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Prediction of Tensile and Deep Drawing Behaviour of Aluminium Tailor-Welded Blanks

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1. Introduction

Tailor-welded blanks (TWB) are blanks with sheets of similar or dissimilar thicknesses, materials, coatings welded in a single plane before forming. Applications of TWB include car door inner panel, deck lids, bumper, side frame rails etc. in automotive sector (Kusuda et al., 1997; Pallet & Lark, 2001). Aluminium TWBs are widely used in automotive industries because of their great benefits in reducing weight and manufacturing costs of automotive components leading to decreased vehicle weight, and reduction in fuel consumption. The general benefits of using TWBs in the automotive sector are: (1) weight reduction and hence savings in fuel consumption, (2) distribution of material thickness and properties resulting in part consolidation which results in cost reduction and better quality, stiffness and tolerances, (3) greater flexibility in component design, (4) re-usage of scrap materials to have new stamped products and, (5) improved corrosion resistance and product quality[1]. The forming behaviour of TWBs is affected by weld conditions viz., weld properties, weld orientation, weld location, thickness difference and strength difference between the sheets (Bhagwan, Kridli, & Friedman, 2003; Chan, Chan, & Lee, 2003). The weld region in a TWB causes serious concerns in formability because of material discontinuity and additional inhomogeneous property distribution. Above said TWB parameters affect the forming behaviour in a synergistic manner and hence it is difficult to design the TWB conditions that can deliver a good stamped product with similar formability as that of un-welded blank. Designers will be greatly benefited if an expert system is available that can deliver forming behaviour of TWB for varied weld and blank conditions. Artificial neural network (ANN) modelling technique is found to show better prediction of any response variable that is influenced by large number of input parameters. Artificial Neural Networks are relatively crude electronic models based on the neural structure of the brain. The building blocks of the neural networks is the neuron, which are highly interconnected. In the artificial neural networks, the neurons are arranged in layers: an input layer, an output layer, and several hidden layers. The nodes of the input layer receive information as input patterns, and then transform the information through the links to other connected nodes layer by layer to the output nodes. The transformation behavior of the network depends on the structure of the

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network and the weights of the links. A neural network has to go through two phases: training and application. During the learning, the training of a network is done by exposing the network to a group of input and output pairs. In the recognition phase, after it is trained, the network will recognize an untrained pattern. Application of ANN modelling technique in predicting the formability of TWB will definitely be helpful in understanding and designing the TWB conditions that can deliver a better stamped product.

This chapter describes the tensile and deep drawing forming behaviour of aluminium TWBs and prediction of the same using expert system based on ANN models. Standard tensile testing and square cup deep drawing set up are used to simulate the tensile and deep drawing processes respectively using elastic-plastic finite element (FE) method. The sheet base materials considered for the present work is a formable aluminium alloy. Global TWB tensile behaviour like yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent, strength coefficient, limit strain, failure location, minimum thickness, and strain path, and deep drawing behaviour viz., maximum weld line movement, draw depth, maximum punch force, draw-in profile are simulated for a wide range of thickness and strength combinations, weld properties, orientation, and location. Later, ANN models are developed to predict these tensile and deep drawing behaviour of TWBs. ANN models are developed using data set obtained from simulation trails that can predict the tensile and drawing behaviour of TWB within a chosen range of weld and blank conditions. To optimize the training data and thus the number of FE simulation, techniques from design of experiments (DOE) have been used for systematic analyses. The accuracy of ANN prediction was validated with simulation results for chosen intermediate levels. The results obtained are encouraging with acceptable prediction errors. An 'expert system framework' has been proposed by the authors (Veerababu et al., 2009) for the design of TWBs and the study described in this chapter is part of this framework to predict the formability of aluminium TWBs (Abhishek et al., 2011; Veerababu et al., 2009, 2010).

2. Formability studies on aluminium TWBs

The forming behaviour of aluminium TWBs is critically influenced by thickness and material combinations of the blanks welded; weld conditions like weld orientation, weld location, and weld properties in a synergistic manner. The impact of above said parameters on the tensile and forming behaviour of TWB in general viz., stress-strain curve, forming limit strain, dome height, deep drawability, and weld line movement can be understood from the existing work (Bhagwan et al., 2003; Chan et al., 2003, 2005). The variation of the experimental formability results found in the literature for aluminium TWBs appears to be large (Davies et al., 1999). Aluminium TWBs for automotive applications are particularly problematic because of the low formability of aluminium weld metal. Friction stir welding (FSW) is a process recently applied to aluminium TWBs that has the potential to produce a higher quality weld. Friction stir welding utilizes frictional heating combined with forging pressure to produce high-strength bonds virtually free of defects. Friction stir welding transforms the metals from a solid state into a plastic-like state, and then mechanically stirs the materials together under pressure to form a welded joint. In this process the tool is a dowel which is rotated at speeds depending on the thickness of the material. The pin tip of the dowel is forced into the material under high pressure and the pin continues rotating and moves forward. As the pin rotates, friction heats the surrounding material and rapidly produces a softened plasticized area around the pin. As the pin travels forward, the material behind the pin is forged under pressure from the dowel and consolidates to form a bond. In a study (Miles et al., 2004), three aluminium alloys: 5182-O, 5754-O, and 6022-T4 were considered and TWBs were made using gas tungsten arc welding process. All three of these alloys are being used to fabricate stamped automotive parts. The gas tungsten arc welding process has been used to make aluminium TWBs industrially, so results using this process were compared to FSW results. The results of tensile and formability tests suggest that the 5xxx series alloys had similar tensile ductility and formability regardless of the welding process. However, the 6022-T4 sheets joined using FSW had better formability than those joined using gas tungsten arc welding because FSW caused less softening in the heat-affected zone. Other welding processes like non-vacuum electron beam (NVEB) and Nd:YAG laser techniques have also been studied for welding aluminium TWBs (Shakeri et al., 2002). In that study, a limiting dome height (LDH) test is used to evaluate formability of the AA5754 sheet TWBs with gauge combinations 2 to 1 mm, 1.6 to 1 mm and 2 to 1.6 mm. Different weld orientations were considered and the failures of TWBs were studied. In general the failure occurs in welds and the thinner gauge. Weld orientation has a predominant effect on the formability of the TWBs. In a study (Stasik & Wagoner, 1998), laser welded 6111-T4 and 5754-O blanks were tensile tested, and longitudinal weld TWB's were formability tested using the OSU formability test. In the study, press formability was found to be much greater than the inherent weld ductility. Both materials had satisfactory TWB formability under longitudinal deformation, but 6111-T4 was severely limited under transverse loading, because of a softer heat-affected zone in the heat-treatable alloy. The effects of welds with transverse and longitudinal orientations on the formability of aluminium alloy 5754-O laser welded blanks using the swift cup test has been reported (Cheng et al., 2005). The results showed that longitudinal TWBs underwent considerable reduction in the forming limit when compared with transverse TWBs, and an un-welded blank. Transverse welded blanks exhibit approximately the same forming limit as that of an un-welded blank. However, the effect may change if the weld is placed at critical locations, say, at some offset from the centre-line.

