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ALUMINUM HIGH PRESSURE VACUUM DIE CASTING APPLICATIONS FOR THE MULTI MATERIAL LIGHTWEIGHT VEHICLE PROGRAM (MMLV) BODY STRUCTURE

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Abstract

Vehma/Cosma Engineering a Division of Magna International, the U.S. Department of Energy and Ford Motor Company initiated the Multi Materials Lightweight Vehicle (MMLV) Project in 2012. The goal was to design and build prototype vehicles, maintaining donor vehicle architectural space in an effort to reduce mass relative to a 2002 baseline vehicle target. The result of this study was a 23.5% reduction in vehicle weight compared to the current donor vehicle.

This paper reviews the mass reduction and performance of aluminum high pressure vacuum die cast (hpvdc) body structure components, integral to the lightweight BIW architecture of a C/D segment an aluminum-intensive vehicle. Selected stiffness, durability and crash requirements are assessed. The BIW structure incorporates aluminum castings and extrusions, as well as aluminum and steel sheet, assembled using structural adhesive bonding and a variety of joining technologies. No other body structure in high volume production incorporates this combination of materials and joining processes. The eight hpvdc aluminum castings in the MMLV body structure were specially designed to maximize crash performance and assembly costs (part count reduction), offsetting the differential in material cost relative to steel construction.

Program Overview

The MULTIMATERIAL LIGHTWEIGHT VEHICLE (MMLV) is the result of a collaboration effort between Magna International Inc. and Ford Motor Company, to develop a lightweight passenger car "concept vehicle", comprised of commercially available or demonstrated materials and manufacturing processes. The MMLV Program is co-founded by the U.S. Department of Energy and part of the Vehicle Technologies Office, part of the lightweight materials project portfolio addressing future CAFE (fuel economy) legislation. The MMLV concept vehicle design achieved a 23.5% mass reduction relative to the 2013 Ford Fusion production model (1170 kg vs 1,559 kg), without compromise of utility, performance or occupant safety. Drivable test vehicles were manufactured, by integrating the lightweight MMLV subsystems with 2013 Fusion baseline vehicle components, to facilitate select NVH, durability and crash testing.

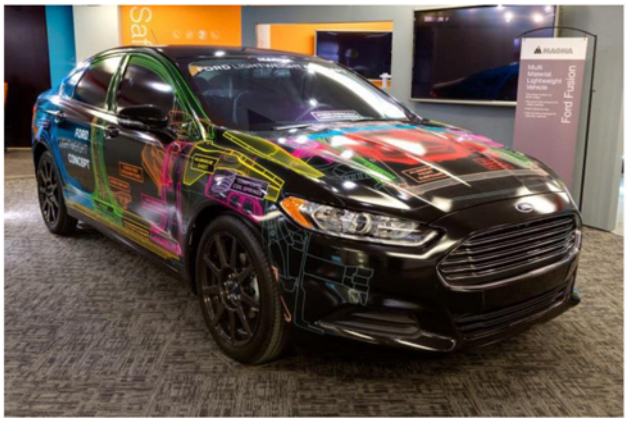

Figure 1. MMLV concept vehicle

Introduction

The selection and use of advanced materials for reducing weight of passenger vehicles has become part of regular automotive engineering practice. Numerous lightweight automotive body components and BIW structural investigations have been published over the last few years [1-5]. The majority of these studies have shown excellent potential to save mass and improve performance.

Achieving a significant mass reductions, while maintaining vehicle packaging, safety and performance, potentially impose a significant cost and bill of process changes in the body shop. Previous efforts have been focused monolithic material solutions comprised of steel, high strength steel or all aluminum solutions [1,2,5,7]. Despite the corrosion and joining benefits associated a monolithic material solution, high volume production of lightweight BIW structures have not been realized in the automotive mainstream, primarily due to cost, incompatibility with existing body shop infrastructure and global capacity to manufacture lightweight components. To date, multi material approaches for body structure applications have been limited to component-level integration. [3, 4].

