Modelling Spotweld Fracture Using CrachFEM

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1 Introduction

In recent years, a number of research institutes have concentrated on trying to develop fracture models that are generally applicable to a wide range of engineering problems. Examples of some of these fracture models are from Gurson and various extensions to Gurson[1], Dell and Gese (CrachFEM)[2], Xue-Wierzbicki[3], Wilkins (EWK model)[4], and du Bois (*MAT_GISSMO)[5].

The key features of these models are a dependency of the fracture strain on the stress triaxiality and a means of accounting for void growth or instability due to necking. Some of these models also incorporate non-linear strain accumulation, kinematic hardening and sophisticated plasticity models, which may be necessary for modelling certain types of materials. The Dell and Gese (CrachFEM) material model is a popular choice in the European automotive industry and has been used in this study.

One of the application areas of concern is at or near to spot welds, where the material properties of the weld and Heat Affected Zone (HAZ) are very different to the sheet and fracture predictions can be signicantly affected by this. This work investigates the potential for developing an accurate 3D weld model to describe the lap shear and cross tension plug fracture modes observed in DP600.

Obtaining stress strain curves for the weld nugget and HAZ is a challenge. The standard approach is to use heat treated test coupons to perform a range of non-standard material coupon tests, with test coupons having the same micro-structures as the weld nugget and HAZ. To prepare the heat treated test samples requires spot welding simulation to determine the required temperature time curves observed during spot welding followed by Gleeble testing to reproduce the required temperature time cycles on test coupons. This is difficult to achieve in practice and several iterations may be needed to achieve the required micro-structures. This set of tasks is a significant undertaking and has been the subject of a number of university PhD and post-doctorate research studies. Dancette [6] and Sommer [7] are very good examples of this research.

In this study, a simplified approach has been adopted using weld micrographs and micro-hardness indentation tests to infer the geometry and stress strain properties and to assume the fracture properties are the same as the sheet. This approach lacks the rigour of material testing coupons with tailored heat treatments but does provide a simpler approach that can be implemented more easily in industry.

2 CrachFEM Material Model

In this study, the Dell and Gese fracture material model (CrachFEM) has been used in the simulations. CrachFEM is a *MAT_USER_DEFINED material model available from MATFEM, which can be used with LS-DYNA® simulations. CrachFEM can be used without significant time or cost penalties in component models and full vehicle models as part of a comprehensive CAE and design process.

CrachFEM is a modular material model and includes:

- A wide choice of Yield Loci
- Kinematic hardening model
- Choice of models for including strain rates
- Non linear strain paths for multi-step processes
- A Forming Limit Curve and Post-Necking model for modelling fracture in thin sheets (i.e. for shell elements at through thickness integration points)
- A Comprehensive fracture model where fracture strain is a function of stress triaxiality (Equation 1), considers shear and ductile fracture modes, includes orthotropic and anisotropic

fracture, and can be used for shell elements (2D stress state) and solid elements (3D-stress state)

$$\eta = (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_{\mathrm{VonMises}}$$

Equation 1: Stress Triaxiality Definition

Both Ductile Normal Fracture (DNF) and Ductile Shear Fracture (DSF) modes are considered in the material model. DNF occurs as a consequence of void growth and DSF occurs by shear failure along shear slip planes (Figure 1).

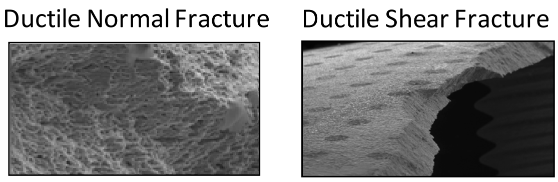

Figure 1: Fracture Modes Considered in CrachFEM

3 Anatomy of a DP600 Spot Weld

In DP600 spot welds, there are two distinct regions in the HAZ (Figure 2). The region adjacent to the weld nugget has been called the Coarse-Grained HAZ (CGHAZ) and the region further away has been called the Sub-Critical HAZ (SCHAZ). This terminology is consistent with the work of Dancette[6]. In the CGHAZ, the temperatures observed are high enough for austenitic transformation to occur and the material subsequently cools so quickly that martensite is formed. In the SCHAZ, the temperatures are not sufficient to cause a transformation to austenite, but are sufficiently high to slightly alter the mechanical properties of the SCHAZ after cooling. The micro-hardness measurements clearly show the influence of the HAZ cooling on the hardness values in the weld nugget, CGHAZ and SCHAZ regions of the weld.