Few research groups have aimed at predicting the formability of aluminium welded blanks by using different necking theories and FE simulations. For example, Jie et al. (2007) studied the forming behaviour of 5754-O Al alloy sheets, where in the forming limit curve (FLC) of welded blanks with thickness ratio of 1:1.3 was experimentally evaluated and predicted using localized necking criterion based on vertex theory. It is found from the analysis that the forming limit of the TWB is more closer to thinner material FLC and the experimental and predicted FLCs correlate well with each other. Davies et al. (2000) investigated the limit strains of aluminium alloy TWB (1:2 mm thickness), where in the FLCs predicted by Marciniak-Kuczynski (M-K) analysis are compared with the experimental results. Here the geometrical heterogeneity, i.e., the initial imperfection level, involved in the welded blank is modelled by using the strain-hardening exponent determined from miniature tensile testing together with the Hosford yield criterion, to determine a level of imperfection that exactly fits an failure limit diagram (FLD) to each experimentally evaluated failure strains. These empirically determined initial imperfection levels were statistically analyzed to determine the probability density functions for the level of imperfection that exists in un-welded and welded blanks. Since the imperfection level is not a single value and follows a statistical distribution, a means of selecting a single value for imperfection is formulated. Two different FLCs – namely, failure FLC and safe FLC – were defined. The first FLC was based upon an imperfection that represents a 50 per cent predicted failure rate and was designated the average or failure FLC. The second FLC was based upon an imperfection level that represents a 0.1 per cent predicted failure rate. This second FLC represents a failure rate of 1 part in 1000 and was defined as the safe FLC. The safe FLCs thus predicted are found to have good agreement with the experimental safe FLCs, except in the bi-axial stretching region. The influence of considering different constitutive behaviour of weld region on the prediction levels and strength imperfections across the weld region in the model are also discussed in the work. Recently, Ganesh & Narasimhan (2008) predicted the forming limit strains of laser welded blanks by using thickness gradient based necking theory incorporated into a FE simulation code PAMSTAMP 2G®. It is found that the predictions are good in drawing region of FLD, with deviation in stretching region.

Studies on deep drawability and other forming behaviour of welded blanks involving both experimental and simulation are available for some aluminium base materials. In a study (Buste et al., 2000) numerical prediction of strain distribution in multi-gauge, aluminium alloy sheet TWBs welded by NVEB and Nd:YAG process is performed by modelling LDH. The study indicates that the Nd:YAG process is superior to the NVEB process considered. Nd:YAG welded blanks generally fail in the thinner parent metal away from the fusion zone. In general, the model agrees with measured strain distributions relatively well, particularly in cases when weld failure dominates as in the NVEB welds. Heo et al. (2001) investigated the characteristics of weld line movement during rectangular cup deep drawing where in draw bead has been used in the thinner blank side to restrict the movement of weld zone. Finite element simulations were also performed and compared with experimental results. An analytical model has been developed by Bravar et al. (2007) and Kinsey & Cao (2003) to predict the weld line movement and dome height for a typical application. This has been compared with numerical simulations and results were quite satisfactory. An interesting work was done by Lee et al. (2009) in predicting the forming limit and load-stroke behaviour of FSW blanks. In this investigation, wide variety of automotive sheet materials including 5083-O aluminium alloys sheets were experimentally tested and their forming limit were predicted using M-K model. The predictions are in good agreement with the experimental FLCs. From the above discussion, it is clear that one has to follow a limit strain theory in conjunction with numerical or analytical methods to predict the forming limit strains of welded blanks for different base material and weld conditions.

Designing TWB for a typical application will be successful only by knowing the appropriate thickness, strength combinations, weld line location and profile, number of welds, weld orientation and weld zone properties. Predicting these TWB parameters in advance will be helpful in determining the formability of TWB part in comparison to that of un-welded base materials. In order to fulfil this requirement, one has to perform lot of simulation trials separately for each of the cases which is time consuming and resource intensive. Automotive sheet forming designers will be greatly benefited if an 'expert system' is available for TWBs that can capture the wealth of knowledge created by the simulations and experiments and deliver the forming behaviour for varied weld and blank conditions. Experts system like "TENSALUM" (Emri & Kovacic, 1997) have shown the significant advantage of using them for computer-assisted testing of aluminium and aluminium alloys according to various standards. The authors are presently working on an research scheme to develop an 'expert system' for welded blanks that can predict their forming behaviour including tensile, deep drawing behaviour under varied base material and weld conditions using different formability tests, material models, and formability criteria. The knowledge base is constructed using learn by analogy engines based on ANNs that can predict the tensile behaviour and other forming characteristics of TWBs for a wide range of thickness, strength combinations and weld properties. The knowledge is acquired using simulations that simulate the tensile or other forming process using computer aided analysis of material behaviour. The expert system framework created the knowledge acquisition and inference methods are described further in the following sections.

3. The expert system framework

Developing artificial intelligent system like expert system, especially in fields like material forming and deformation behaviour, die design, casting design, machining processes, energy engineering, metallurgy, condition monitoring etc. is of interest to manufacturing, design engineers and scientists for long time (Asgari et al., 2008; Cakir & Cavdar, 2006; Dominczuk & Kuczmaszewskim, 2008; Ebersbach & Peng, 2008; Palani et al., 1994; Stein et al., 2003; Yazdipour et al., 2008). There has been a sustained interest in the sheet metal industry to create and use expert systems. Computer aided blanking process planning for aluminium extruded material using an expert system has been reported (Ohashi et al., 2002). The system identifies blanking features and sequences them to prepare the final product from the raw material. Specific to sheet metal forming and deep drawing studies, Manabe et al. (1998) have created an expert system framework for predicting and controlling blank holding force in a drawing process as the friction changes during the process. In summary, one can see the significance of the application of expert system in sheet metal process industry.