The MMLV body structure highlights the broader application of purpose-specific steel and aluminum alloys. The strategic use of several lightweight and high strength materials have been applied in the multi material lightweight vehicle. The aluminum industry and component suppliers are investing heavily in global manufacturing capacity to address the OEM demand to meet fuel economy and environmental legislation.

High vacuum aluminum casting technologies have evolved in the past decade, enabling vacuum die cast components to be incorporated into new vehicle designs by automakers [6]. There are several cost-effective light weighting applications which incorporate high integrity aluminum die cast components into a steel-intensive vehicle architecture. Commercial application of hpvdc components is the result of the improved castablity of the new high silicon aluminum alloys, enabling lighter weight stiffer assemblies, with wall thickness less than 2mm thick. The lack of entrapped gas has enabled the opportunity to heat treat die cast components to increase yield strength, enabling further reduction in mass by reducing section size. Increased ductility associated with vacuum die cast components has also enabled a variety of new joining techniques. Applications are not limited to vehicle body structure applications, but also include powertrain, chassis and suspension. Vacuum die cast components achieve mass reduction through parts consolidation and product design freedom to achieve product strength and stiffness performance characteristics. Aluminum hpvdc castings have the potential to make vehicles lighter and improve performance at the same time.

Since 1997, weight-saving high vacuum aluminum casting technology has been applied to body structures in vehicles, although the overall vehicle weight has increased due to occupant safety legislation and consumer preferences. A significant contribution to improved fuel economy is likely to be achievable at a reasonable cost by utilizing lightweight cast aluminum technology for net weight reduction. Weight savings obtained by broader applications of aluminum castings and design best practices have been demonstrated in the MMLV program which resulted in the body structure being optimized for cost effective performance.

MMLV Lightweight Body in White Structure

The lightweight Body in White (BIW) structure design incorporates the best material characteristics of steel (37% mass) and aluminum (63% mass) for the various applications. Intelligent lightweight design also includes optimizing components and subassemblies for their specific application. For instance, the MMLV BIW structure includes an array of aluminum alloys and manufacturing processes. Integration of high pressure high vacuum die cast components, with an extruded profile or aluminum sheet with varying wall thicknesses provides the opportunity to develop a subassembly which has high stiffness, improved performance characteristics and 12% (32pcs) fewer components. High-strength steel tubes are integrated into the A-pillars for safety reasons. The objective is to integrate preferred material and part-production process for each function. The multimaterial BIW design is comprised of 63% aluminum and 37% steel.

Both the 2013 Fusion and MMLV body structure represent 21% of the vehicle curb weight. A mass reduction of 76 kg (23.5%) was achieved, relative to the 2013 Fusion baseline BIW structure. The MMLV BIW is comprised of eight aluminum high pressure vacuum die castings, six aluminum extrusions, twelve major steel stampings and many aluminum stampings. The MMLV BIW design includes a 32 piece part count reduction relative to the 2013 baseline. The materials used for the BIW are shown below:

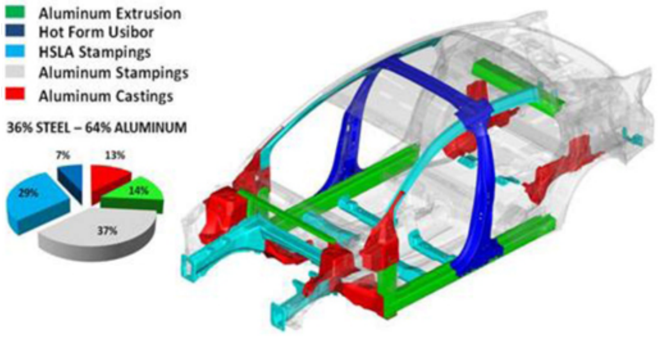

Figure 2. MMLV BIW Design

- HPVDC Aluminum - front shock, front kick-down, hinge pillar and rear mid rail
- HSLA Steel - Front Rails for frontal impact
- Press Hardened Steel - B-pillar and roof rail for side impact and roll over
- Aluminum 6061-T6 extrusions for sill, hinge pillar, and rear package shelf reinforcement
- Aluminum 5xxx-series – cross car stampings

Figure 3. MMLV BIW concept prototype

MMLV Body Structure hpvdc Aluminum Components

Recently steel and aluminum are competing for body structure and chassis applications. Steel has a wide range of available properties including excellent formability and high strength, but it is also quite dense. Also, high strength steel usually comes at the expense of good formability.

