Integrated Data-led Studies of Electrical Resistance Spot Welded Joints

X. Qing[1], T. Kaid, C. Yildizand[2], F. Ates[2], V. Zevallos Herencia[1], L. Wang[3], G. Mehmet[2], and J. Ren[2]

[1] School of Engineering, Liverpool John Moores University, Liverpool L3 3AF, UK
[2] Ermetal Otomotiv, Bursa ,TÜRKİYE
[3] School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, UK
x.qing@2020.ljmu.ac.uk; X.J.Ren@ljmu.ac.uk

Abstract. Welding techniques, such as electrical resistance spot welding, are widely used in automotive manufacturing. Welded joints of metals consist of complex material zones and regions of different shapes that need to be reflected in the modelling process. Parametric modelling is an efficient tool to develop data and knowledge for the understanding of mechanical behaviour and the effect of key design and material parameters for the applications and technological developments related to the welded joint. This paper presents the focus of an integrated data-led approach for studying electrical spot welding. The use of predictive modelling to evaluate the effects of key parameters of welded joints is analysed. Typical data from a parametric finite element model is presented and used to analyse the effects of sheet thickness on the deformation, stress and strain data. One approach is through comparing the data before fracture and the other approach involves analysing data at comparable displacements before the onset pf severe deformation stage. The use of the data-led predictive modelling in materials and process development, as well as training and application-specific research-technology integration, are discussed.

Keywords: Parametric Modelling; Electrical Resistance Spot Welding; Finite Element Modelling; Data-Led Analysis,.

1 Introduction

Welding techniques, such as electrical resistance spot welding, are important joining processes for automotive industries and associated supply chains [1]. Integration of technologies and data of materials, processing and testing directly influence the effective use of materials and applications of advanced metals, which is essential to enhance the sustainability of automotive structures and technology development. Parametric modelling of the behaviour of welded joints under different loadings and boundary conditions is an effective approach to combine data at different scales and domains, thus offering efficient information for design and process optimizations and training.

Welding is a complex thermal-mechanical process and the weldment consists of regions with significantly different microstructures and properties [2-5]. For example, the melting zone of carbon steels typically consists of a martensite structure due to the high cooling rate while the heat-affected zone (HAZ) is a mixture of tempered structures [6]. The structure is more complicated when welding materials with multiple alloying systems (such as stainless steels, duplex stainless steels, high strength steels and complex phase steels, etc.). When developing models of welded structures, many factors have to be considered that directly affect the welding process, structure integrity, testing and evaluation, service life prediction and materials development. In many cases, the choice of data and technical focus needs to be components-specific to produce relevant knowledge for different applications.

Systematic research and data systems covering the key relevant aspects are important for linking the production control to the structure data and their influence on the mechanical and functional properties of welded joints. This is important for research, industrial developments as well as industrial training processes. Many experimental and modelling techniques have been used in studying the welded joints and the key phases such as numerical modelling, molecular dynamic (MD) modelling, phase field modelling (PFM) and Ab initio (first principle) calculation. Engineering simulation such as finite element (FE) modelling has been extensively used to establish the effects of key design and materials parameters on the mechanical performance of welded structures under different loading conditions such as tensile-shear, bending, torsion, etc. [2,7].

Simulating the mechanical behaviour of spot welded joints with balanced accuracy and efficiency is a challenging process. The modelling program needs to consider many different aspects, such as sheet thickness, nuggets size, indentation, surface finish, or misalignments. In industrial practice, the design also needs to follow some empirical specifications such as the governing metal thickness and stack orientation. Increasingly, with the development of both modelling and advanced experimental techniques, part or service-specific design or loading conditions tailored for different materials/structure design is becoming feasible, which offers greater opportunities in the design and manufacture of multi-material lightweight components for automotive. The production process also needs to be integrated with non-destructive and destructive testing for full production line quality management. There is a pressing need to develop a systematic approach to generate modelling data linking factors with significance related to different materials behaviours (e.g. stiffness, yielding, failure, etc.). One of the important aspects of data-led or informed materials and process development is parametric modelling, which will also contribute to the development of comprehensive frameworks for better quality control and training of workforces within the scheme of industry 4.0 and 5.0.