An expert system is domain specific system which emphasizes the knowledge used by an expert for solving problems in that domain (Wang et al., 1991). Typical expert system has a knowledge acquisition facility, a knowledge base and an inference subsystem that helps the end user as well as in continuous updating of knowledge base. Expert systems incorporate three basic types of knowledge: factual or data-oriented knowledge, rule-based or judgmental knowledge, and procedural or control knowledge embodied within a model base. An important trend in knowledge bases is the convergence of these three kinds of knowledge within a single system. There are several expert system frameworks reported in literature for application in computer aided engineering and one of the earlier work (Dym, 1985) provides a comprehensive discussion. The present expert system is data driven system with the knowledge acquisition enabled by modelling and simulation and knowledge base using artificial neural networks (Veerababu et al., 2009). The proposed expert system design is shown in Figure 1. This expert system is expected to involve three different phases viz., Phase 1 where in input base materials, TWB conditions and material model selection will be done, Phase 2 where in different forming behaviour can be selected for prediction, and Phase 3 involves use of the results as well as updating of the expert system if the prediction errors with simulation results are not acceptable. All the three phases have a design mode of operation where an initial expert system is created and put in place. The created expert system is then operated in use and update mode.

In Phase 1, while the expert system is designed, a range of material properties and TWB conditions are defined within which ANN models are developed to predict the results as will be discussed in the later sections. The same phase while operated in the usage mode, the user selects base material properties and TWB conditions within the chosen range for application and prediction of formability. In this phase, user can select different material models viz., strain-hardening laws and yield theories to predict the forming behaviour.

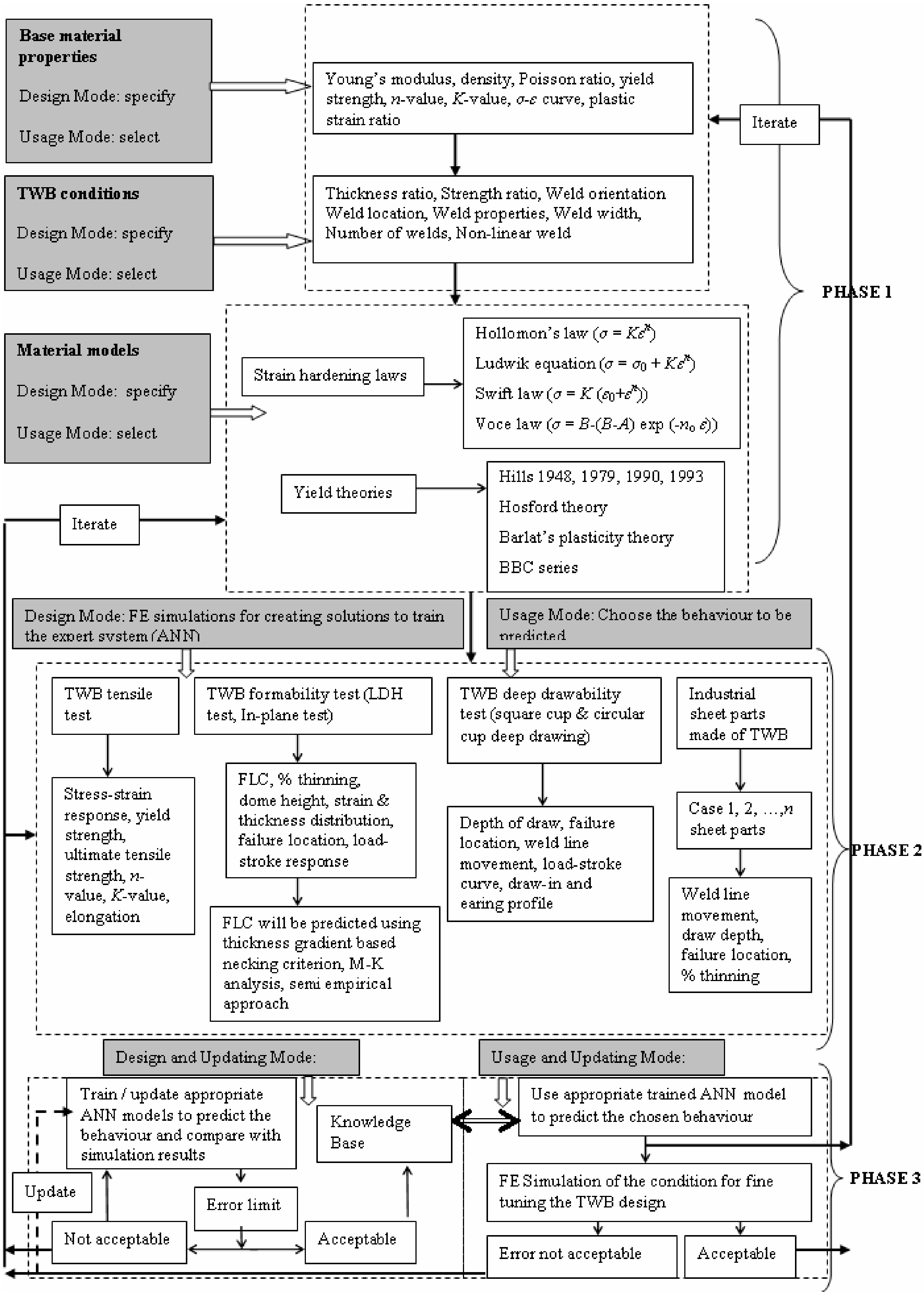


Fig. 1. Expert system framework (Veerababu et al., 2009)

