Emphasis on Heat Affected Zone (HAZ) Modeling Around MIG Welded Joints in Crash CAE Virtual Predictive Full Vehicle Models

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1 Abstract

Current challenges in the auto industry are compelling virtual simulations to predict strength and rupture of MIG welded joints. Rupture prediction of such joints enhances the design and development process. In body-on-frame vehicles most metal parts are joined using MIG welds and strength evaluation of such joints are crucial to vehicle crash and safety performance. Virtual simulation capabilities with these predictions help in enormous ways to reduce cost and time involved in proto-type testing of vehicles in the product development cycles.

Advancements in material models using GISSMO enable CAE analysts to capture ruptures for sheet metal parts. This is an effort to extend the rupture prediction of the Heat Affected Zone (HAZ) which is a residual effect of the MIG welding process. This study is to develop an inclusive procedure using hardness data for predicting strength and rupture of MIG welded joints between steel sheet metals with gauges ranging from 2mm to 4mm. Hardness testing of welded joints, CAE methodology to represent MIG welds, CAE simulations with component level validations, and verification in full vehicle models were performed during the study.

2 Introduction

Permanent joinery of two metals are established by using a welding process which involves localized application of suitable combination of temperature and pressure with metallurgical standards. Different combinations of temperature and pressure comprise of various welding types and widely used in automotive industry. Metal Inert Gas (MIG) welding is the most commonly used welding method for automotive applications. MIG welded semi-thick structures (sheet metals 2mm to 4mm thick) are employed to increase structural weight effectiveness and improve payload. High deformation in welded structural joints could cause substantial problems that may end up in loss of structural integrity. In automotive structure design, welds have to sustain tensile, shear and combined loads for safety critical components designed to absorb energy in crash events. Loss of critical welded joints could lead to unstable structural behaviors. Hence it is very crucial to predict in an effective way any separations of these welded joints. Heat-affected-zones (HAZ) near MIG welds are areas with inhomogeneous metallurgical properties that increases stress concentrations. It is challenging to develop accurate and computationally reasonable models to predict HAZ structural behaviors [1].

Computational challenges are on the anvil to anticipate complex fracture crash modes like IIHS small overlap impact load case. Body-on-frame vehicle strategy is to contain a significant amount of the impact energy by frame and its critical joints. These joints are developed by MIG welding high strength low alloy or ultra-high strength steel sheet metals. MIG welding introduces Heat Affected Zones (HAZ) adjacent to the weld lump. Typically, mechanical strength of HAZ is degraded by the MIG welding process. In order to predict the separations and ruptures, CAE models need to capture strengths of the joints along with their HAZ. It is possible to model the parts and joints in detail with very small mesh sizes (approximately 0.5mm or even lower), but the down side of this would be higher computational time to run the models. We have to adhere to the calculated balance between computational time and accuracy of the CAE models.

Determination of elasto-plasticity with rupture dependency on different stress states can be formulated by testing specimens taken from sheet steel blanks and such complex GISSMO material models are developed in-house. However, Heat Affected Zone size (~ 3mm to 5 mm) makes it very difficult to generate coupons and their corresponding GISSMOs. In order to investigate the mechanical strength of HAZ, hardness testing methods are employed. It is well known that the hardness is directly related to strength of metal, hence micro-hardness tests are conducted on test specimens to get insights of the HAZ strength degradations. Furthermore, HAZ hardness degradations are compared with parent sheet metal hardness and accordingly parent material GISSMOs are scaled to mimic the properties of HAZ.

Different CAE modeling methods (shells, solid and beam) for representing the MIG weld and HAZ areas were investigated. Shell modeling method was adopted due to limitations of mesh size and computational time.

3 HAZ (Heat Affected Zone) metallurgical insights

3.1 MIG Weld Introduction

MIG welding is a versatile technique suitable for both thin sheet and thick section components. An arc is struck between the end of a wire electrode and the workpiece, melting both of them to form a weld pool. The wire serves as both heat source and filler metal for the welding joint. The wire is fed through a copper contact tube which conducts welding current into the wire. The weld pool is protected from the surrounding atmosphere by a shielding gas fed through a nozzle surrounding the wire [2].