This paper introduced some work on developing models and data for welding, using electrical spot welded joints as a typical case. A parametric modelling program has been developed to produce data with information at different levels. The key aspects and focus are presented and analysed. The relevant parameters (materials properties, dimensions as well as technical parameters such as partitioning and meshing) are presented. Some data at critical locations and deformation stages are evaluated to help with the understanding of the material deformation process and used to analyse the effect of some key factors in particular the sheet thickness on the deformation and failure under tensile-shear loading. The use of the approach and main focuses in design optimization for R& D as well as training in interdisciplinary knowledge are also discussed.

2 Research Methods and Models

One main aspect of the work involved developing parametric models considering the materials, dimension, partitioning, meshing, stress concentration/singularity, data storage and output. The option to realistically represent the welding zones through automatic partitioning is critical for parametric modelling to assign structure-related properties. Meshing is important as it may affect the stress singularity at joint with sharp corners and connecting points/interface, in the meantime directly influencing the calculation speed and computational cost. The capacity of simulating different loading conditions is important for modelling both standard tests with well-controlled loading conditions and the combined loading modes. In industrial settings, the testing standard may vary with components/assemblies used in different applications, which need to be reflected in the model. A comprehensive structure and flexibility in the development cycle are essential to balance its application for research, design as well as collaborative developments, training and education.

Figure 1 shows a typical generic FE model of electrical resistance spot-welded joints. The model can be simplified/modified for different conditions. For example, in tensile shear modelling, the model can be converted into a plane-symmetric model to reduce the demand for computational resources. During the tensile shear tests, one side of the assembly is fixed, while the other side is pulled. Multiple axial loads can also be assigned to suit different conditions. The size and dimensions of the model can be modified through parameters when using it as a research tool to map the effect of key parameters such as sheet thickness, nugget size, as well the shape of the nuggets. Static, implicit and explicit analysis can be selectively applied for different conditions such as yielding, hardening, damage and fracture. The meshing is an important aspect in parametric models with multiple partitions. A key focus of the meshing is to reduce the effect of stress singularity which could cause artificially high-stress points locally. The choice of mesh density is also important for balancing the computational resources to avoid over-meshing pending on the geometries, materials and main focuses (e.g. strain or deformation levels). Adaptive meshing has been applied for ABAQUS/Explicit to determine the optimum mesh sizes, which has guided the parametric meshing design. For the model shown in Figure 1, the workpiece sheet is 100 mm long, 25mm wide and 0.8 mm in thickness. The length of the overlap zone between the two plates is 25 mm. The nugget size is 4.5mm for the data reported in this work. Typically, the heat affected was partitioned into different zones to reflect the different microstructures and properties of the material. For the boundary condition of a tensile-shear model, one end of the model is fixed through displacement control, while a velocity is applied to pull the sample from the movable end. The reaction force is recorded. Both structured mesh and hybrid mesh schemes have been evaluated in the works. The main element type used is the reduced volume element C3D8R. Mesh refinement is being applied to the nugget and HAZ zones to increase the modelling accuracy and efficiency. The base model was validated by comparing numerical force-displacement data and experimental works based tests on auto steel sheet with known properties [9], before being used as the base model of the parametric studies for comparing the effect of the dimensional parameters on deformation and fracture process [9].

Key geometry parts are partitioned, and the area of interests are defined as key set (geometry, nodes or elements) for the purpose of generating data for regions relevant to potential high deformation or damage identified based on extensive literature review and analysis. The example presented in the paper is a simple case with the nugget being treated as a cylindrical part, this approach has been used by many researchers for electrical resistance spot welding [8]; The HAZ can be divided into different zones to represent the zones (3-5) for different materials system and structures. The flexibility in the choice of the subzone in HAZ makes it easier to cover different materials systems in similar and dissimilar welding. Apart from the partitioning for meshing, special sets were designated to conveniently extract the data from areas of interest, e.g. the high deformation or potential failure zones). For example, the HAZ zones can be represented by the set of nodes at different thickness positions for critical deformation and facture (such as circumstance failure and interfacial failure). By defining specific sets and paths in these critical regions (e.g. the red dotted line is a typical in -plane path across the key welding zones), detailed historical data can be extracted, stored, and used when comparing the effects of key variables such as thickness, nugget sizes, and materials properties either interactively in the modelling program or accessed offline from the database.