Aluminum castings can be competitive with steel in a number of situations, such as the following:

1. When components are loaded in bending. Stresses are inversely proportional to the thickness squared and stiffness is proportional to the thickness cubed. This means aluminum (lower density than steel) is more favorable.

2. When several components or functions can be consolidated into a single part such as a high pressure die casting, which requires multiple steel parts that then must be assembled.

The use of aluminum castings on the BIW have been designed to maximize stiffness and part count reduction. The aluminum castings provided engineers more design flexibility and the component applications are the best way to provide local attachment points for the assembly.

Again, the boundary conditions for bending are stiffer for the casting than steel stamped assemblies and provide enhanced performance, ride and handling, NVH, etc. The improved stiffness of the castings also allow the associated steel applications to be thinner gauge also reducing mass and thus saves on the overall weight. The largest obstacle for hpvdc applications in high volume production is the cost but on a majority of BIW applications, the improvements in performance and mass reductions are sometimes enough to justify the replacement of steel components.

The MMLV body structure design uses different structural materials, forming operations, and joining techniques that are commercially available though not all are available in high volume applications. In general, aluminum high pressure vacuum die castings offer the prospect of reduced mass, part consolidation and fewer assembly processes.

The eight MMLV castings (four each L&R) are: front shock tower, hinge pillar, kick down rail and the rear mid rail castings.

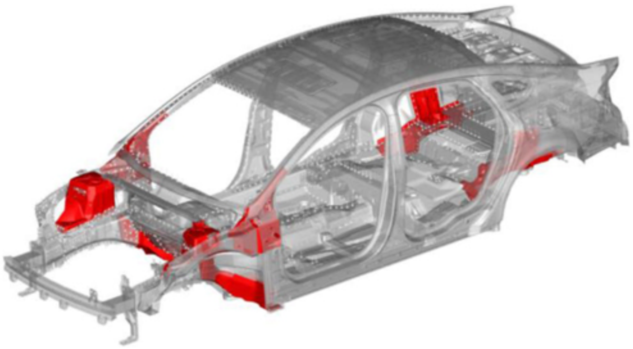

Figure 4. MMLV BIW aluminum hpvdc castings

Table I. MMLV Design hpvdc Aural Aluminum Alloy Mechanical Properties

Mfg Process	Alloy	Temper	YS (MPa)	UTS (MPa)	% El	MMLV Design
hpvdc	Aural 2 (AlSi10MnMg)	T7	120	200	14	Shock Tower
hpvdc	Aural 5S (AlSi8MnMg)	T5	130	210	8	Kick Down Rail, Hinge Pillar, Rear Rail

Due to the low quantity of MMLV test vehicles and high tooling costs associated with hpvdc tooling, seven of the eight body castings were manufactured by using a low pressure precision sand casting process. The low pressure precision sand castings utilized an advanced gating design, low iron A356 alloy composition and heat treatment (T6) to simulate production hpvdc mechanical properties. The low pressure castings are based on the hpvdc designs and have nominal wall thickness of 2.5 mm and include all the hpvdc manufacturing features; ejector pin pads, parting line, etc. to best mimic production hpvdc castings.

The front LH kick-down Rail hpvdc component was manufactured using the Magna Cosma Casting hpvdc process. The Kick-down Rail is an integral component in the front impact Offset Deformable Barrier ODB full vehicle test and thus the decision was made to create the actual hpvdc component for vehicle crash testing.

