Identification Plastic Properties of Spot Welded Joints Using the Instrumented Indentation Technique

I N Budiarsa¹, I N G Antara¹, I M G Karohika¹, I W Widhiada¹, N L Watiniasih²

¹Mechanical Engineering, Udayana University, Bali. Indonesia
²Faculty of Marine and Fisheries, Udayana University, Bali. Indonesia

nyoman.budiarsa@unud.ac.id

Abstract. The parameters of elastic-plastic material and fracture 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 material properties based on the Indentation 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 numerical finite element (FE) model that simulate the geometry and boundary conditions of the experiment. The numerical approach based on the Finite Element (FE) model has been developed and validated. The established formulation is used for reverse (inverse) prediction of the nature of constitutive material (i.e., yield stress ($\sigma_y$), strain hardening coefficient (n)) for the welded joint zone namely the nugget, HAZ and parent metals (base). Then able to predict the effect of the nugget size and the thickness of the sheet metal on the strength of the spot welded joint with dissimilar material.

1. Introduction
The application of dissimilar metal welding (such as: steel and lighter material) on the vehicle body is an increasing effort to reduce the weight of the vehicle's body as well as increasing protection against corrosion and increasing crashworthiness [1, 2]. In the assembly industry many applications are used using welding with different materials [3]. Most research is carried out on the influence of the thickness and length of the welding point with an emphasis on physical and mechanical properties with variations in welding time [4]. Another problem with diameter size of nuggets [5]. Different weld joints are still being researched and developed intensively, besides because the weld results are interactions between electrical, thermal, metallurgical and mechanical phenomena [6]. Also because of the complex nature of the structure at the joint deformation.

One of the main problems is to characterize material properties. The parameters of elastic-plastic material and material fracture parameters can be easily determined when standard tests are available. However, for spot welded joints, standard testing is not applicable to characterize HAZ and nuggets due to their complex structure and small size. Therefore, requires a non-standard method to be able to predict its characteristics more accurately. The most active research currently being carried out is the prediction of the dimensions and strength of the weld joint with finite element modelling to simulate the welding process [4, 7]. Another active area of research is Instrumented indentation of their complex structures [4]. Previous studies have shown the value of hardness is closely related to the correspondence between representative stress ($\sigma_r$) and representative strain ($\varepsilon_r$) which is the average
value of the plastic strain produced in the indentation process [8-10]. The numerical approach through
the finite element model developed has been successfully used in analysing representative strains and
stresses based on Instrumented indentation with sharp indenter (Vickers) using a fixed indenter angle.
In this case the resulting relationship between the parameters of material properties with force -
indentation depth (ph curve) is finally used to estimate the hardness of material parameters.
Simulations with validated models have been carried out over various ranges of material properties (σy:
100 - 900 MPa, and n: 0.0 - 0.3) the relationship between the yield stress (σy), the strain hardening
coefficient (n), and the known hardness (HV) value. This will lead to the predictive results of their
plastic properties (σy and n) in spot welded joint because of their complex structures, can be predicted
more accurately through Instrumented indentation.

2. Materials and Experimental
Specimens for spot welded with dissimilar materials consisting of two materials with different
thicknesses (stainless steel and mild steel) were used in this study. The material specifications used are
grade 304 stainless steel with a width of 25 mm, thickness of 0.8 mm. Other specimens are Mild steel
with dimensions of width 25 mm and thickness of 1.44 mm. The welding process by applying Spot
welding to the joining of different combinations of materials is prepared and tested. The hardness is
carried out at the welded joints and the parent metal samples are sectioned and mounted prior to
testing with a diameter elliptical φ5 mm and a length of 90 mm. The Vickers hardness test was carried
out using the Duramin-1 Struers Vickers hardness test machine using the direct loading method with
various loads from 19.61 N to 490.3 mN. Indenter has the right pyramidal shape with a square base
and angle 136° to face the opposite side [11].
Welding joints of dissimilar material sheet metals are prepared and tested. Tensile shear test on
welded joint is carried out using the Lloyd LR 30K Universal material testing machine with a
maximum capacity of 30 kN with accurate readings of up to 0.5% of force. Test specimens Tensile
shear is carried out using an initial load of about 50 N, clamped with two gaskets to avoid bending
during testing. Tensile testing was carried out at a loading rate of 5 mm/min based on ASTM E 8-04.