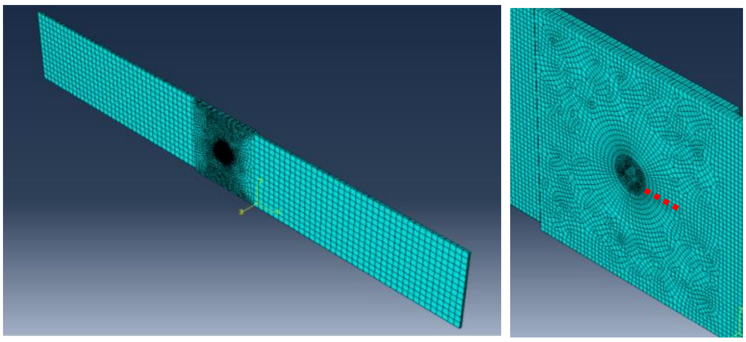

Fig.1 Typical finite element model of electrical a spot welded joint. The close-up view shows a typical path to extract the data across the HAZ.

The model can incorporate different materials models such as elastic model, elastic-plastic property and failure/ damage models. Most of the materials involved in spot welding operations are of typical elastoplastic behaviour. The plastic behaviour is normally described by constitutive material equations. The three-parameter power-hardening rule can be used:

$$\sigma = \sigma_0 + K\, \varepsilon^n \qquad (1)$$

Where the parameter 'σ_0' is the yield stress, 'ε' is the plastic strain, K is the strength coefficient and 'n' is the strain hardening exponent. A simpler form can also be used for isotropic elastic-plastic behaviour with isotropic work-hardening described by the Ludwig power equation:

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \qquad (2)$$

where 'ε_0'is the yield strain. The parameters of the model are normally obtained from the stress strain curves. The yield stress and ultimate tensile strength (UTS) can also be estimated from microhardness tests, which are commonly used in characterising the properties of the HAZ zones in welded joints.

Many damage models have been used in modelling spot welded joints in the published literature. In this work, we also incorporated some complex micromechanical models such as the Gurson–Tvergaard-Needleman (GTN) model. GTN model was subdivided into the following groups: Parameters of the material, i.e. Young's modulus, E, Poisson's ratio, ν, and the initial true stress-strain curves, initial parameters of the rigid inclusion, i.e. the initial void volume fraction f_0 and the volume fraction of void nucleating particles f_n. Parameters affecting the nucleation, growth and coalescence of voids during the loading process includes q_1, q_2, q_3, ε_N, S_N, f_c, f_F. Large-scale direct/inverse mechanical modelling and testing of different sample shapes and size is required to determine the parameters. Materials characterization such as analysis of the size, distributions, and volume fraction of inclusions could also be used to help estimate the key parameters [9]. One typical set of the materials properties used in the work for auto steel: the effective yield stresses for the three welding zones of steel are 180, 230 and 400 MPa, respectively, for the base, HAZ and nugget; the *n* values are 0.18, 0.16 and 0.09. The Porous Metal Plasticity was set as (1.5, 1., 2.25) and the Porous Failure Criteria was aet as (0.4, 0.35). This is used in the parametric studies to establish the effects of sheet thickness. The parameter was based inverse modelling and fitting of samples with different notch sizes from previous work [9,10]. The framework gives the flexibility of using different models and using the data to analyse the effect of parameters. The joint use of the micromechanical model and other approach such as load limit models could help in effectively linking design and materials in the longer term as more and more data becomes available from different sources for different materials. The use of parametric modelling also offers the capacity to develop output considering the uncertainty of some difficult-to-determine parameters, providing data within a statistical range [10-15].

3 Typical Results and Analysis

The output data is defined into two levels. One level is forces-displacement under different loading conditions, deformed shapes, etc. Another level is the directional stress/strain, and energy in the materials. These can be directly extracted from the modelling. Some general terms are used to form more in-depth data to research the material behaviour or change of potential failure modes such as Von Mises Stress, Equivalent Plastic Strain (PEEQ), stress triaxiality etc., which can provide data/indication to analyse the damage and failure process.