Table II. MMLV Actual Low Pressure A356.2 Precision Sand Cast & Aural 5S – T5 Mechanical Properties

Mfg. Process	Alloy	Temper	YS (MPa)	UTS (MPa)	% El	MMLV Component
low pressure precision sand	A356.2	T6	122	209	10	Shock Tower, Kick Down Rail (RH), Hinge Pillar, Rear Rail
hpvdc	Aural 5S (AlSi8Mn Mg)	T5	154	253	9.2	Kick Down Rail (LH)

All the castings used on the MMLV test vehicles have been subjected to 100% x-ray (radiographic) inspection. All critical areas in the castings satisfy ASTM E155 (hpvdc) and ASTM E505 (sand cast) plate level 2 criteria. All the castings also passed 100% dimensional lay out using a tolerance of +/- 0.7 mm for cast surfaces and +/- 0.25 mm for machined surfaces. The castings were hard coat (type II) anodized to enhance structural adhesive bonding and increased corrosion resistance prior to assembly.

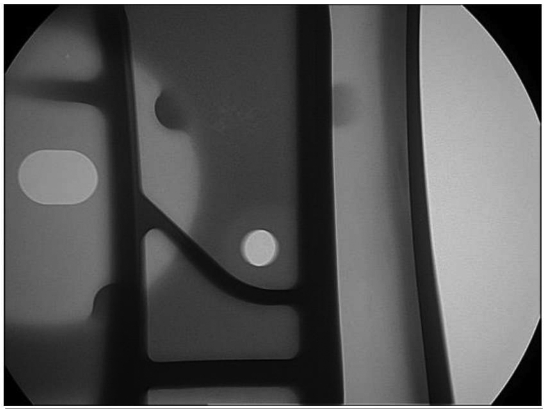

Figure 5. MMLV aluminum shock tower casting x-ray

Tooling Design and Simulation Modeling

Magna Cosma Casting used MAGMASOFT® (finite differential based) simulation software to simulate casting fill and solidification, to improve part/tool design and reduce process development time. The MAGMASOFT® simulation has been optimized by Magna Cosma Casting for the hpvdc casting system in order to improve the manufacturability, quality and productivity of cast aluminum components. These efforts result in lighter weight components, shorter design and product development cycles and lower overall cost.

The MAGMASOFT® fill simulation software is based on the Navier-Stokes fluid-dynamics equations for the overall tooling gate and runner design to achieve a non-turbulent fill pattern. The solidification models simulate the thermal behavior of the tooling and its role during the solidification of the aluminum and provide a prediction of the microstructural and mechanical properties of the casting. Probably no process is more complex to model than the hpvdc process.

The software has the capability to display both temperature distributions in the mold material (H13) and in the solidifying casting (Aural series of aluminum alloys). The progression of solidification identifies isolated hot spots, which have a high probability to result in shrinkage porosity. Microstructural characteristics such as grain size and secondary dendrite arm spacing (DAS) are determined by the solidification rate in the casting. The ability to simulate and predict characteristics such as isolated hot spots and DAS provides the designer opportunity to modify the part design or the number/location of cooling lines to achieve directional solidification, avoiding the presence of isolated hot spots. These factors have a direct relationship on mechanical properties like tensile strength and ductility. Simulation is critical to part and process optimization to achieve mass reduction and optimize part performance.

The capability to conduct casting simulation, avoided cost and time delays, very important factors in today's competitive worldwide foundry industry.

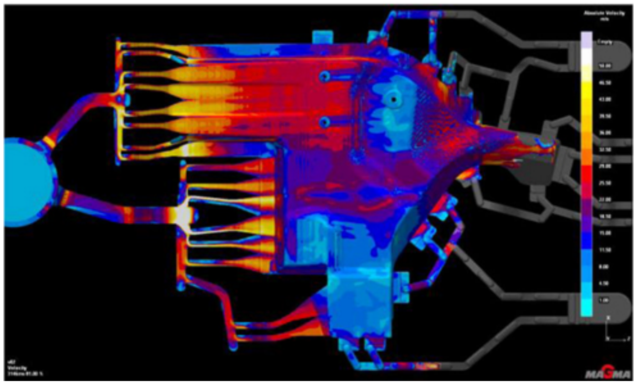

Figure 6. MMLV kick down rail Magmasoft Casting Fill Simulation

Cosma Casting Process Control

Magna Cosma Casting utilizes a specialized molten metal handing system that includes a degassing treatment of the aluminum melt to reduce hydrogen gas level and minimize gas porosity.