There is no single strain-hardening law and yield theory that can predict the forming behaviour of TWBs made of varied sheet materials accurately. Hence in the design mode, ANN models will be developed to predict the forming behaviour using different material models. As a result, in the usage mode of the expert system, the user can opt for desired material models to predict the forming characteristics. The Phase 2 involves selecting the forming behaviour to be predicted for chosen base material and weld conditions. In the design mode, tensile behaviour, formability characteristics, deep drawability of welded blanks will be simulated by standard formability tests. Different category of industrial sheet parts will be simulated and expert system will be developed to predict their forming behaviour. For example, the global tensile behaviour of TWB viz., stress–strain curve, yield strength, ultimate tensile strength, elongation, strain-hardening exponent and strength coefficient will be monitored. Formability properties like forming limit curve, thinning percentage, maximum thinning, dome height at failure, failure location will be predicted by LDH test and in-plane stretching tests using different limit strain theories (say M–K analysis, thickness gradient based necking criterion, semi empirical approach). Cup deep drawing response like draw depth, weld line movement, drawing force, failure location, earring and draw-in profile can be predicted. Also it is planned to develop ANN model and expert system for predicting the formability of application specific sheet parts made of welded blanks. In the usage mode, the user selects the type of test results he is interested in predicting. In Phase 3 the training, testing, usage and updating the ANN predictions with simulation results will be performed. In the design mode operation, various ANNs are created and validated for predicting the forming behaviour (enumerated in Phase 2) for various combination of material properties and TWB conditions and constitutive behaviour (enumerated in Phase 1). In the usage mode, the user uses to predict the required forming behaviour for an initially chosen material, TWB condition and constitutive behaviour. If the forming behaviour predicted is not indicative of a good stamped product, the user changes the above said conditions till he gets satisfactory results.
In the absence of this expert system, the user will have to run time consuming and resource intensive simulation for this iterative stage. In the usage mode, if the results are not with in the expected error limit, user will have the choice of selecting different material models for predicting the required forming behaviour as described earlier and/or the expert system is updated with the specific case by updating the ANN models to predict the case within acceptable error limits. In this way, the expert system also learns form the application cases, enhancing the range, success rate of predictions. The three main functions of the expert system viz., knowledge base and its acquisition and inference are done in all the three phases as can be inferred from the design and usage mode of operation. The methods devised for these three functions for predicting formability of aluminium TWBs are discussed in the forthcoming section.

4. Simulation of formability behaviour of aluminium TWBs

The study presented here comprises of tensile and deep drawing behaviour of aluminium TWBs. The methodology followed for the study is described in Fig. 2. The first part of methodology involves FE simulation design and deals with the design of experiments to generate required data for expert system development.In order to conduct the exercise with optimum simulations, DOE using the Taguchi's statistical design (Taguchi, 1990) is followed. Simulation models for predicting the tensile as well as deep drawing behaviour of

TWBs are constructed as per the DOE parameter tables. The second part of the methodology is the ANN modelling and validation. The post processed results of FE simulations are used to train the ANN. Finally the ANN models for the expert system is validated with simulation results for chosen intermediate levels and other test data available. The methodology is discussed in the following subsections.

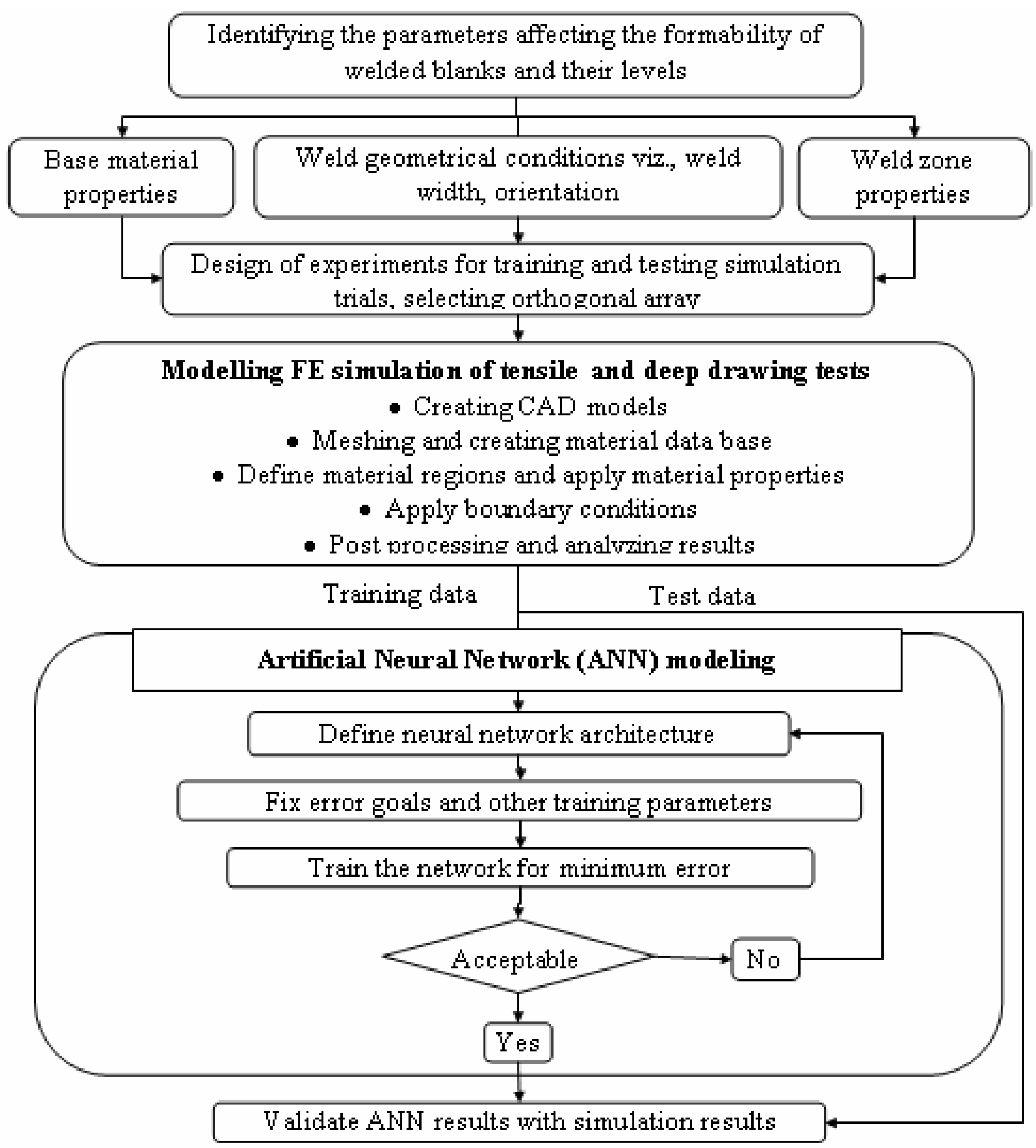


Fig. 2. Methodology of TWB simulation and developing expert system

4.1 Base material properties and TWB parameters

Initially for conducting simulation trials the material and process parameters that affect the TWB tensile and deep drawing behaviour are identified from available literature. The mechanical and forming properties of aluminium base metal and weld region used in FE simulations are shown in Table 1. The plastic strain ratios of weld zone are assumed to be 'one' in all the rolling directions as it is assumed isotropic. In order to generate the required data for expert system with optimum simulations, the Taguchi's statistical design is followed.

