ramped loading and thermal excursions for the shake testing of the metal-to-composite interfaces

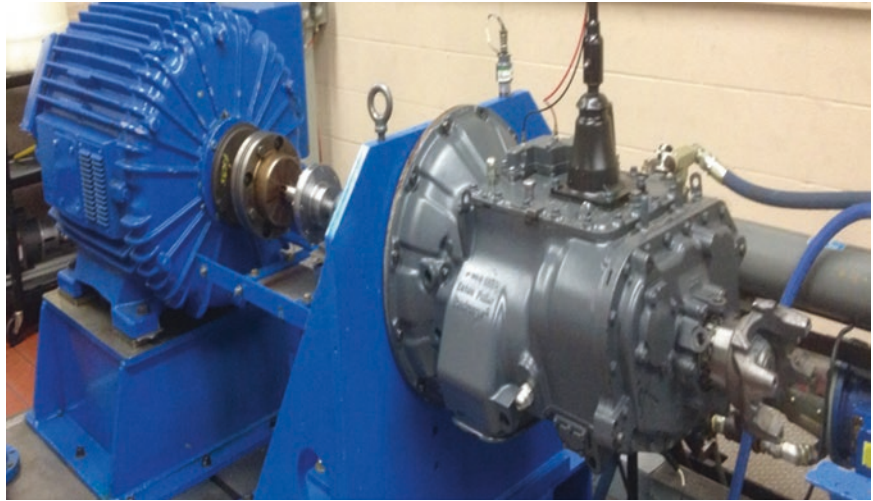


12.4.3 Thermal Capability of Composite to Metal Interfaces

Rotational parts bonded with thermoset adhesive were subjected to forces of over 1000 N. No damage (microcracking or disassembly) was observed by visual, tactile, CMM, or NDE. Multiple “baseline” rotational components that were interference-fit assembled (no van der Waals or covalent bond) failed by disassembly in this testing procedure as shown in Fig. 12.6, indicating that the thermoset adhesive and overmold bond did have a significant role. Although this testing indicates significant capability for thermoset adhesive interfaces, it is well known that both the base composite material, and the thermoset adhesive material can be weaker at temperatures at our use of 175 °C (350 F), compared to room temperature structural performance [3].

In another situation, with a thermoplastic composite overmolded to metal, the van der Waals (polymer to metal) bond was sufficient for the component to survive multiple cycles of extreme hot and cold with no exterior structural loading, successfully, as proven by ultrasonic and thermographic testing to assure metal-to-composite bonding without gapping.

Fig. 12.8 Metal-and-composite components are prototyped full-scale and tested inside existing subassemblies as shown in the dynamometer test cell here



12.5 Structural Behavior

12.5.1 Structural Behavior Samples

Samples of rotational equipment were prototyped and loaded into drivetrain assemblies to test duty cycles to failure. The metal-to-composite interfaces had mechanical interlocks, and were attached by overmolding in some parts, interference-fit in some parts, and adhesive bonding in some parts. The rotational components were tested for noise, torsional strength, and fatigue life in dynamometers. The rotational parts were made of metal components and composite components. The composite components were attached to the metal by van der Waals forces (overmolding), friction (interference fit), and by covalent bonds (two-component adhesive bonding), depending on how these were assembled. All were built to current standards for such equipment, and tested in existing housings that are readily available in the marketplace.

12.5.2 Structural Behavior Verification

The components were prototyped to full scale, assembled into a drivetrain subassembly, and mounted on dynamometers that were customized to perform the duty cycles of vehicles, in a stationary test cell. For the rotational components that were overmolded, as reinforced thermoplastic on textured metal, the parts failed after conventional all-metal subassembly components failed and were replaced, but before the duty cycle was completed, for verification testing. The metal-and-composite rotational part assembled by overmolding failed just before achieving 20% of the duty cycle, where the baseline is an all-cast-iron part that achieves five-times more cycling to failure. This metal-and-composite rotational part assembled by overmolding showed in testing that it was significantly weaker than the all-metal current production part.

In other verification testing, for significantly different rotational components made with thermoset adhesive to bond the composite to the textured metal, all of the components survived the entire duty cycle for that component, as did the current all-steel part. This thermoset adhesive method of assembly was fully successful, and indicates a significant method for successful joining of metal and composite. A dynamometer test cell for rotational equipment is shown in Fig. 12.8, with the dissimilar material component inside the blue housing.

12.5.3 Full Prototype Dynamometer Duty Cycles

For full-scale testing, on various drivetrain components, the material choice, processing, surface preparation, and component loading for the duty cycle, influence the outcome of the verification testing. Although there were mixed reports in the described results, the outcome is dependent on multiple inputs, making broad conclusions difficult. But it is clear that certain designs and materials in drivetrains, with cylindrical geometries, can be made successfully, by use of large interface-areas with mechanical-interlocks, with the appropriate choices of materials, process, and interface bonding method.

12.6 Conclusion: Utility of Composite-and-Metal Components for Use in Drivetrains

Drivetrains represent the highest demand of performance for materials used in the Eaton vehicle and aerospace group, with regard to structural and thermal capability, and indicate potential capabilities of primary-structural components, such as control arms, for vehicles. Verification testing here for metal and composite two-component parts have shown that metal-to-reinforced-thermoplastic and metal-to-reinforced-thermoset driveline components are achievable in current vehicle configurations and envelopes. Metal-to-composite components have the capability for base-material-attachment, cylindrical interfaces, thermal excursions, and full duty-cycle durability. Furthermore, the interfaces can be enhanced by any metal surface preparation that leads to additional surface area and mechanical interlock of base materials. Driveline applications for lightweighting can greatly influence vehicle dynamics, as rotational components tend to be unsprung components, components that add to the rotational inertia of the vehicle, components that add to the translational inertia of the vehicle, and components that generate undesired vibration, harshness, or noises. Metal-and-composite components have now been built, analyzed and verification tested, so are available for new designs where lightweighting, and NVH need to be enhanced.

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