The Cosma Casting foundries also monitor a number of functions during the casting process to ensure quality including; pressure, slow shot velocity, fast shot velocity, vacuum level, die temperature (heating circuits, etc.), melt temperature and humidity level inside the die cavity.

The High-Q process control system also helps achieve improved mechanical properties required for the MMLV castings by eliminating oxides, inclusions and porosity during the casting process.

Maintaining the tight dimensional tolerances required several steps during the casting and cooling of the MMLV kick down rail. The process begins with a tooling design that incorporates supports that enable the part to be removed without deformation. Before casting, a robot applies casting die lubricant on critical areas of the tooling to ensure easy removal of the casting. A transport system then carries the part to the heat treatment area. The T7 heat treatment is done with a forced air quenching (4 °C/sec) to keep the dimensional tolerances consistent throughout the manufacturing process.

Shock Tower

The aluminum shock tower casting is the most common hpvdc body application to date [1]. The MMLV front shock tower (a.k.a. strut towers, spring bucket, etc.) design combines several traditionally steel-constructed parts into a single, lightweight component. The cast aluminum shock tower is about 40-percent lighter and eliminates about 7 component parts compared to the steel baseline components. The MMLV cast aluminum shock tower lowers the weight from the base line of 7.5 pounds to 4.6 pounds. The MMLV shock tower casting is joined to the steel rail by SPR (self-piercing rivets) and adhesive and also joined using CMT (cold metal transfer) welding for the cross car beam.

Figure 7. MMLV aluminum shock tower casting

Figure 8. MMLV aluminum shock tower casting joined to the front end assembly by SPR and CMT methods

Kick Down Rail

The front kick down rail (a.k.a. torque box) cast component is integrated from five different steel stampings and is about 35 percent lighter. The MMLV cast aluminum kick down rail lowers the weight from the base line of 13 pounds to 10 pounds. The kick down rail casting acts as chassis reinforcements for the front structure. The cast kick down rail adds stiffness, torque load capacity and torsional rigidity to the MMLV body structure. The MMLV design team uses an innovative application for a casting in regards towards crashworthiness. The design was optimized and validated using finite-element analysis. The front structure of the MMLV vehicle can properly restrain the forward deformation of the cabin by efficiently transmitting the impact load at the vehicle frontal 40% offset impact test. The FEA analysis shows that body structure castings allows improved intrusion characteristics as compared to the of the baseline vehicle the frontal 40% offset impact. Therefore the addition of the kick down rail casting allows for reduced mass, reduce part count and an increase in performance.

Figure 9. MMLV kick down rail

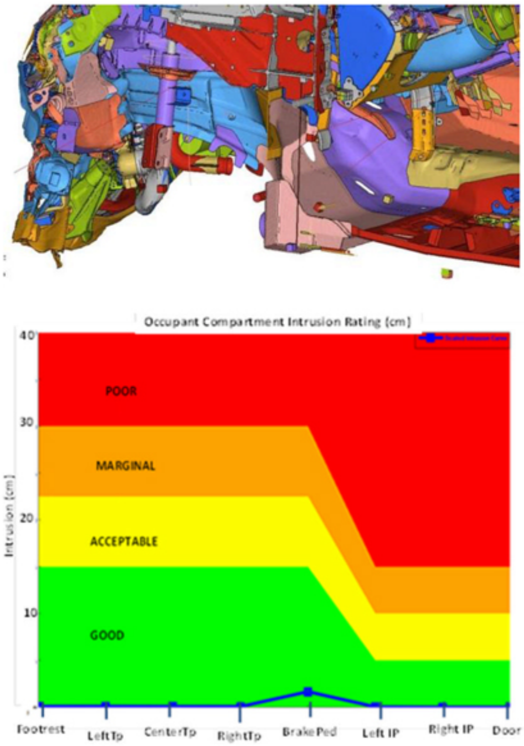

Figure 10. MMLV Frontal 40% off-set impact FEA with improved intrusion over baseline

