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Strength Based Numerical Approach Constitutive Material Prediction of Spot Welded Joints of Steel

I Nyoman Budiarsa

Mechanical Engineering, University of Udayana, Bali. Indonesia

Abstract

The deformation of spot welded joints is challenging research problem due to the complex nature of the structure. One major problem is to characterize the materials properties. The elastic-plastic material parameters and the fracture parameters of materials can be readily determined when standard specimens are available, however, for a spot welded joint, standard testing is not applicable to characterize the heat affected zone (HAZ) and the weld nugget due to their complex structure and small size. This has opened up the possibility to characterize the material properties based a dual indenter method to inversely characterize the parameters of the constitutive material laws for the nugget, HAZ and the base metals. In a mixed numerical-experimental approach, the load-deformation data of the material is used as input data to a finite element (FE) model that simulate the geometry and boundary conditions of the experiment. With indentation tests, the local plastic properties can be calculated by solving the inverse problem via finite element analysis by incrementally varying properties in 3D modeling to find a similar simulated load–displacement curve as compared with experimental one. The approach will then be used to test different welding zones and the material parameters thus predicted used to simulate the deformation of spot welded joints under complex loading conditions including tensile shear and drop weight impact tests. The evaluation based on numerical experimental data showed similar accuracy to the continuous indentation curve approach.

Keywords: HAZ, finite element (FE) model, Vickers Indentation, Dual indenter

Corresponding Author: I Nyoman Budiarsa; email: nyoman.budiarsa@unud.ac.id

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1. Introduction

In a spot welding process two or three overlapped or stacked components are welded together as a result of the heat created by the electrical resistance [1]. The welding process is a complex thermal mechanical process and the finished assembly consists of regions with significantly different microstructures and properties, including the base metal, heat affected zone (HAZ) and weld nugget. Many research has been conducted to improve the understanding on spot welded joint as the interactions between electrical, thermal, metallurgical and mechanical phenomena. [2]. One active research field is on the prediction of the dimension of spot welded joints by simulating the welding process with the finite element modeling [3]. Another active research field is on the study of microstructure development [4]. These works have resulted in several models to describe the

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simultaneous formation that has made it possible to predict the microstructure development and transformations during spot welding process, and also to investigate the characteristics and behavior of materials, relating with the applied load conditions on the spot weld joint. The deformation of spot welded joints is challenging research problem due to the complex nature of the structure. One major problem is to characterize the materials properties. The elastic-plastic material parameters and the fracture parameters of materials can be readily determined when standard specimens are available. However, for a spot welded joint, standard testing is not applicable to characterize the HAZ and nugget due to their complex structure and small size. This has opened up the possibility to characterize the material properties based a dual indenter method. However, the method involved intensive data fitting which has to be performed based on a computational program. This work aims to further develop this method based to enable more direct parameter prediction based on analytical or semi-analytical approaches with either continuous indentation loading curve or conventional hardness tests. The approach will then be used to test different welding zones and the material parameters thus predicted used to simulate the deformation of spot welded joints under complex loading conditions. These works have resulted in several models to describe the simultaneous formation that has made it possible to predict the microstructure development and transformations during spot welding process, and also to investigate the characteristics and behavior of materials, relating with the applied load conditions on the spot weld joint.

2. Materials Behaviours and the Properties of Different Welded Zones

The plastic behavior is normally described by the constitutive material equations. In many cases, the three parameter power law hardening rule (Eq. 1) is used for steels:

$$\sigma = \sigma_0 + K\varepsilon \tag{1}$$

Where the parameter (σ_0) is the yield stress, K is the strength coefficient and 'n' is the strain hardening exponent. These material parameters influence both the yielding strength and work hardening behavior of the spot welded joint. A measure of strain often used in conjunction with the true stress takes the increment of strain to be the incremental increase in displacement (dL) divided by the current length (L). Prior to necking, when the strain is still uniform along the specimen length, The ratio L/Lo is the extension ratio, denoted as λ. Using these relations, it is easy to develop relations between true and engineering measures of tensile stress and strain

$$\sigma_t = \sigma_e(1+\varepsilon_e) = \sigma_e \cdot \lambda$$
$$\varepsilon_t = \ln(1+\varepsilon_e) = ln \cdot \lambda \tag{2}$$

These equations can be used to derive the true stress-strain curve from the engineering curve. The failure of spot welded joints can be overload failure and fracture. Gurson model is widely used in ductile fracture mechanics, in which, the fracture of material is considered as the result of void growths in the material volume. The Homogenous material surrounding the void is called matrix material. The Gurson model can realistically represent failure, provided the loading state in the coupon used to determine the Gurson parameters, is similar to that in the rupture zone of the structure. The most commonly used model based on the Gurson was called Gurson-Tvergaard-Needleman (GTN) model (ABAQUS Theory Manual