3.2 Microstructure of MIG weld HAZ

The cooling rate is the prime parameter for the strength of the welded joint. Both heat flux and cooling rate decides the composition and overall microstructure of the Base Metal (BM) and the Heat Affected Zones (HAZ) as seen in Fig. 1. Fig. 2 shows a schematic cut section of weld and its HAZ region. The lump is called as Weld Metal (WM) and the unaffected region farther away from the WM is called as Base Metal (BM) as shown in Fig. 1 & 2. After the weld cools down, the HAZ zone is typically characterized into four dissimilar metallurgical zones [3].

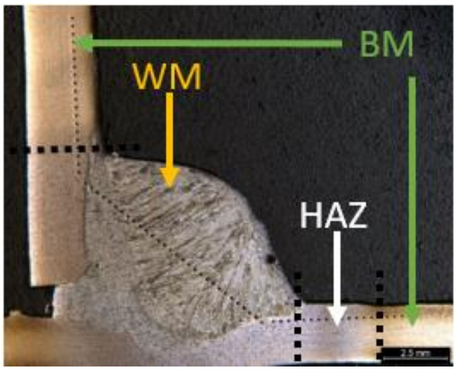


Fig. 1. Weld Zones

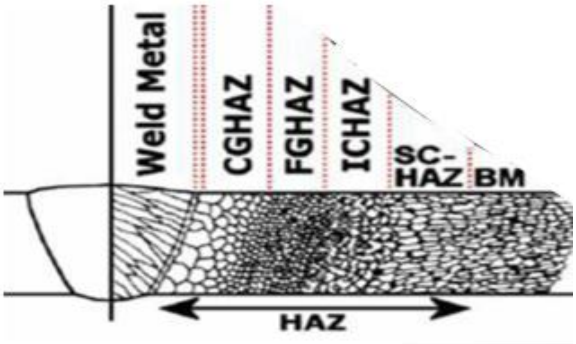


Fig. 2. Sub sets of Heat-affected zone [3]

In the refered paper, the microstructural zones were observed under optical microscope on cooling. They are called as Coarse Grain HAZ (CGHAZ), Fine Grain HAZ (FGHAZ), Inter-Critical HAZ (ICHAZ) and Sub Critical HAZ (SCHAZ). Typically the Heat Affected Zone ranges from 3mm to 5mm from the weld metal. The strength and rupture characteristics of these Heat Affected Zones dictate the strength and toughness of the welded joint [3].

4 Design and modelling of MIG welded connections in LS-Dyna.

In LS-Dyna, welded connections could be represented using `*CONSTRAINED_NODAL_RIGID_BODY (NRB)` (Fig. 3). This is simple to create and computationally effective. However, NRB's typically rigidize the local area and fracture prediction using NRB's coupled with force based separations will not be accurate.

The welds can be represented by discrete beams, but the preprocessing requirements and vector alignments are time consuming. Using the beams with the HAZ will be investigated as next steps as a hybrid methodology.

One more method of representing welded connections is by using solid elements (shown in Fig. 4) in line with the base metal with different material cards. This approach is suitable for component level investigations. In the full vehicle crash analysis, using solid elements to represent the weld geometry can be quite complex in terms of preprocessing, LS-Dyna runtime and timestep issues. Therefore, it is not suitable for design iteration studies.

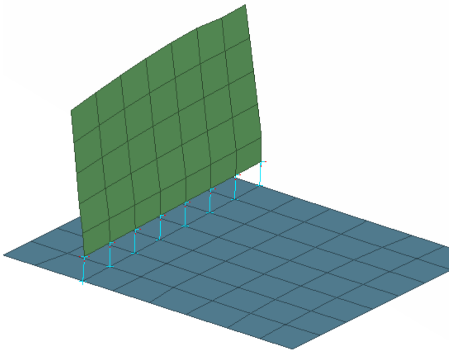


Fig. 3: MIG welds using NRBs & Beams

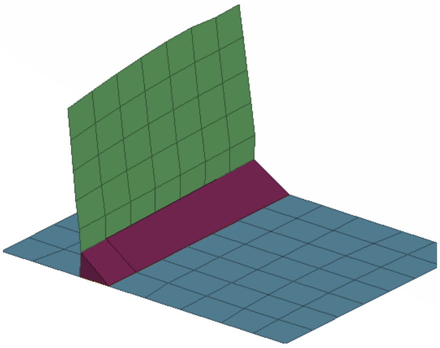


Fig. 4: MIG welds using solid elements

For the practical reasons involved in the full vehicle crash analysis, welded joints are represented with shell elements which are connected at their node junctions (MIG welding area as seen in Fig. 5). Creation of weld with shell elements is less time consuming and on other hand LS-Dyna calculations are quicker than the solid elements. The shell elements representing the Heat Affected Zones (HAZ) are created on either side of the node connections (MIG welding Area) with different GISSMO material cards.