3. Identification of Materials parameters of Spot Welded Zones
The plastic behavior is normally described by the constitutive material equations. In many cases, the
three parameter power law hardening rule (equation 1) is used for steels:

\[ \sigma = \sigma_0 + K\varepsilon \]  

(1)

Where the parameter (σ0) is the yield stress, K is the strength coefficient and ‘n’ is the strain hardening
coefficient. These material parameters influence both the yielding strength and work hardening
behavior of the spot welded joint. The ratio L/Lo is the extension ratio, denoted as λ. Using these
relations, it is easy to develop relations between true (\( \varepsilon_t \)) and engineering (\( \varepsilon_e \)) measures of tensile stress
and strain.

\[ \sigma_t = \sigma_0 (1 + \varepsilon_e) = \sigma_0 \cdot \lambda \]  

(2)

Based on Hooke's law and Von Mises criteria, then the true strain (\( \varepsilon \)) is generally expressed as:

\[ \varepsilon = \begin{cases} 
\sigma/E & \text{for } \sigma \leq \sigma_y \\
\sigma_y/E \left( \frac{\sigma}{\sigma_y} \right)^{1/n} & \text{for } \sigma > \sigma_y 
\end{cases} \]  

(3)

where E is Young's modulus, n is the strain hardening coefficient. In the plastic region strain can be
described as yield strain (\( \sigma_0 \)) and true plastic strain. Due to the complex structure of the welds to find
out the behavior of the nature of the failure and fracture of the weld spot joints more use the Gurson
Model approach. This model is widely applied in ductile fracture mechanics, where material fractures
are thought to be the result of void growth in the volume of material. The Gurson model most
commonly used in failure behavior analysis is the Gurson Tvergaard Needleman (GTN) model [12]
the model approach assumes that the plastic properties are produced from a porous material, where the yield surface is a function of emptiness formulated as follows

\[ \Phi = \frac{3S_{jk}S_{jk}}{2\sigma_{ys}} + 2q_1 f \cosh \left( \frac{3q_2 \sigma_m}{2\sigma_{ys}} \right) - \left( 1 + q_3 f^2 \right) = 0 \]  

(4)

where \( \sigma_y \) is the yield stress of the material, \( \sigma_m \) is the average stress, \( f \) is the volume fraction of voids. \( f=0 \) means that the material is fully dense and conditions Gurson yield reduces von Mises; \( f = 1 \) means that the material is full void and has no stresses.

\( S_{jk} \) is a component of the deviator (\( j,k=1,2,3 \)), is defined as

\[ S_{jk} = \sigma_{jk} - \sigma_m \delta_{jk} \]

and \( \delta_{jk} \) is Kronecher delta

\[ \delta_{jk} = 1 \text{ if } j=k \text{ and } \delta_{jk} = 0 \text{ if } j \neq k. \]

While the parameter values \( q_1, q_2, q_3 \) are material constants, the values most found in most of the literature areas. \( q_1 = 1.5, q_2 = 1, q_3 = 2.25 \).