In this work, L_{27} orthogonal array with linear graph indicating the allocation of individual factors in orthogonal array is followed. Here L_{27} orthogonal array corresponds to three levels with six factors. However, this design fundamentally does not account for all the interaction among the processing parameters. In view of cost saving and time restriction higher order interactions are neglected. The six factors considered at three levels are shown in Table 2 for the tensile testing and deep drawing simulation of aluminium alloy TWBs. The five common TWB parameters considered for the analysis are thickness ratio, yield strength ratio, weld orientation, weld yield strength and weld width. For tensile testing weld '*n*' value and for deep drawing simulation weld location are considered as the sixth parameter. The schematic representation of these parameters for tensile testing and deep drawing are depicted in Fig. 3a & b. Each parameter has three levels (1, 2 and 3). The levels of parameters are chosen in such a way that the range covers practically all the combinations in typical experiments and industrial parts (Raymond et al., 2004; Saunders & Wagoner, 1996; Stasik & Wagoner 1998). In case of tensile test simulation the weld orientations that are significant i.e. longitudinal, transverse and 45° weld orientation are considered. In case of deep drawing simulation since both 0° and 90° orientations will be similar, an orientation of 60° was chosen as the third level. The weld zone yield strength was chosen such that it is higher or lower when compared to that of base materials as seen in most of the steel and aluminium alloy TWBs (Ganesh & Narasimhan, 2008; Miles et al., 2004; Stasik & Wagoner, 1998). Generally weld zone exhibits lesser ductility when compared to that of base materials (Ganesh & Narasimhan, 2008; Stasik & Wagoner, 1998) and hence strain-hardening exponent (*n*) of weld zone was selected such that it is lower than that of base materials. The average thickness of thinner and thicker sheets is assumed as weld zone thickness in simulation trials.

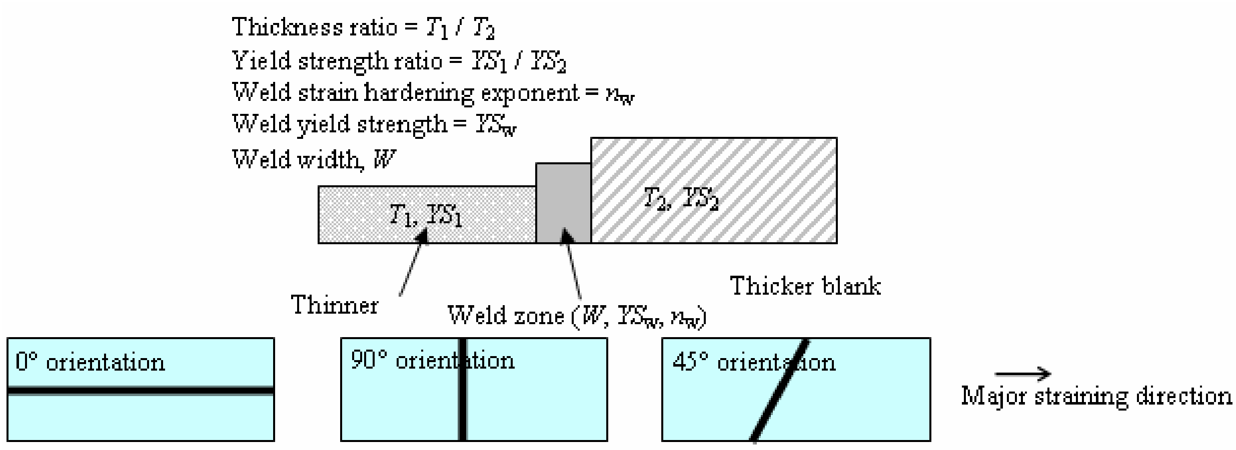
Since L_{27} orthogonal array is followed, 27 simulations are performed to generate data for ANN modelling. In case of tensile testing simulation, the tensile behaviour, viz., yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent (*n*), strength coefficient (*K*), limit strain, failure location, minimum thickness, and strain path are predicted for each test simulation. The important deep drawing behaviour predicted are maximum weld line movement, draw depth, maximum punch force, and draw-in profile for varied TWB conditions. These parameters are sensitive to the input conditions and are suitable representatives of the deep drawing behaviour of welded blanks (Ganesh & Narasimhan, 2006), specifically weld line movement and draw-in profile has industrial importance too.

Material properties	**Aluminium alloy sheet**	
	Base metal	**Weld zone**
Young's modulus (*E*), GPa	77	77
Density (ρ), kg/m^3	2700	2700
Poisson's ratio (ν)	0.3	0.3
r_0	0.7	1
r_{45}	0.6	1
r_{90}	0.8	1
Strain-hardening exponent (*n*)	0.172	See Table 2

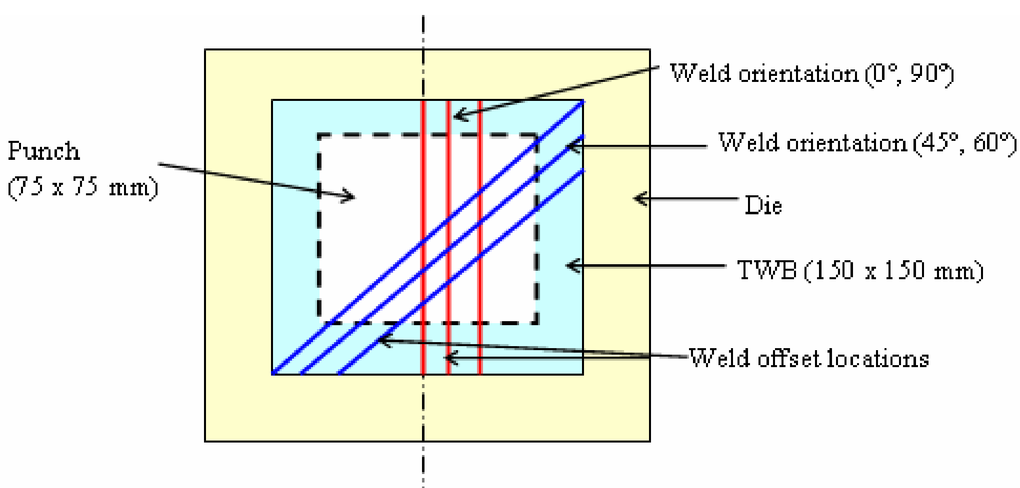
Table 1. Material properties of aluminium alloy base material