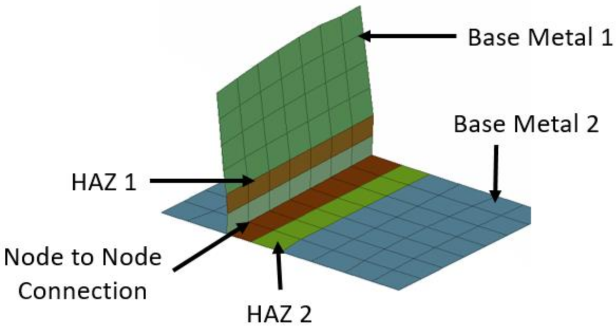


Fig. 5: Welding with HAZ representation using shell elements

5 Hardness and Material Strength definition and Hardness Experiments for HAZ, Weld Metal (WM) and Base metal (BM)

5.1 Relationship between material hardness and strength

Strength and hardness of material are the important mechanical properties of structural steels [5]. Tensile tests and experimental evaluations are used in defining the ultimate load and yield strength of a material. Other faster approaches are used to measure mechanical properties and the most commonly employed technique for approximating tensile strength and yield strength is Vicker's hardness. It uses a small indentation by a diamond indentor [8] on the area of material whose strength or hardness has to be determined. By using simple formula, yeild strength(YS), tensile strength (TS) and hardness (H) can be derived as follows in equation (1) [4].

TS=H.k-----(1)

Where "k" is a coefficient. Cahoon et al. [6,7], offered expressions relating the hardness (H), tensile strength (TS) and yield strength (YS) as follows in Equation (2) and (3):

$$\mathrm{TS} = \left(\frac{H}{2.9}\right)\left(\frac{n}{0.217}\right)^{2} \qquad (2)$$

$$\mathrm{YS} = \left(\frac{H}{3}\right)(0.1)^{n} \qquad (3)$$

Where “n“ is strain hardening exponent.

Hardness is directly proportional to YS and TS which gave us an insight to proportionally scale the GISSMO material model. In this study Vicker’s micro-hardness experiments were performed to measure hardness of HAZ and Base Metal.

5.2 Experimental evaluation of material properties of HAZ, WM and BM

Micro-hardness testing is a non-destructive method of determining a material’s hardness. Among all, Vicker’s hardness test is a commonly adopted method. In the Vicker‘s test, a square-pyramidal shaped diamond is pressed against a material at a predetermined force. The force is applied over 10-15 seconds and then released. To calculate the hardness, the average length of the diagonals of the indent’s base is measured. This average length is used with the applied force to calculate the Vicker‘s hardness number [8][9].

Micro-hardeness experiments are carried out for welded joints areas to evaluate the hardness variation on Weld Metal (WM), HAZ area and the Base Material (BM). Hardness degradation at the HAZ area is the key component to characterize the strength of it. We performed experiments on welded joints with two different types of materials namely high strength steel and ultra-high strength steel as shown in Fig. 6. Vicker‘s hardness numbers are recorded on the cut-section of the specimen by traversing at every step-length as seen by the back spots in Fig 6. First the hardness was recorded on High Strength Steel, then on the Weld Metal and finally on the Ultra High Strength Steel. From these experiments we could establish two HAZ hardness numbers as seen in Table 1.