6.13), which is briefly described below. The original model developed by Gurson, assumed plastic yielding of a porous ductile material, where the yield surface was a function of a spherical void as follows

$$\Phi = \frac{3S_{ij}S_{ij}}{2\sigma_{ys}^2} + 2f\cosh\left(\frac{3\sigma_m}{2\sigma_{ys}}\right) - (1-f^2) = 0 \quad (3)$$

Where σ_y is the yield stress of the material, σ_m is the mean stress, f is the void volume fraction. f = 0 Implies that the material is fully dense, and the Gurson yield condition reduces to that of von Mises; f = 1 implies that the material is fully voided and has no stress carrying capacity. S_{ij} is the components of stress deviator (i, j = 1, 2, 3), defined as

$$S_{ij} = \sigma_{ij} - \sigma_m \quad \delta_{ij} \quad (4)$$

And δ_{ij} is the Kronecher delta $\delta_{ij} = 1$ for i=j and $\delta_{ij} = 0$ for $i \neq j$

3. Fe Modeling Dual Indenter and Effects of Material Properties

Figure 1(a). show the FE Models of the Vickers indentation. Only a quarter of the indenter and material column was simulated as a result of plan symmetric geometry [5]. The sample size is more than 10 time the maximum indentation depth, which is sufficiently large to avoid any sample size effect or boundary effect. The element type used is C3D8R (reduced integration element used in stress/displacement analysis). The material of interest was allowed to move and the contact between the indenter surface and the material was maintained at all the time. The Vickers indenter has the form of the right pyramid with a square base and an angle of 136° between opposite face. It is normally made of diamond with Young's modulus of over 1000 GPa, which is significantly stiffer than steel (E=200 GPa). The indenter was considered as the rigid body to improve the modelling efficiency. This work is focused on the studies of plastic parameters, so only the loading curve was utilised to predict the plastic material parameters.

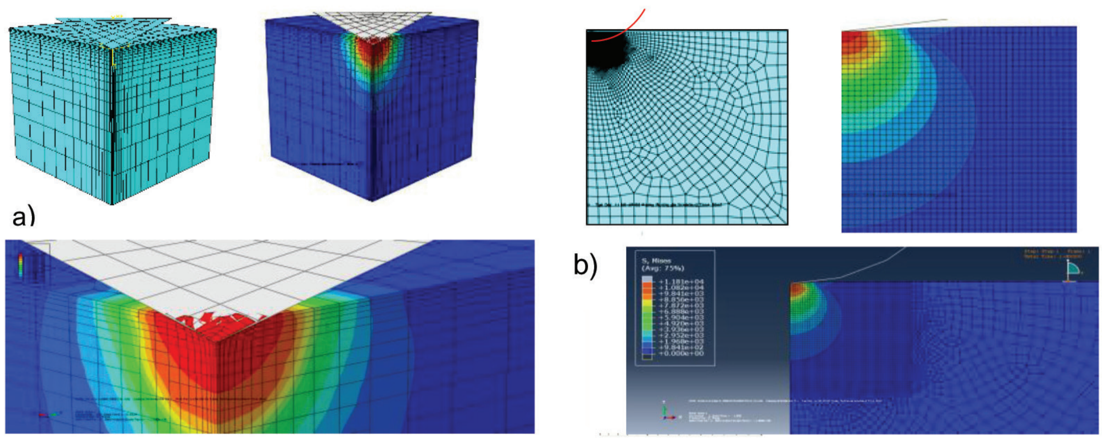


Figure 1: a). Typical Vickers indentation and b). Spherical Indentation.

Different from the Vickers indenters, spherical indenter is fully asymmetric, a typical FE model is shown in Figure.1(b). A planar specimen (3x3mm^2) has been used and this specimen size is large enough to avoid potential sample size effect. The movement of the indenter was simulated by displacing a rigid arc (rigid body) along the Z axis. The bottom line was fixed in all degree of freedoms (DOF) and the central line was symmetrically constrained. The element types used in the spherical indentation model are CAX4R and CAX3 (4-node bilinear asymmetric quadrilateral and 3-node linear asymmetric triangle element used in stress/ displacement analysis without twist). A gradient meshing scheme has been developed for different regions. The mesh size is 5 μ m in the region underneath and around the indenter, while the mesh size of other regions from the nearest region to the outer edge varied from 10 μ m, 0.05 mm and 0.1mm;

A plane symmetric FE model of the spot welded joint has been established (as shown in Figure 2). The material properties used in this model will be predicted by the inverse FE modelling. An element type of C3D8R (a reduced-integration element used in stress/displacement analysis) was used. Due to symmetry the y-direction displacement at the mid-section (bottom surface) was set to zero. The left side of the specimen was fixed ($U_{x,y,z}$=0) and a displacement (U_x=L) was applied on the movable end. The z displacement at the mid-section was set to zero. The dimensions of the welding zones were based on the micro-hardness experimental data and optical observation. All these zones were assumed to have elasto plastic properties.