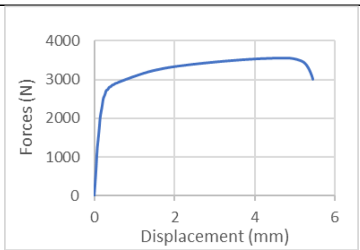	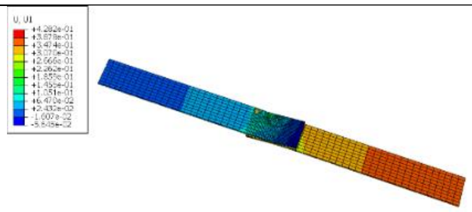
(a)Typical Force -Displacement (in mm) data.	(b)Typical displacement field in tensile shear test.

Fig.2 Typical force-data and deformation of electrical spot welded joint.

Figure 2 shows typical force-displacement data for a tensile shear test. It includes the elastic deformation phase, Yielding phase, Strain hardening phase, Effective necking phase and Severe deformation and Fracture phase. This data is important for analysing the load bearing capacity, ductility and energy absorption. The elastic region is associated with the stiffness of the material, the yielding, and the hardening and the fracture phase will provide the maximum load bearing capacity as well as the maximum displacement at fracture. Pending on the loading rate, the area under the curve reflects the energy absorption capacity of the welded joints.

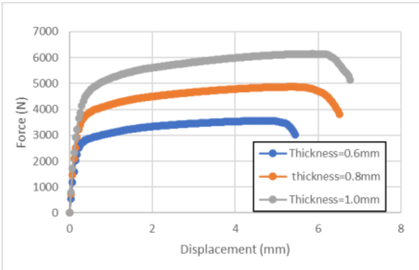

Fig.3 Typical force-displacement data for spot welded joints with different thicknesses from 0.6mm, 0.8mm and 1mm).

One main focus in using parametric modelling data is studying/predicting the effects of key materials or design parameters. For electrical resistance spot welding, thickness is an important factor. In industrial practice, the specification is often linked with the governing metal thickness. Figure 3 shows a typical set of FE force-displacement data of a spot-welded joints with different sheet thicknesses for carbon steel. The three models have a nugget diameter (4.5 mm) but different sheet thicknesses (0.6mm, 0.8mm, and 1mm, respectively), to show the effect of sheet thickness on the force-displacement data. The force-displacement shows a similar elastic deformation phase with a comparable displacement/strain point for yielding. The plastic deformation and hardening stage follows a similar trend at different strain levels. Apart from the difference in force levels, the displacement at the effective necking phase and severe deformation phase is also different. The maximum elongation is increased with the thickness, but the increase between the data for 0.8mm and 1 mm is not as significant as the one between the thickness of 0.8mm and 0.6mm. All of these reflect a potential change in deformation state and stress-strain conditions, which can be analysed further with detailed data.

One of the uses of the data is to comparatively analyse the effect of thicknesses on the deformation at different stages associated with different strain/displacement levels. Figure 4 shows the *Von mises* stress of the three joints at different displacements. Von mises is a scalar measure of the shear stress at a point. The picked displacement points for showing the data includes 0.1mm in the elastic deformation regime and 2.0mm in the plastic deformation stage. The stress at the point before necking for the three thicknesses data is also presented. As shown in Figure 4 (a(i), (b(i) and c(i), the stress pattern in the elastic regime between these thicknesses are comparable with no major differences. At larger strain in the plastic zones, there is also no major difference between the pattern (a (ii), b(ii) and c(ii)), but data shows that there is a variation in the peak stresses before the necking stages as shown in (a(iii), b(iii) and c(iii)). In general, the location of regions with high stresses is in good agreement with the experimental observations of circumstantial failure in the HAZ zones.