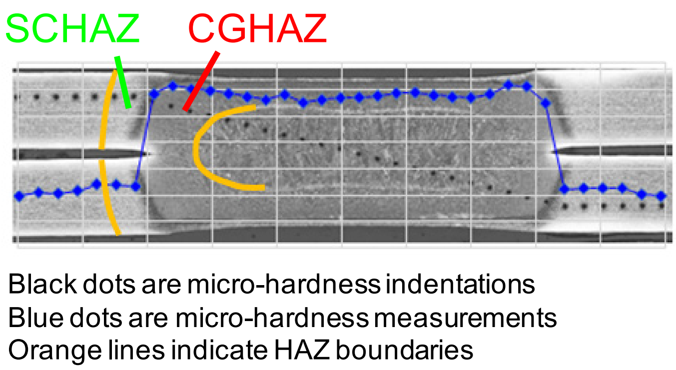

Figure 2: DP600 Spot Weld Micrograph and Micro-Hardness

4 Spot Weld Test Method

In order to verify the strength of spot welded joints in a material and provide confidence to customers, a number of simple destructive welded coupon tests are available. The 2 standard tests which are usually required by customers are the Cross Tension [8] and the Lap Shear tests [9] (Figure 3).

The objective of these tests is to apply the most severe spot weld loads possible in tension and shear and to observe fracture modes. Thus, the tests are not really designed with the final application in mind and may not cover the range of loading types observed in a welded structure. Nevertheless, engineers often characterise spot weld failure models using the cross tension and lap shear tests. In practice, spot weld configurations and loads in engineering structures are often more complex, and may require a more rigorous testing and correlation approach to achieve a satisfactory spot weld failure model.

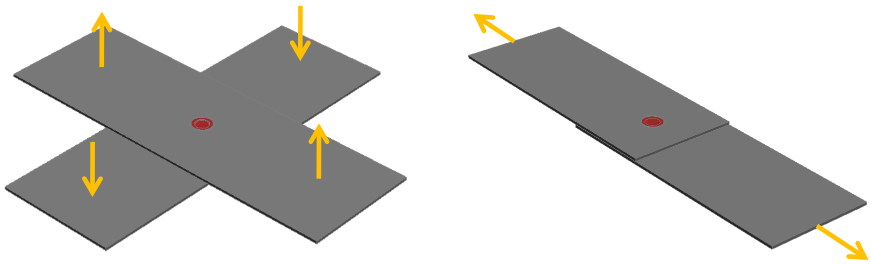

Figure 3: Cross Tension and Lap Shear Test Configurations

5 Spot Weld Failure Modes

Spot welds fail in a number of ways, but traditionally, spot weld failure modes have been classified into 2 types: plug and interface failures (Figure 4). Sometimes an additional classification is called a partial plug failure. In this case the failure starts as an interface failure, but the fracture propagation changes direction at some point and the final fracture appears to be in a plug failure mode.

Figure 4: Spot Weld Failure Modes

As a convention in industry, plug failures are preferred. A plug failure mode indicates failure of the sheet rather than failure of the spot weld (i.e. spot weld stronger than the sheet). Interface failures are considered undesirable, indicating a poor spot weld. (i.e. spot weld weaker than the sheet). For Advanced High Strength Steels (AHSS), the traditional view of plug failures and interface failures is over simplistic. Sometimes, a plug failure may occur in the SCHAZ or CGHAZ rather than the sheet and interface failures do not necessarily give a reduced load bearing capacity when compared to a plug failure.

6 Motivation for Developing a 3D FE Fracture Model of Spot Weld

For AHSS and many non-ferrous grades, there is a benefit to be gained from a deeper understanding of the geometric, loading and material factors that trigger the different failure modes and how the load bearing capacity of the spot weld is affected. By using a 3D spot weld model together with a fracture model that is able to model a wider range of fracture modes, a more comprehensive set of simpler spot weld failure models can be developed more easily.

7 CAE Model

Figure 5 shows the 3D Computer Aided Engineering (CAE) model of the spot weld, with the weld nugget, CGHAZ, SCHAZ and sheet regions determined from the DP600 spot weld micrograph in Figure 2. Solid elements have been used to model the weld, HAZ regions and adjacent sheet.

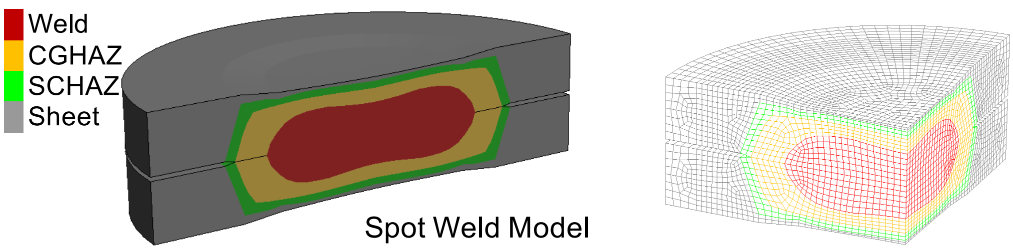

Figure 5: CAE Model of Weld, CGHAZ, SCHAZ and Adjacent Sheet

The same D3 solid element mesh and material data have been used in both the Cross Tension and Lap Shear models.