Parameters	**Level 1**	**Level 2**	**Level 3**
Thickness ratio (T_1/T_2), mm/mm	0.5 (0.75/1.5)	0.75 (1.125/1.5)	1 (1.5/1.5)
Strength ratio (YS_1/YS_2), MPa/MPa	0.5 (190/380)	0.75 (285/380)	1 380/380)
Weld yield strength, (YS_w), MPa	150	300	400
Weld width (W), mm	2	5	10
Tensile testing			
Weld orientation (°)	0	45	90
Weld 'n' value (n_w)	0.1	0.13	0.15
Deep drawing			
Weld orientation (°)	0	45	60
Weld location, mm	0	10	20

Table 2. TWB parameters for aluminium alloy TWB and their levels



a) TWB parameters for tensile testing



b) TWB parameters for deep drawing

Fig. 3. Schematic representation of control factors in tensile and deep drawing simulation

4.2 Modelling simulation of tensile test without pre-existing notch

Two sets of simulations were done to analyse the tensile behaviour. The first set of simulations consisted of observing the engineering stress-strain behaviour of TWB by monitoring the effective strain evolution at safe region of tensile sample for every small progression and later used to evaluate the tensile behaviours like yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent (n) and strength coefficient (K). The second set of simulations involved a notched specimen and observing the limit strains by allowing the failure to occur. For the first set of simulations CAD models of tensile specimen were generated as per the ASTM E 646-98 specifications (ASTM, 2000) (Fig. 4.) in Pro-E® a solid modelling software and imported into PAM STAMP 2G® an elastic plastic FE code for pre-processing, performing simulations and post processing. These CAD models were meshed using 'Deltamesh' facility in PAM STAMP 2G®. The meshing was done with quadrilateral shell elements of the Belytschko–Tsay formulation, with five through-thickness integration points. The meshed blank thus obtained was divided into three different regions viz., weld region (without HAZ), base material 1 and base material 2 (Ganesh & Narasimhan, 2006, 2007) to construct meshed models of TWB for varied weld orientations. A constant mesh size of 1 mm was kept in the weld region and base metal (Fig. 5.) as this has been reported to validly predict the forming limit of TWBs acceptably in Ganesh & Narasimhan (2008). The material properties were assigned to weld zone and base metals according to the different parameter levels (Tables 1 and 2) in the orthogonal array. Displacement boundary conditions (Fig. 6.) are applied to the tensile sample such that one end of the specimen is fixed and the other end is given some finite displacement with a velocity of 0.5 mm/min.

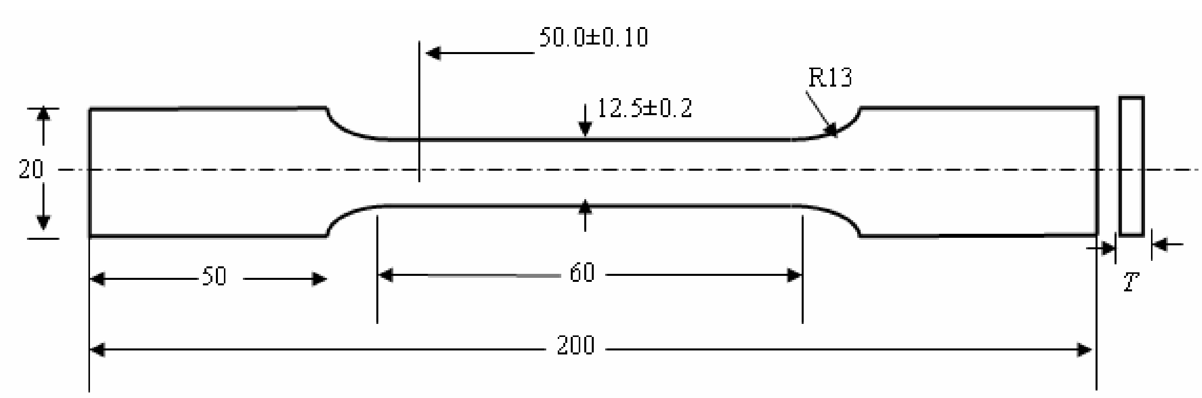


Fig. 4. ASTM E 646-98 standard tensile testing specimen, all dimensions in mm

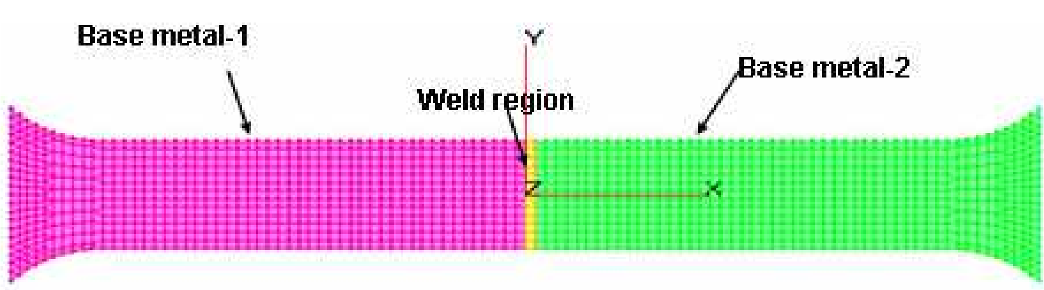


Fig. 5. Meshed model of TWB for tensile test simulations in PAM STAMP 2G®

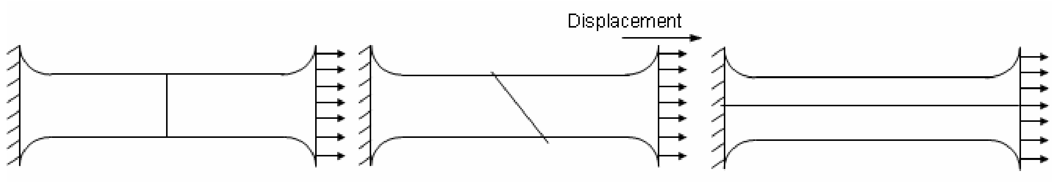
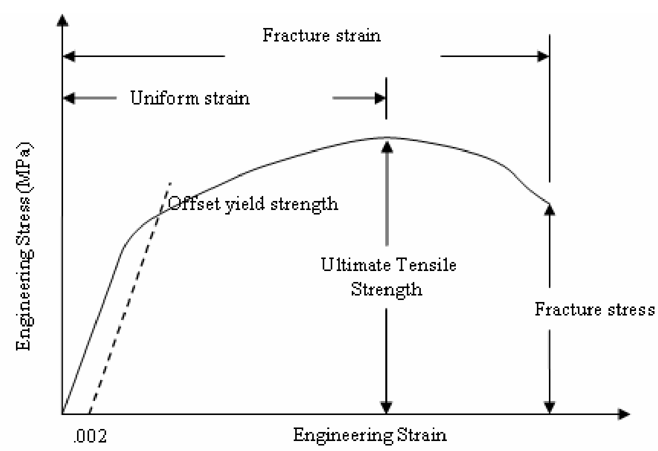