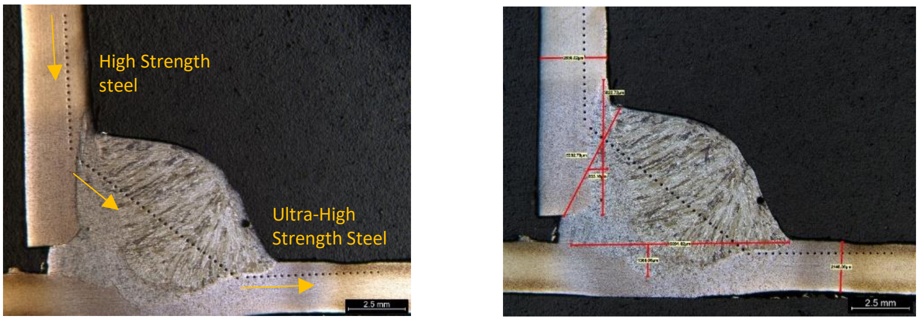


Fig. 6: Micro-Hardness Experiment at the weld joint area cross section

Microhardeness number corresponding to the High strength steel softened around 22% relative to the Base Metal in the HAZ area and similarly Ultra-High Strength steel softened around 33% in its HAZ area as seen in Fig. 7. In the figure, we can see the HAZ region varies between 3mm-5mm. From this data, we established the HAZ element length to be about 3.00mm and the scaled GISSMO material model was applied to the HAZ region. This information (scaled GISSMO and HAZ element length) was used in the sub system level CAE models to predict the test behaviour and the same methodology used in full vehicle analyses.

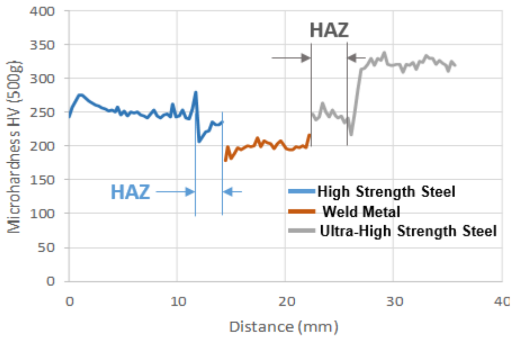


Fig. 7: Micro Hardness vs length of specimen

	Microhardness Relative to Base Metal
Material	HAZ Softening
High Strength Steel	-22%
Ultra-High Strength Steel	-33%

Table 1: HAZ Hardness relative to Base Metal

6 GISSMO Material Rupture models:

6.1 GISSMO Material Overview

GISSMO (Generalized Incremental Stress State Models) material models (`*MAT_PIECEWISE_LINEAR_PLASTICITY + *MAT_ADD_EROSION`) are state of the art ls-dyna rupture models for sheet metals, extrusions and solid cast parts. To generate such a model, coupon tests need to be carried out in tensile, shear, plane-strain and biaxial stress-state modes and local rupture strains are measured through Digital Image Correlation (DIC). These tests are simulated and the GISSMO models are developed and calibrated with regularization so that they work with mesh sizes from 1 to 4mm in size. The process of obtaining such a GISSMO model which is a CAE material separation prediction tool is shown in Fig. 8. We have developed a database for most of the steel and aluminum sheet/extrusion/cast materials. CAE engineers use these material models for prediction of rupture of parts and it gives them the opportunity to iterate for a better design [10].