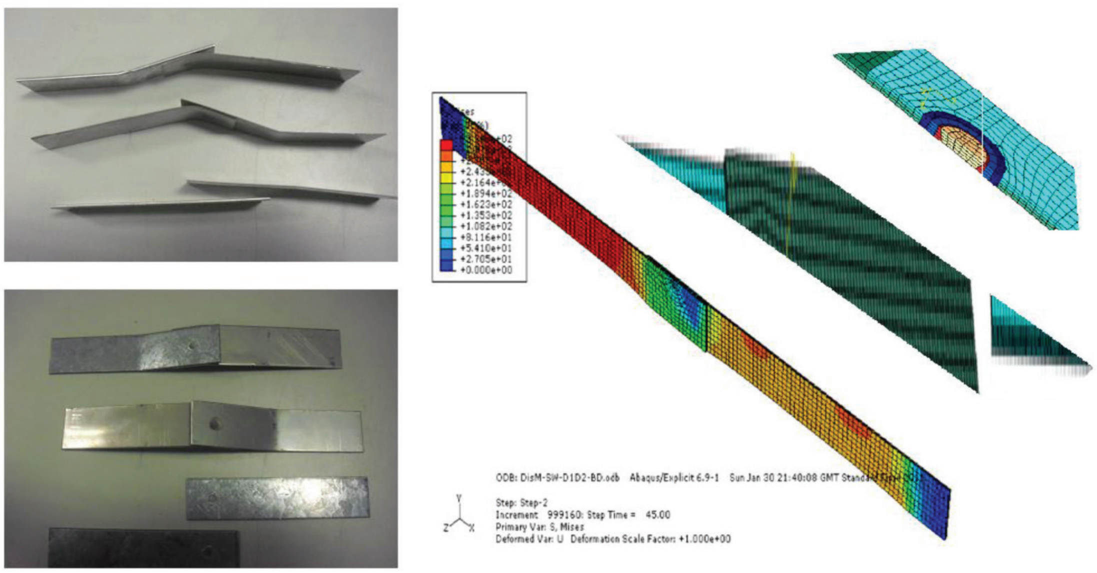


Figure 2: Specimens testing results and Typical FE to be used for simulating the tensile shear for spot welded joint.

4. Identification of Materials Parameters Based on Static Indentation

The P-h curves for both Vickers and Spherical indentation obtained the following relationship:

$$C = P/h^2 \qquad (5)$$

Where P and h are the load and indentation depth on the loading curve respectively. C is the curvature coefficient with the curvature for the Vickers Indentation and spherical indenter designated as C_v and C_s respectively. The curvature is a function of the yields stress and the work hardening coefficient. The three approaches have been comparative developed to assess their suitability to predict the materials properties based on the dual indenter approach. The relationship between the curvature for both the Vickers and spherical were developed then used a chart to predict all the material sets with the same curvature. The relationship is used to predict the material sets have the sane indentation curvature. Evaluation of accuracy on the approach using 3D. The selected input data with variations in the value (n) and σ_y = 100, 140, 190 and 300. Accuracy study chat mapping 3D-Linier on average accuracy error $\Delta n / n$ (%) is 0.1% both the prediction (n) on Vickers Indentation and on Spherical Indentation. This shows the selected predictors significantly acceptable within the limit of level confidence less than 0.5%.

Tensile-Shear test of spot weld joint has objectives for determining the elastic plastic behaviors of the welded joints being tested. Two specimen with different materials (stainless steel and Mild steel) and thickness were used. Stainless steel used is stainless steel grade 304 with a width of 25mm and thickness of 0.8mm, the other specimen is mild steel with a width of 25mm and thickness of 1.44mm. The machine has a maximum loading capacity of 30kN, with the readings being accurate to 0.5% of the force. Drop mass tests were performed in order to determine the effect of materials on deformation of welded joints under dynamic loading, which represents the crash and energy absorption characteristics of structure.