Figure 6 shows the cross tension and lap shear CAE model configurations, with shell elements used to model the sheet away from the weld. At the contacting faces of the solid elements and shell elements, a layer of shell elements has been meshed around the outer surface of the solids as a coating. This is in order to enable any rotations in the shell elements to be transferred into the solid elements. The diameter of the 3D solid element model has been chosen carefully to ensure that any unrealistic localised stresses at the interface are some distance away from the HAZ regions and do not interfere with the results of interest.

Symmetry has also been used in the CAE models in order to reduce the calculation effort required.

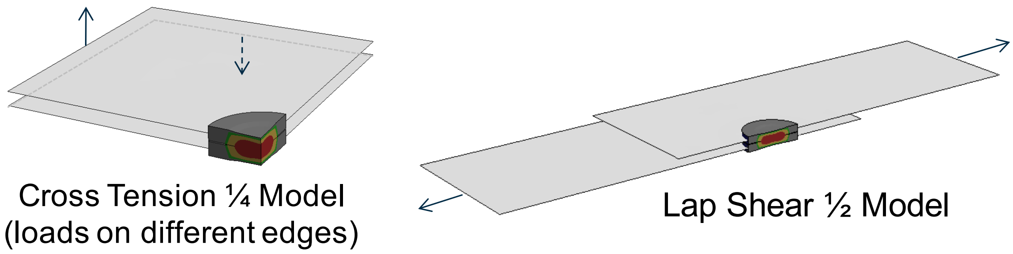

Figure 6: Cross Tension and Lap Shear CAE Model Configurations

8 Material Data

The standard CrachFEM material model for DP600 sheet has been used in the weld, CGHAZ, and SCHAZ. To enable the CrachFEM material model to work for 3D models, the instability data is switched off, a Von Mises yield locus is used and the β-model for ductile fracture is required [10].

For the weld, CGHAZ and SCHAZ, the stress strain curves are scaled linearly with relative hardness measurements obtained in the microhardness indentation tests (Figure 7). All other material data, including fracture properties are assumed to be the same as the sheet.

This approach to modelling the weld nugget, CGHAZ and SCHAZ is a simplistic one and ignores differences in fracture strain in the heat affected regions and the sheet. This could potentially be a source of inaccuracy but the motivation is to investigate if this is a valid assumption in order to minimise the requirement for material testing and for estimation of complex material data parameters. The only material data which are modified to account the the HAZ region properties are the y-axis values of the stress strain curves for the weld nugget and HAZ regions in line with the microhardness measurements.