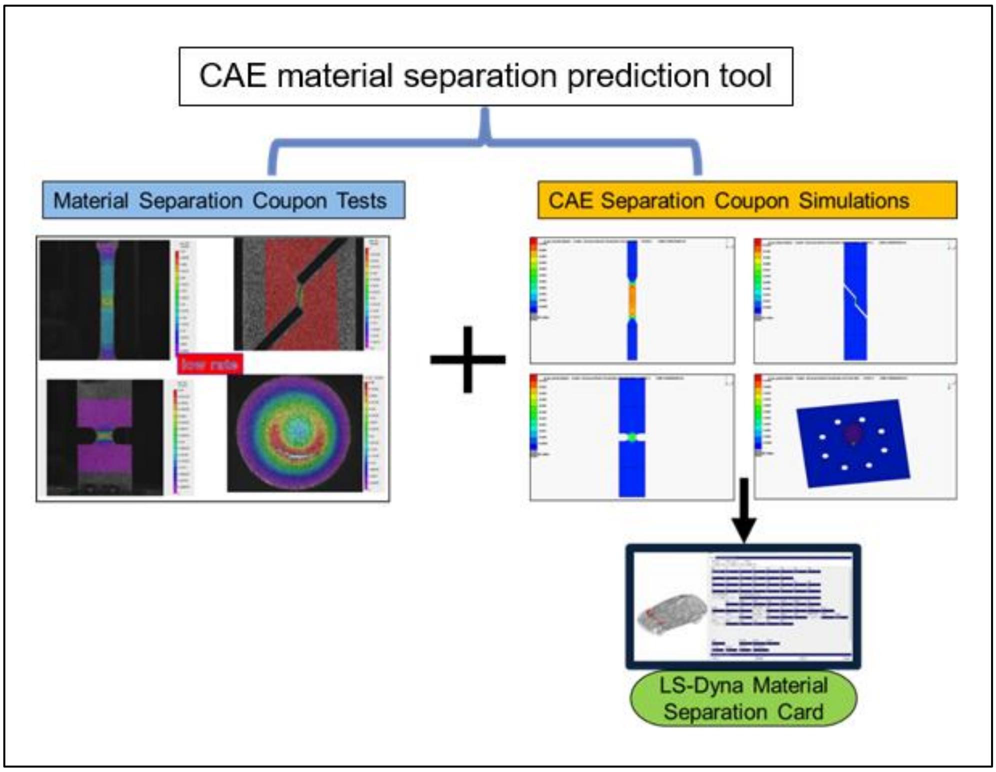


Fig.8: CAE material separation prediction tool.

6.2 Scaling of Gissmo models for HAZ

Since hardness is directly proportional to strength (both YS and TS), the stress-strain curve of the base metal is scaled down by the same percentage of the hardness degradation obtained by hardness tests as tabulated in Table-1 to represent the strength and stiffness of HAZ. Also the element erosion criteria and instability curves were also scaled down by the same proportion. Both down scales mimic the weakening of the HAZ area. Fig.8 & 9 shows a typical stress-strain curve and triaxiality / instability curve for a sheet metal.

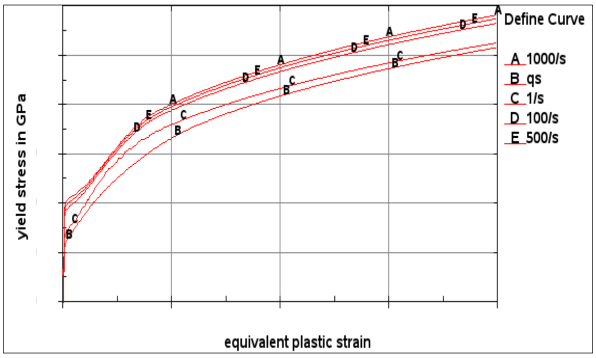


Fig.8: Typical stress-strain curve

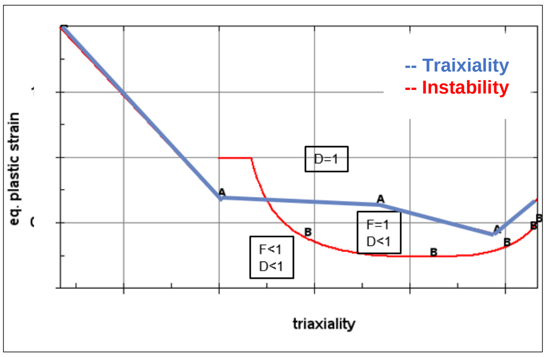


Fig.9: Typical triaxiality & instability curve .

7 Sub-system level validation tests and CAE prediction

7.1 Sub-system level test setup

For the structural integrity and crashworthiness of a vehicle, it is very important to know the critical subsystem's impact behavior and strength. Such load bearing member's abrupt separations may lead to catastrophic vehicle structure separations in the crash test. Sub-system level tests are beneficial to understand the possible separations of the components by representing the potential impact scenarios. In this investigation, impact stack-up is well known to us for development of the sub-system strength. Based on the available data, sub-system level test boundary conditions and impact loading directions were established as shown in Fig. 10.

In test setup, the sub-system was secured to the test rig with bolts and the pusher was designed to represent the impact loading as in vehicle tests. Pusher was used to load the sub-system at 1 in/min rate until complete component fracture was attained. Force vs. Displacement (FD) data was recorded during the test. Multiple tests were conducted to confirm similar FD responses, thereby proving the robustness of the test setup.