Hinge Pillar Casting

The MMLV hpvdc hinge pillar reinforcement member is attached on the lateral inner surface of the distal end of the support member. The door hinge brackets are incorporated into the outer surface of the design and increased the rigidity of the front pillar to the compressive load in the longitudinal direction of the vehicle body. The hinge pillar cast component is integrated from five different steel stampings and is about 35 percent lighter. The MMLV cast aluminum hinge pillar lowers the weight from the base line of 9.8 pounds to 7.4 pounds.

During the assembly, there is only access to one side of the hinge pillar component so the MMLV team used flow drilled screws. The flow drill screw spins at a high speed to heat and soften the metal. It must be stopped at the precise moment to cool and form the thread screw.

Figure 11. MMLV hinge pillar

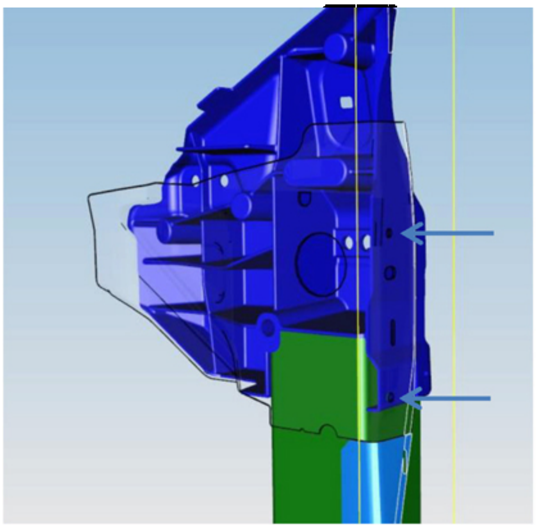

Figure 12. MMLV hinge pillar casting one sided joining with flow drill screws

Mid Rail

MMLV design integrates the rear shock tower and rear rail components to a one piece casting reducing the part count from 12 to one and is about 35 percent lighter. The MMLV cast aluminum mid rail lowers the weight from the base line of 12.5 pounds to 9.2 pounds. The rear rail assembly utilizing both mid rail cast components, which are joined to extruded components, meet or exceed all critical design specifications. The mid rail casting design provides a unitary rear shock tower casting which includes attachment locations for a pair of lateral suspension links and the rear shock assembly.

Figure 13. MMLV mid rear rail

Figure 14. MMLV mid rear rail assembly

Dissimilar Materials Joining

When bare aluminum contacts steel surfaces, galvanic corrosion is a concern. The MMLV program includes two corrosion mitigation strategies. The "traditional" method includes the use of galvanized steel panels and Type II hard coat anodized aluminum casting surfaces. An adhesive/sealant is utilized to electrically isolate the materials prior to joining with self-piercing rivets. The protruding end of the self-piercing rivet is later sealed. After assembly, the entire vehicle is subjected to a phosphate bath and ecoat.

The "alternative" corrosion strategy includes e-coating the steel components and hard coat anodizing the aluminum castings prior to the application of the adhesive/sealant and assembly using self-pierce rivets, avoiding the cost the phosphate and e-coat bath after assembly.

Most of the MMLV aluminum castings are joined to steel materials by a mechanical joining method with a structural adhesive. The SPR's (self-piercing rivets) are the most commonly used method for this type of joint. The MMLV cast shock tower to the front rail is 1.0 mm DP600 steel to 2.5 mm A356.2 (substitute for hpvdc Aural-2) aluminum casting joint and uses a Ø5 x 5H6 (KM) rivet with DC10-150 die @ 120/200 Bar.