As shown in Figure 3. The modeling results showed a good agreement with the experimental data. This suggests that material laws predicted by dual indenter FE modeling of indentation test for different zones (σy, n) is accurate. The slight differences between numerical and experimental results on the fracture behavior suggest that detailed fracture for each material zone has to be obtained rather than using parameters from the base material, which requires further investigation.

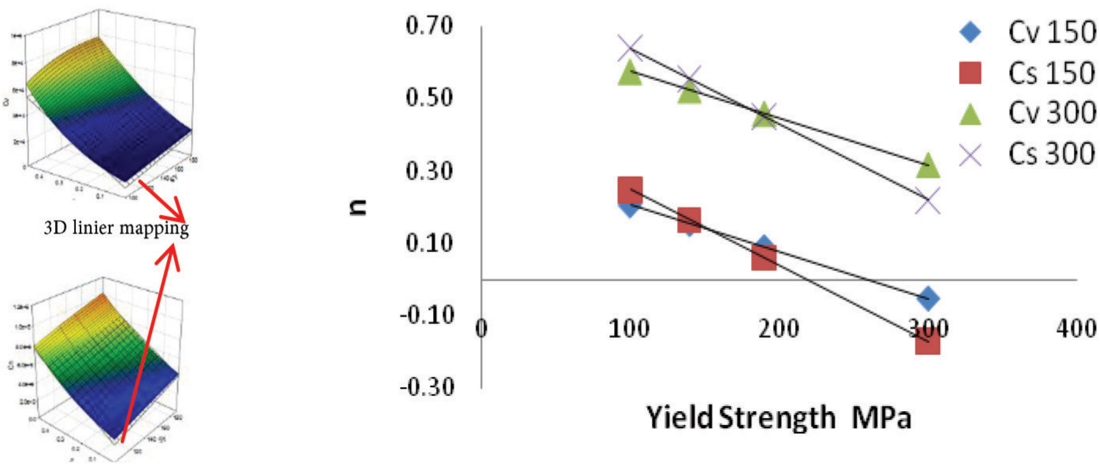
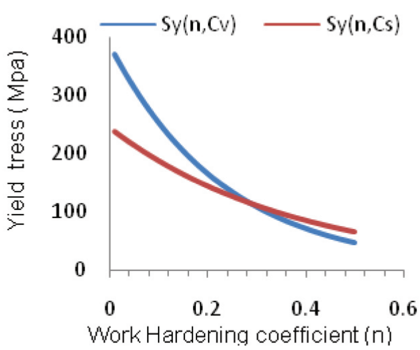


Figure 3: Typical results of inverse FE modelling on Vickers and Spherical indentation by Plotting and mapping data result from Cv and Cs chart to used predicted materials parameter.



Input data				Accuracy study					
				Vickers Indentation + Spherical indentation					
Material properties		Value curvature		Predicted value	Different with input value	Accuracy (error %)	Predicted value	Different with input value	Accuracy (error %)
n	σy	Cv	Cs	n	Δn	Δn/n	σy	Δσy	Δσy/σy
0.10	100	15725.80	303841.60	0.09	0.01	0.10	102	-2.00	-0.020
0.20	100	22631.70	387159.40	0.19	0.01	0.05	105	-5.00	-0.050
0.30	100	32535.10	495483.90	0.29	0.01	0.03	111	-11.00	-0.110
0.10	200	27710.00	526000.00	0.10	0.00	0.00	202	-2.00	-0.010
0.20	200	37670.00	629700.00	0.20	0.00	0.00	195	5.00	0.025
0.30	200	50610.00	754700.00	0.30	0.00	0.00	195	5.00	0.025
0.10	290	37340.00	689200.00	0.12	-0.02	-0.20	285	5.00	0.017
0.20	290	48850.00	803900.00	0.22	-0.02	-0.10	278	12.00	0.041
0.30	290	63490.00	936500.00	0.31	-0.01	-0.03	280	10.00	0.034

Figure 4: Typical materials parameter prediction process (σ_y=100 Mpa, n=0.2) and Accuracy study results based on the intersection between properties line for the Vickers and Spherical indentation.

5. Conclusion

A new inverse modeling using numerical approach constitutive material based on static indentation has been developed and validated. The evaluation based on numerical experimental data showed similar accuracy to the continuous indentation curve approach. The approach developed was successfully used to characterize the plastic properties of different zones in spot welded joints. These plastic material parameters were used in modeling the tensile shear deformation of the spot welded joint and showed good agreement with experimental results. The validated FE models were further used to predict the effect of nugget size and the thickness of the metal sheet on the strength of welded joints.

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