Fig. 6. TWB sample with different weld orientations and boundary conditions

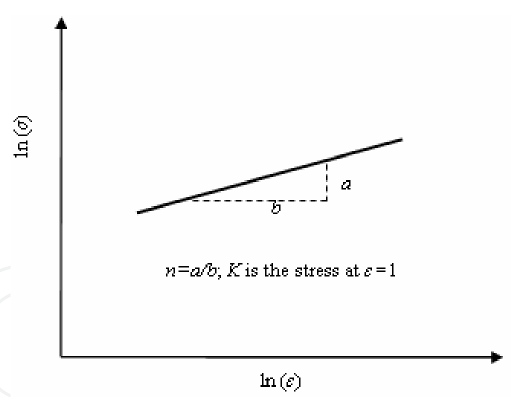
For this set of simulations, Hollomon's power law ($\sigma = K\,\varepsilon^n$; where, K – strength coefficient and n – strain-hardening exponent) was used to describe the strain-hardening behaviour of base material and weld region. Hill's 1948 isotropic hardening yield criterion (Banabic, 2000) was used as the plasticity model for the aluminium alloy base material. This quadratic yield criterion has the form,

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L(\sigma_{23})^2+M(\sigma_{31})^2+N(\sigma_{12})^2=1 \quad (1)$$

where F, G, H, L, M, N are constants defining the degree of anisotropy and σ_{ij} are the normal and shear stresses. The tensile response i.e., stress-strain curve of TWB was obtained by monitoring effective stress and corresponding strain values in safe regions of TWB tensile sample for each unit of progression. From this engineering stress-strain data and required global mechanical properties of TWBs viz., yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent (n) and strength coefficient (K) were evaluated. The methodology for evaluating these properties is schematically described in Fig. 7 a-b. Similar procedure was followed for all the 27 tensile simulation of first set.



(a)



(b)

Fig. 7. a) Evaluating tensile properties from stress-strain curve, b) evaluating n, K values from true stress, strain data for TWBs

The results of the tensile test simulation of aluminium TWBs within the safe progression are discussed. Three modes of failure are generally seen in TWBs. They are, (i) Failure occurs perpendicular to weld region in the case of TWB with longitudinal weld, (ii) Failure occurs in the thinner or weaker base material in the case of TWB with transverse, stronger weld (YS_{weld}>$YS_{basematerials}$), (iii) Failure occurs in the weld region in the case of TWB with transverse, weaker weld (YS_{weld} < $YS_{basematerials}$). In TWB with longitudinal weld, higher load requirements are seen in the case of stronger weld zone when compared to weaker or softer weld zone. This can be understood from load sharing principle between the weld zone and base materials. In the case of transverse weld, TWB with stronger weld zone exhibits better tensile behaviour than TWB with softer weld zone. This is mainly because of the gauge effect, and TWB tensile behaviour is found to deteriorate with increase in thickness or strength ratio. Fig. 8. shows the failure location of TWB tensile sample for varied weld orientations. It is observed that (i) TWB with longitudinal weld witness failure normal to the weld region (Fig. 8a), (ii) Failure occurs only in the base material (Fig. 8b- c) in transverse and 45° weld zone because of stronger weld zone (YS_{weld}>$YS_{basematerials}$), and (iii) Weld failure is seen in the case of softer weld zone (Fig. 8d; YS_{weld} < $YS_{basematerials}$). This is consistent with results obtained in many literature including Ganesh & Narasimhan (2006). Fig. 9. depicts the engineering stress-strain data generated by simulations for varied TWB conditions for TWB with aluminium alloy base material. In this, curve numbers 1, 2,….27 represent stress-strain curves corresponding to 27 simulation trials in the orthogonal array. The TWB tensile behaviour viz., yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent, strength coefficient were evaluated from these curves. It is seen from Fig. 9. that (i) Longitudinal weld with stronger weld zone (curve 7) exhibit higher load requirements when compared to TWB with softer weld zone (curves 4, 1) for same strain values, (ii) Transverse weld with stronger weld zone exhibit base metal failure and hence shows better stress-strain behaviour (curves 3, 9, 13, 23, 26) when compared to the case with softer weld (weld failure is witnessed in this case; curves 6, 10, 16, 20), and (iii) In the case of transverse weld, with increase in thickness and strength ratio, the tensile behaviour is found to deteriorate.

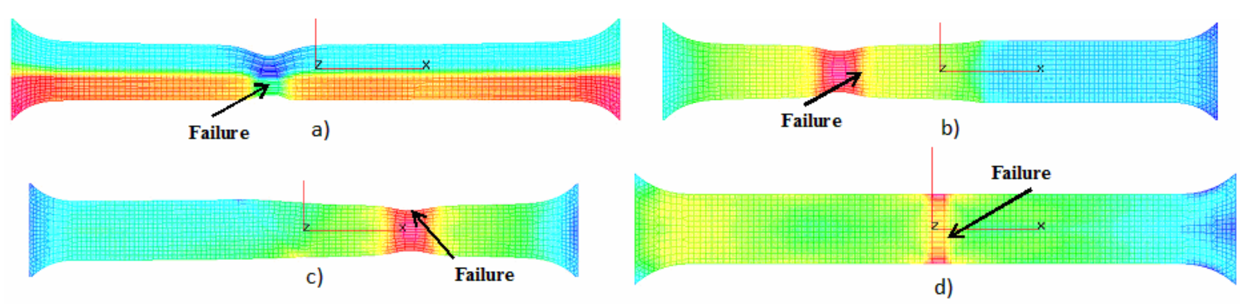


Fig. 8. a) Failure normal to weld region in TWB with longitudinal weld, b) base metal failure of TWB with transverse, stronger weld, c) base metal failure of TWB with 45°, stronger weld, d) Weld region failure of TWB with transverse, weaker weld

4.3 Modelling simulation of tensile test with pre-existing notch

The second set of tensile simulations were done with CAD models of tensile specimen as per geometry shown in Fig. 10. (Holmberg et al., 2004) in Pro-E® and imported into ABAQUS 6.7® for pre-processing, performing simulations and post processing. Since the aim of this set of simulations was to induce failure in the TWBs during simulation, a geometrical notch of 10 mm width is provided. The limit strains are predicted by thickness gradient based necking criterion. This notch geometry is decided based on trial simulations such that the entire deformation is concentrated only in that region and finally necking occurs, without much deformation happening in the shoulder region. For this, varied notch widths 14 mm, 10 mm, and 8 mm were simulated and compared with each other. Finally the notch of 10mm width is selected, wherein the effect of different TWB factors is not suppressed because of the notch effect and lesser deformation is observed in the shoulder region during simulations. The meshing, material assignment and boundary conditions are similar to the first set of simulations.