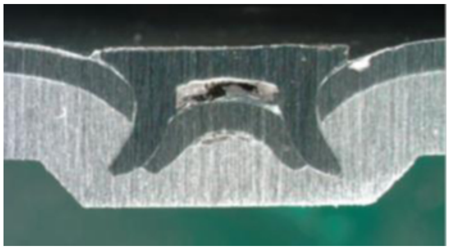

Figure 15. SPR of MMLV shock tower casting to front rail

Where SPR's could not be used in the BIW and closure joints due to single side access, insufficient gun clearance, or base material issues, flow drill screws and Huck rivets were used along with structural adhesive.

All mechanical fastened MMLV joints have an adhesive for increased strength and reduce galvanic corrosion. The two adhesives used for this program are; Dow Betamate™ 73305, a heat activated adhesive for any modules that will go thru an E-coat process and Dow Betamate™ 73326, an air cured activated adhesive that will be used for the final framer and modules that do not get e-coated.

Aluminum Materials Joining

The MMLV joining team investigated aluminum spot welding, but cleanliness was a concern because of aluminum's rapid surface oxidation characteristics. For optimum quality and weld performance, expensive cleaning procedures to remove the surface oxides would be required and the added expense of ensuring a high-quality weld for high volume production was determined to be non-feasible. Because of this reason, SPR's were also used for aluminum to aluminum joints for the BIW & closures design. The aluminum shock tower and hinge pillar castings were joined to aluminum extrusions, using the cold metal transfer (CMT) process. In the vehicle build phase of this program, the CMT process was simulated by TIG welding. Please note that aluminum castings were masked in certain areas during the hard anodization process prior to TIG weld and assembly.

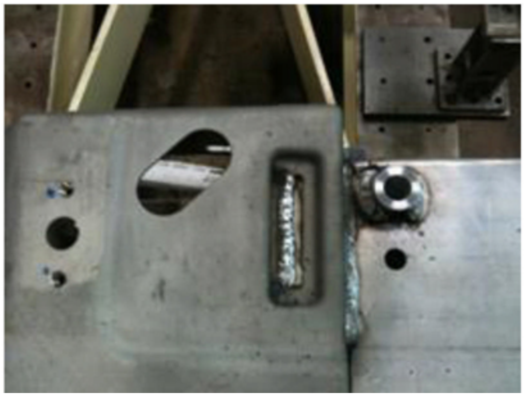

Figure 16. MMLV cast aluminum hinge pillar to cast aluminum extruded rail TIG weld.

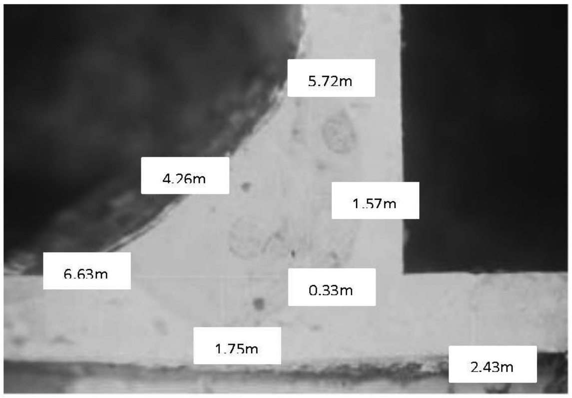

Figure 17. MMLV TIG weld detail

Conclusions

The MMLV aluminum-intensive multi-material BIW architecture incorporates eight aluminum hpvdc structural body castings as well as aluminum extrusions, HSS and AHSS steel, providing a cost effective means of achieving fuel efficiency and environmental compliance legislation, while maintaining the utility, performance or occupant safety of a C/D segment passenger car vehicle. Cost optimization of a lightweight BIW structure is realized by leveraging the intrinsic cost/material characteristics of various materials, minimizing the integration cost of assembly and corrosion mitigation. The MMLV body structure is unique, incorporating a variety of materials, high volume production manufacturing processes and assembly techniques. The eight hpdvc aluminum castings are the centerpiece of the aluminum-intensive BIW, specifically designed to reduce mass, maximize stiffness and minimize part count, all of which contributed to the 23.5% mass reduction of the MMLV design relative to the 2013 Ford Fusion baseline.

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