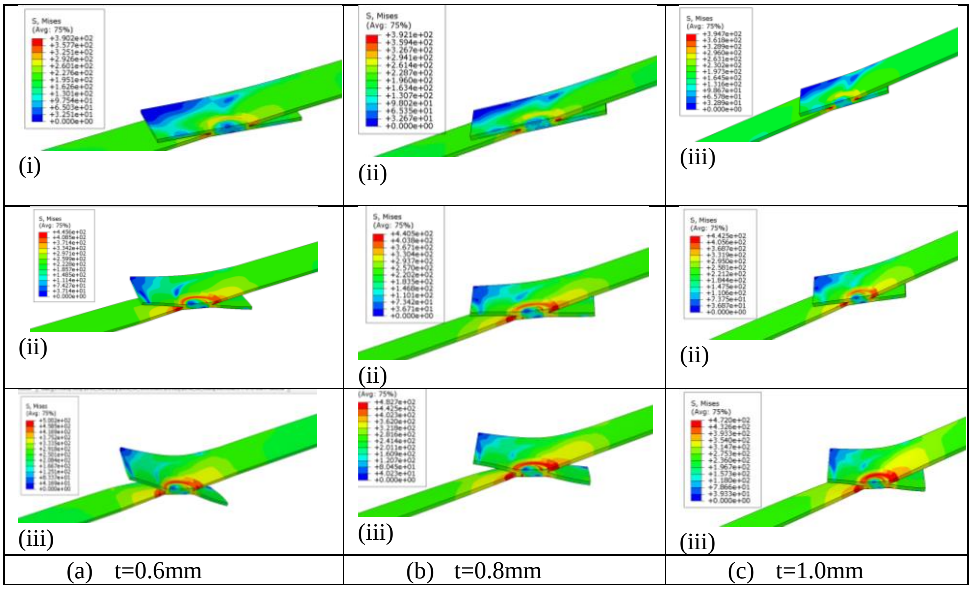

Fig. 4 Typical plot of von Mises stress in the welded joints with different sheet thicknesses at different stages. (i) Elastic stage; (ii) Plastic stage; (iii) Before Necking.

Strain is an important data for comparatively analysing the deformation. The critical strain at key positions can be linked to the damage process and failure. One general indicator is the equivalent plastic strain (PEEQ), which is a scalar measure of all the components of equivalent plastic strain at each position. To further quantify the effect of stress and strain associated with the sheet thickness as there is a clear difference in the displacement point at necking for the three thicknesses for the material. A comparative study has been conducted by systematically comparing the data at different strain levels. A typical data for around 5mm displacement is presented in Figure 5. At this point, the thickness 0.6mm sample is close to the necking point as shown in Figure 3, while the thickness 0.8mm and 1mm samples are still in the stable plastic region. It can be seen that the stress level for the two thicker samples is lower than the ones for the thin sample, and the strain (PEEQ) is also lower, but the PEEQ for the samples didn’t follow the thickness progressively, which suggest that thickness effect is more complicated, which can’t be represented by simple values. Further systematic quantitative analysis is required to be certain about the actual failure point as the damage and failure may be affected by tension, bending as well as torsion deformations, but it clearly shows that the generalized modelling data such as PEEQ could provide indication/reference on the role of critical stress and strain on the failure process associated with thickness effects in this case.

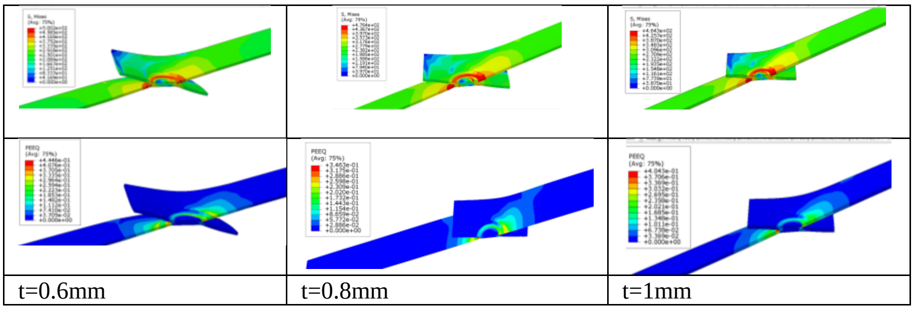

Fig.5 Data used to analyse the effect of thickness on stress and PEEQ under comparable displacement.