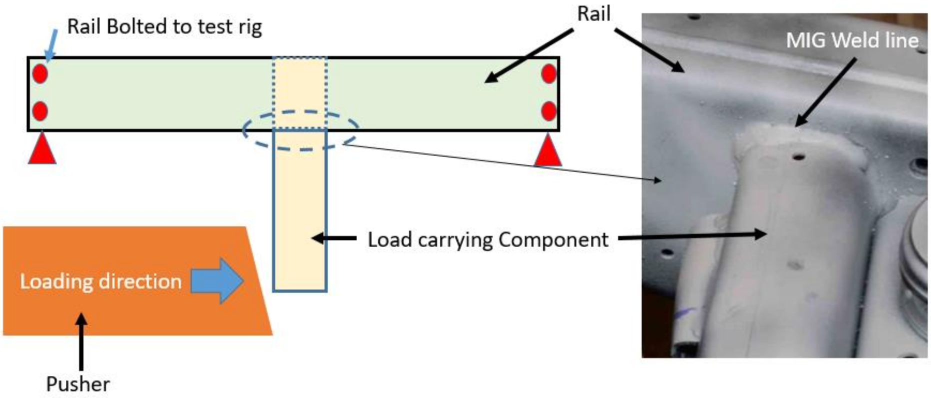


Fig. 10: Subsystem level test set-up at FCA.

7.2 Subsystem level CAE model development

Using micro hardness test data, HAZ material models were formulated by scaling down the Base Metal GISSMO as shown in Table 1. To capture the welded joints of subsystem models, shell elements were used as discussed in section 3. In the shell modelling method, welded joints were represented as node to node connections with two different weld zones namely Weld Metal and HAZ. Average element length used was 3.00mm which is recommended for the GISSMO regularization. HAZ size was also modeled with 3.00mm length. Further studies were conducted to determine the number of rows of elements to represent HAZ. These studies showed that 3.00mm one row was good enough to represent HAZ as shown in Fig. 11. For Weld Metal (WM), twice(2x) of the Base Metal (BM) thickness was assigned (shown in Fig.10), however the contact thickness was maintained same as Base metal using LS-Dyna card `*PART_CONTACT` to avoid numerical issues associated with thickness penetrations.

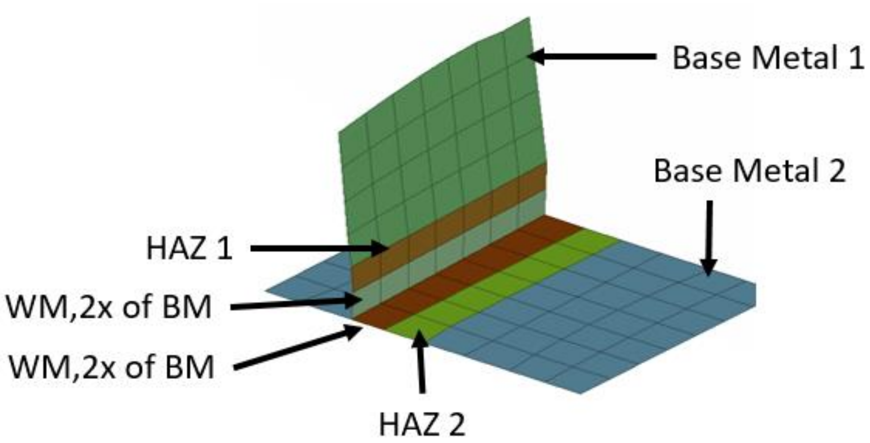


Fig.11: Weld Metal(WM), HAZ and Base Metal(BM) representation using shell method

7.3 Sub-system level test vs CAE predictions

Sub-system level test force vs. displacement (FD) plots and fracture area pictures were processed for CAE comparisons purposes. CAE fracture load predictions are similar to the test conducted as shown in the FD plot Fig. 12 and MIG welded joint fracture initiated at HAZ areas as predicted in the CAE prediction analysis shown in Fig. 13. CAE predictions were comparable with the test.