In Elasto's plastic power law if the representative strain (\( \varepsilon_r \)) is a plastic strain point of reference, the Representative stress strain (\( \varepsilon_r \)), represents the average plastic strain defined by Tabor (1948). Techniques for estimating points on the curve true stress-true strain is developed, in this case representative stress (\( \sigma_r \)) can be expressed as:

\[ \sigma_r = \sigma_y \left( 1 + \frac{E}{\sigma_y} \varepsilon_r \right)^n \]  

(5)

Where \( E= \) Young's modulus indenter, and \( v = \) Poisson ratio. By combining the effects of the elasticity of an elastic indenter and elasto plastic solid can be written:

\[ P = P \left( h, E^*, \sigma_y, n \right) \text{ than } P = P \left( h, E^*, \sigma_y, \sigma_r \right) \]  

(6)

Where

\[ E^* = \left[ \frac{1-v^2}{E} + \frac{1-v_i^2}{E_i} \right]^{-1} \]  

(7)

In this work, the main material group to be investigated is steel, so the \( E \) value is fixed at 200 GPa rather than using true \( E^* \) value (~187 GPa with \( E_{\text{indenter}} = 1220 \) GPa and \( E_{\text{steel}} = 200 \) GPa) to avoid uncertainty in the value of \( E^* \) from different sources. So equation (6) can be simplified as \( P = P(h, E, \sigma_y, n) \) and incorporating equation (5). Applying the \( \Pi \) theorem in dimensional analysis, equation (6) becomes

\[ P = \sigma_t h^2 \prod I \left( \frac{E}{\sigma_t}, n \right) \]  

(8)

Where \( \prod I \) is a dimensionless function. similarly, applying the theorem to equation (7), loading curvature \( C \) may alternatively be expressed as [13].

\[ C = \frac{P}{h^2} = \sigma_y \prod I \left( \frac{E}{\sigma_y}, \frac{\sigma_r}{\sigma_y} \right) \]  

(9)

In equation (6), normalization is required with respect to the yielding stress (\( \sigma_y \)) or the representative plastic stress (\( \sigma_r \)). Through simulation formulated the relationship between \( C_v \) Vs normalized relationship between material properties and normalized properties of materials of \( V_s \) \( C_s \) (strain hardening exponents (\( n \)) and yield stress (\( \sigma_y \))), P-h curves for Vickers and Spherical indentations has the following relationship. Where \( \prod I \) is a dimensionless function, the dimensionless given in equation 9 and the normalization was taken with respect to \( E^* \) instead of \( \sigma_t \) or \( \sigma_r \). Curve fitting has been performed by iterating the relationship between loading curvature indentation and properties material (\( \sigma_y, n \) ) also the relationship between normalized \( C_v \) Vs properties material (strain hardening coefficient (\( n \)) and Yielding stress) as following equations.

\[ C_v = 384.08. e^{3.0617 n} \times 8.22.56 (\sigma_y)^{0.7282} \]  

(10)

Where \( P \) is load and (h) indentation depth at each load curve. \( C_v \) is the Vickers indentation curvature coefficient and the ball indenter designated as \( C_s \) and the Curvature is a function of the relationship
between the yield stress ($\sigma_y$) and strain hardening coefficient (n). This will provide a potential relationship allowing the prediction of material parameters of the test continuous indentation.

4. Prediction Plastic Properties Spot welds

The method for determining the properties of plastic materials through indentation instrumentation was developed with an inverse prediction using FE modeling with input hardness values of materials are known to identify constitutive material properties ($\sigma_y$, n). In the first phase, finite element models that are developed systematically with simulation space boundaries cover a variety of potential material properties. In the next stage, the P-h curve established is used in the spatial boundary simulation. A comparative approach has been developed to predict material sets based on actually indented curvature. Through force input data (F) vs depth (h) related to indentation hardness value. Simulations with validated models that have been carried out on various material properties ($\sigma_y$: 100-900 MPa, and n: 0.0-0.5) then the relationship between the yield stress ($\sigma_y$), strain hardening coefficient (n), hardness value (HV) can be known (figure 1).

![Figure 1. Typical intersection curve $\sigma_y$ (n, HRB) and $\sigma_y$ (n, HV) in the FE Modeling approach for the prediction of parameters constitutive material ($\sigma_y$, n) for the parent metal (base).](image)

![Figure 2. Typical prediction of the plasticity for Nugget, HAZ and the parent metal (base metal) as an application of FE Modeling constitutive parameters in the prediction of material ($\sigma_y$, n).](image)

As shown in figure 2 shows the relationship between modeling results with experimental data. This means that the material laws predicted ($\sigma_y$, n) by the Finite element-based instrumentation of indentation elements for different material weld zones are 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.