4 Discussion

The development of data for welding is important for automotive manufacturing in particular in dealing with complex structure and materials issues. In automotive design, thickness is one of the key controlling issues for structure integrity and weight control. In process teat and the destructive test on car bodies or sub-assemblies in Body-In-White (BIW) form is still an important procedure to determine the strength of spot and other welds. It is essential to study the data beyond the elastic-plastic regimes, the work highlights that combined stress and strain data is required to reflect the post necking process to determine the peak load and effective strain before the joint losing it load bearing capacity. The welding process is affected by complex issues such as energy input, phase and structure changes, the modelling data need to reflect these issues through input and output data. The large variety of materials used in automotive and related industries also makes it difficult to describe the deformation of the material through simple fit-for-all models. In addition, the choice of data is also dependent on the purpose of the work such as main loading modes of interest and stain levels. A data-based approach could offer the flexibility to provide information for different targets such as elastic deformation, plastic, damage and/or fracture. It also offers the means to compare the materials and structure behaviour with different designs. As shown in the case of spot-welded joints of samples with different thicknesses, the elastic and general plastic deformation is linked to the constitutive properties. More importantly, for analysis of the strains for the failure in critical regions, the data-based approach gives more information to support the analysis as it offers both quantitative data as well as information on the high strain/stress levels and distributions. For the development of multi-material light structures, the simplified empirical equations are not sufficient even for industrial R&D, so parametric modelling offers a practical way to generate more comprehensive data and information to predictively aid the design and analysis process.

Finite element modelling could be a complex process, many issues may influence the validity and accuracy of the data. The choice of materials models, the partitioning, the meshing scheme and sizes are all important issues. For practical application, the modelling approach needs to balance the accuracy depending on the technical aims as well as the demand for computational resources. Parametric modelling approaches could also offer the capacity to set the upper and lower bounds considering both variation and the uncertainties ranges of key parameters. Apart from the direct impact of using parametric modelling in research and development, developing systematic data in spot welding is also important for quality control and training purposes. In a typical industrial manufacturing process, the welding process and the welded joint went through several quality inspections through non-destructive testing (such as ultrasound) and destructive testing (online mechanical tests and fracture tests). The data at different levels (e.g. force-displacement, stress, strain, energy, etc.) could provide in-depth data for the training and education of the workforce in understanding the importance and key focuses of quality control. This will empower the workforce and integrate them into the R&D process which is a key theme for Inustry5.0.

Parametric modelling offers a practical framework to integrate the knowledge from materials, manufacturing, mechanical testing and management and provide the data for future AI-based development [1] . The material's properties can a critical role in modelling welded joints, the choice and scale of the materials models need to consider different scenarios [11] . Increasingly the material data needs to be extended to consider the key phases with more details, such as secondary phases and brittle intermetallic compounds, which requires the link between engineering modelling and physical-based modelling such as molecular dynamics. For example, in the welding between steel and nonferrous materials, the brittle intermetallic compound is the main dominating issue [11] . The composition of intermetallic compounds formed in welding is not well defined as their bulk materials, but it directly affects the brittleness and fracture processes. In the future, the data from different scales need to be combined to tackle some key issues to enhance the capacity of predictive modelling and the design of complex materials for the welding process. The numerical modelling approach also has the capacity of producing data to reflect the uncertainty and influence of key parameters. This is important for technological development as well as engineering training, in particular in the development of knowledge based process control for industries such as for automotive to further enhance the integration of nondestructive in-process monitoring and staged destructive testing of spot welded parts and full assemblies.

5 Summary

Electrical resistance spot welding is an important joining technique widely used in automotive manufacturing, the performance and quality of the welded joint are controlled by many design and materials parameters. Development of comprehensive data for scientific research, as well as collaborative development, training and education is an important part of Indurtry4.0 and 5.0. Parametric modelling methods offer an effective way to develop data and integrate the knowledge for understanding behaviours of welded joints in standard testing, production control and services. Data-led approach offers the capacity to evaluate the complex effect of key design and material parameters for the applications. This paper presents the focus of an integrated data-led approach for studying electrical spot welding. The data of different levels at different deformation stages in the tensile shear test is analysed. Typical data from a parametric finite element model is used to analyse the effects of sheet thickness on the deformation, stress and strain data. The result of the cases presented show that by selecting data at different deformation stages (elastic, plastic, severe deformation/post necking and fracture), more meaningful data could be produced. The use of combined data (e.g. the Mises and PEEQ) could better reflect the effects of the sheet thickness on the deformation of spot welded joints in the plastic and onset of severe deformation. The work highlights the need of the data-led modelling to provide more support in materials and process development for welding, as well as training of a work force able to deal with complex data.

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