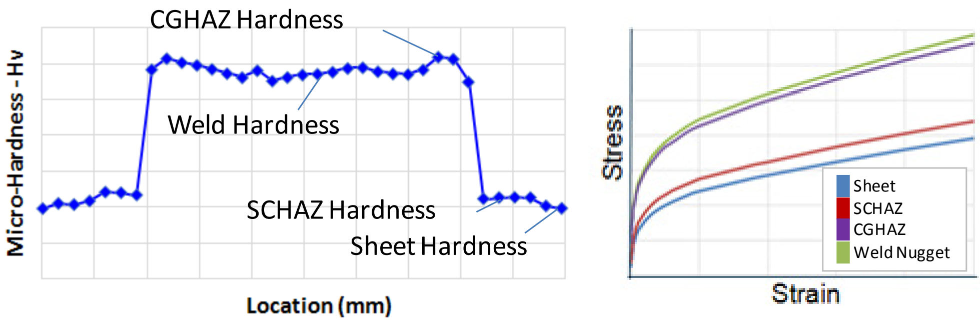

Figure 7: Weld Hardness Profile and Scaled Stress Strain Curves

9 Results

9.1 Lap Shear CAE and Test Results

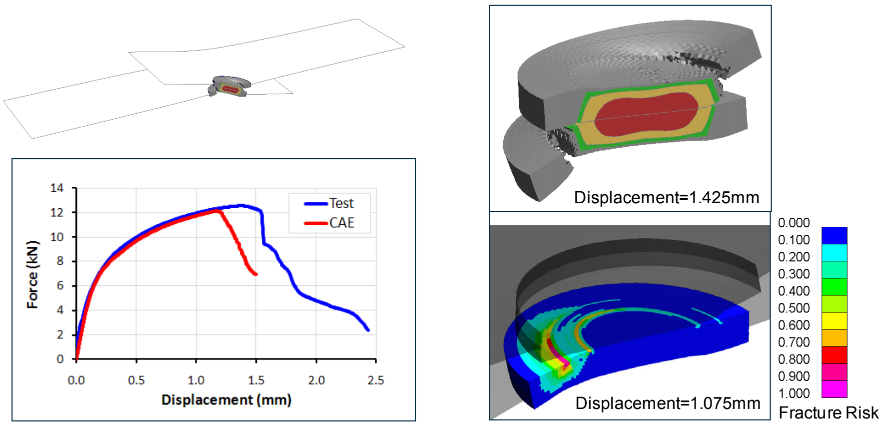

Figure 8: Lap Shear CAE Correlation Results

The lap shear test and CAE results are shown in Figure 8. The mesh plot (upper right) shows how the fracture occurs in the sheet material just in front of the SCHAZ region. This is consistent with DP600 spot weld failures that occur in the lap shear test. The contour plot (bottom right) shows the fracture risks at the last plot state to be output before fracture (i.e. this is not the point immediately prior to fracture). CrachFEM calculates fracture risk as a fraction of 1 with a fracture risk 1 indicating that the fracture limit has been reached. This approach is needed to be able to easily compare different fracture risks for elements having different stress triaxialities and different possible fracture modes. The contour plot is useful as an indicator of other regions that may pose a significant fracture risk. The plot shows that a 2nd location in the CGHAZ immediately adjacent to the weld nugget has a fracture risk of approximately 0.7.

The force displacement curve (bottom left) shows a very good match between CAE and test up to the point of fracture. The fracture load in the CAE model (12kN) corresponds very well with the fracture load in the test (12.5kN). For the displacements at fracture, the CAE model predicts fracture at 1.2mm displacement whereas the test records the fracture occuring at 1.5mm.

The displacement at fracture is slightly lower in the CAE model than in the test, but with the assumptions used in the model, this is considered to be a reasonable result and this model could be used as a basis for calibrating a simpler spot weld model.

9.2 Cross Tension CAE and Test Results

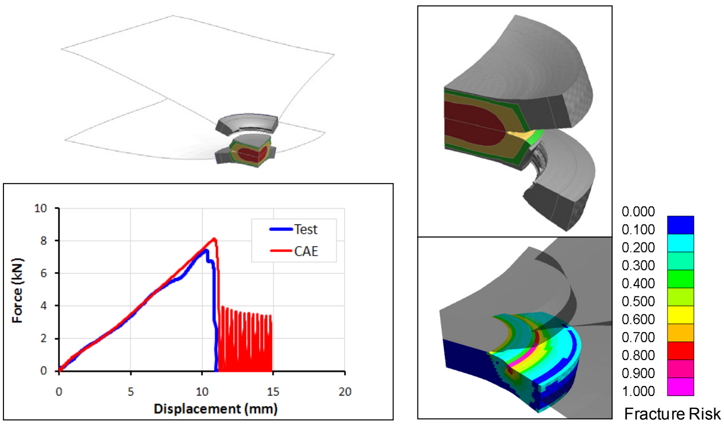

Figure 9: Cross Tension CAE Correlation Results

The cross tension test and CAE results are shown in Figure 9. The mesh plot (upper right) shows the fracture in the sheet. In this case, the material also fractures just in front of the SCHAZ. This is the same as location as in the Lap Shear model and this also concurs with experiments.

The contour plot (bottom right) shows the fracture risks at the last plot state to be output before fracture (i.e. this is not the point immediately prior to fracture). The second highest fracture risk is in an area of the CGHAZ immediately adjacent to the weld nugget and this value is 0.6.

The force displacement curve (bottom left) shows a very good match between CAE and test up to the point of fracture. The fracture load in the CAE model (8kN) is slightly higher than the test (7.5kN). For the displacements at fracture, the CAE model predicts fracture at 10.9mm displacement whereas the test records the fracture occuring at 10.3mm.

The force displacement curves match very well and this model could be used as a basis for calibrating a simpler spot weld model.

10 Conclusion

The findings suggest that CrachFEM is well suited to modelling plug fractures provided an adequate description of the stress strain curves in the weld nugget and Heat Affected Zone (HAZ) are used.

Obtaining stress strain curves for the weld nugget and HAZ can be a challenge. For this study it was found to be adequate to use weld micrographs and micro-hardness indentation tests to infer the geometry and stress strain properties and to assume the fracture properties are the same as the sheet. The results indicate that this is a reasonable starting point when complex heat treatments of test coupons cannot be performed.

11 Literature

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