5. Conclusion

The method for determining the properties of plastic materials through an inverse prediction approach uses finite elements modelling with known input hardness values to identify constitutive material properties ($\sigma_y$, n). has been developed and validated. The results show a good agreement with the experimental data. This means that the material law ($\sigma_y$, n) predicted by the Finite element-based instrumentation of the indentation for different material weld zones is accurate.

An evaluation of the prediction results based on experimental data shows an accurate similarity with the numerical approach of continuous curve indentation. The developed approach has been successfully used to characterize the plasticity of different zones at spot welding, (nugget; $\sigma_y$ = 780 MPa, n = 0.12, HAZ: $\sigma_y$ = 745 MPa, n = 0.15, Base: $\sigma_y$ = 700 MPa, n = 0.17). These plastic material
parameters used in finite element modelling for tensile shear deformation spot welding and welded joints showed good correlation with experimental results. Validated FE models are then used to predict the effect of nugget size and thickness of the sheet metal on the strength of the weld joint points with different materials (dissimilar material).

References

[1] Litman T 2013 Comprehensive Evaluation of Energy Conservation and Emission Reduction Policies, Transport. Res. A, 47 153-66.
[2] Anaraki A G, et al. 2002 Experimental and numerical analysis of low cycle fatigue of spot welded joints under peel-tension loading, Mech. Computational, 221 786-804.
[3] Irfan D, et al. 2012 Mechanical Evaluation of Joining Methodologies in Multi Material Car Body, Int. J. Adv. Eng. Technol. 5(1) 259-68.
[4] Rahman M M, et al. 2008 An Investigation into the effects of spot diameter and sheets thickness on fatigue life of spot welded structure based on FEA, Res. J. Appl. Sci. 3(1) 10-5.
[5] Aslanlar S 2006 The effect of nucleus size on mechanical properties in electrical resistance spot welding of sheets used in automotive industry, Mater. Des. 27 125-31.
[6] Nachimani C 2013 An Experimental Investigation on Spot Weld Growth on Dissimilar Joints of 304L Austenitic Stainless Steel and Medium Carbon Steel (Part1), Int. J. Adv. Appl. Sci. (IJAAS) 2(1) 25-32.
[7] Hou Z, et al. 2007 Finite element analysis for the mechanical features of RSW process, J. mater. Process. Technol. 185(1-3) 160-5.
[8] Budiarsa I N, Antara I N G, Karohika I M G 2019 Indentation Size Effect of the Vickers Indentation to Improve the Accuracy of Inverse, Materials Properties Modelling Based on Hardness Value, IOP Conf. Series: Earth Environ. Sci. 248 012009.
[9] Budiarsa I N, Ary Subagia I D G, Widhiada I W, Suardana N P G 2015 Characterization of Material Parameters by Reverse Finite Element Modelling Based on Dual Indenters Vickers and Spherical Indentation, Procedia Manufact. 2 124-9.
[10] Bucaillle J L, et al. 2003 Determination of plastic properties of metals by instrumented indentation using instrumented sharp indentation, Acta. Mater. 49 3899-918.
[11] Budiarsa N, Norbury A, Su X X, Bradley G, Ren X J 2013 Analysis of Indentation Size Effect of Vickers Hardness Tests of Steels, Adv. Mater. Res. 652-654 1307-10.
[12] Cricri G, et al. 2013 A consistent use of the Gurson-Tvergaard-Needleman damage model for the R-curve calculation, 7(24) 161-74.
[13] Dao M, Chollacoop N, Van Vliet K J, Venkatesh T A, Suresh S 2001 Computational modelling of the forward and reverse problems in instrumented sharp indentation, Acta. Mater. 49(19) 3899-918.