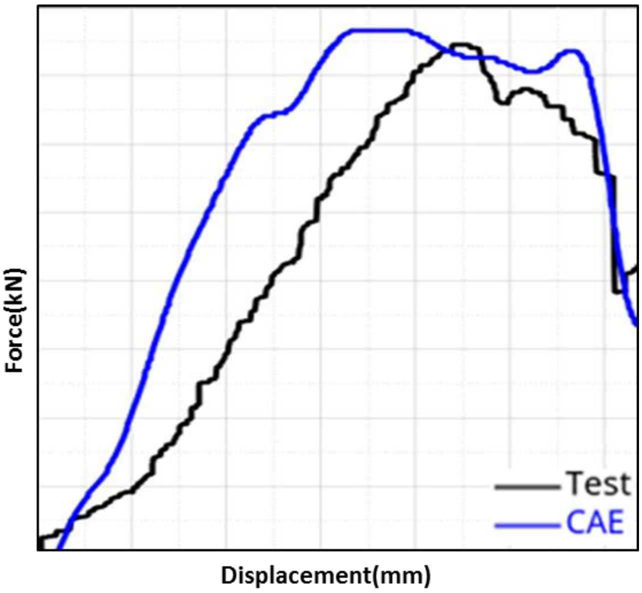
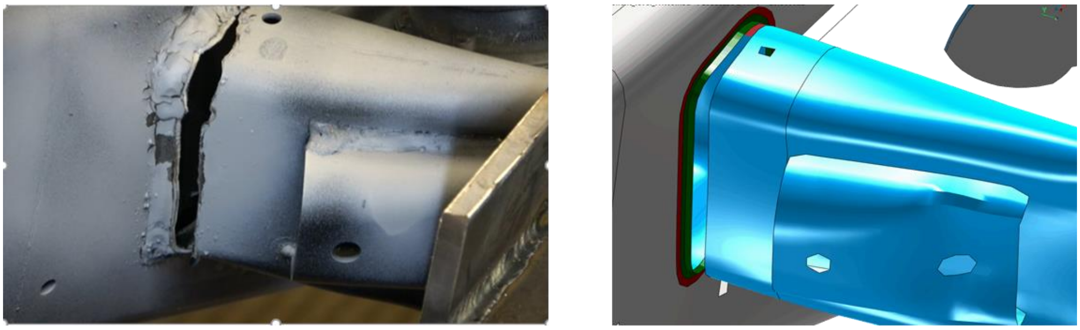


Fig.12: Test vs. CAE Prediction FD

Different designs with different material properties of the critical component were tested with similar test set-up and test results and their CAE predictions were comparable.



Test

CAE Prediction

Fig.13: Component fracture at near HAZ

8 HAZ modeling methodology in Full vehicle CAE Models.

In the full vehicle impact studies, HAZ methodology was used to simulate all other areas of the vehicle that were deemed critical to the load path. Based on the impact analyses, component's material grades and gauges were selected.

HAZ modeling methodology was evaluated in IIHS small overlap test mode. CAE predictions of crash test showed good estimates in terms of predicting critical components separation timings and vehicle velocity. Vehicle test structural intrusions were comparable with the test as shown in Fig.13. In addition, vehicle velocity profiles were compared between test and CAE as shown in Fig. 14. Blue 45-degree line represents test curve and pink dashed curve represents CAE predictions. Vehicle velocity profile, during the time window in which the critical component is stacking-up, matched closer to the test as shown in highlighted window by implementing HAZ methodology.

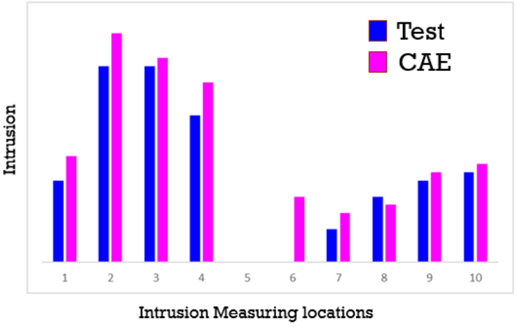


Fig.13: IIHS Structural intrusion Test vs. CAE

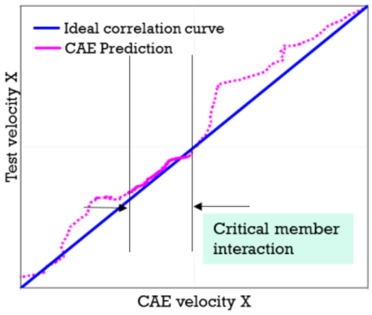


Fig. 14: Test vs CAE Velocity

9 Conclusion and future scope of work.

This paper discusses a predictive methodology to characterize HAZ materials in MIG welded joints. Through experiments and simulations, the structural performance of typical MIG welded structures were evaluated and predicted. CAE predictions showed good agreement to tests in predicting MIG weld separations.

For MIG welded sheet metals with upfront knowledge of their hardness degradation, we can use HAZ separation method as described in this paper. When thick parts like castings are MIG welded, we have used discrete beams with separation criteria in some of our vehicles. In future, we want to investigate combining the HAZ and discrete beam methodologies to develop common approach between sheet and thick parts.

10 Literature

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