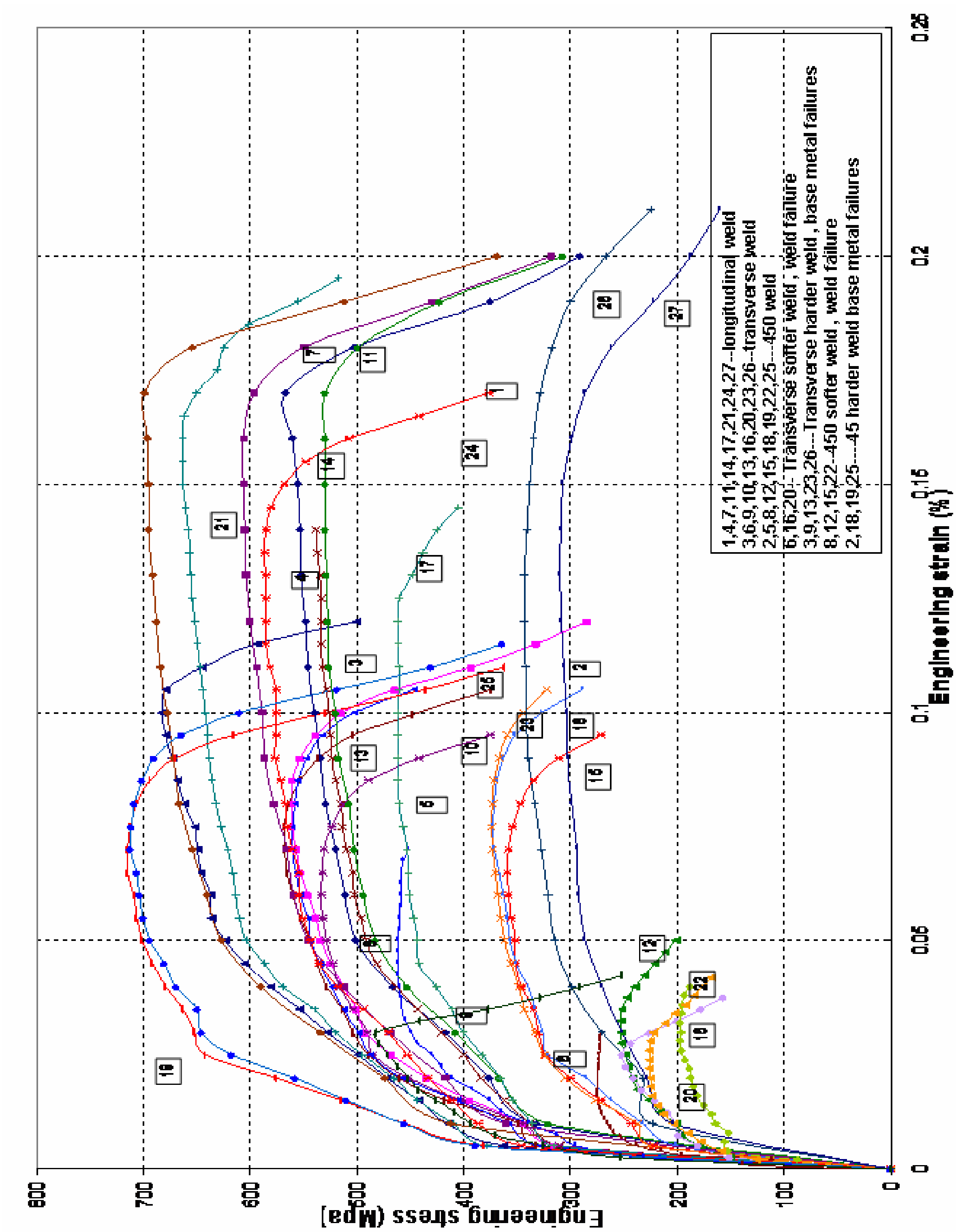


Fig. 9. Stress-strain behaviour of aluminium TWB (27 simulation data) (Veerababu et al., 2009)

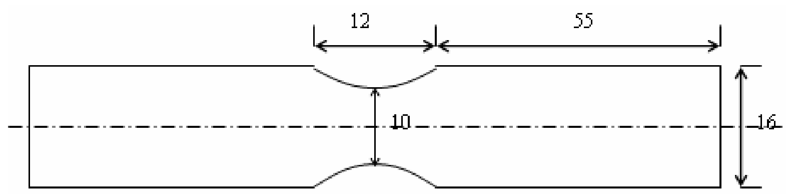


Fig. 10. Schematic of representation of notched tensile sample modelled in ABAQUS 6.7®, all dimensions in mm

For the second set of simulations, Swift law ($\sigma = K(\varepsilon_0 + \varepsilon_p)^n$, K – strength coefficient, n – strain-hardening exponent, ε_0 – pre-strain value of 0.003) is used as strain-hardening law describing the stress-strain relationship of weld and base material with Hill's 1948 isotropic hardening yield criterion. After simulations, five output parameters as described below are predicted for the TWBs.

Limit strain (major and minor strain): as per thickness gradient criterion, necking occurs when the thickness ratio between thinner and thicker element reaches 0.92 (Kumar et al., 1994). The major strain and minor strain of the thicker element, when the criterion is satisfied, is quantified as limit strain of that TWB condition. The thinner element has already failed and hence can not be referred for limit strain prediction. This means that the strain in the thinner element is above actual limit strain value. So the thicker element which is closer to thinner element is referred for the prediction work. This procedure is followed for all the 27 tensile simulations trials of this set. The limit strains are found to be in negative minor strain region of FLD (Fig. 11.), because of the presence of notch and tensile, plane-strain strain paths. Failure location is the distance from the fixed end to the thicker element in the progression where necking has occurred or criterion is satisfied. Minimum thickness is the minimum thickness of the element of specimen in the progression where necking has occurred. Strain path is the plot between major and minor strain from the starting progression to the progression where necking has occurred. This is quantified by the slope of the strain path curve (Fig. 11.).

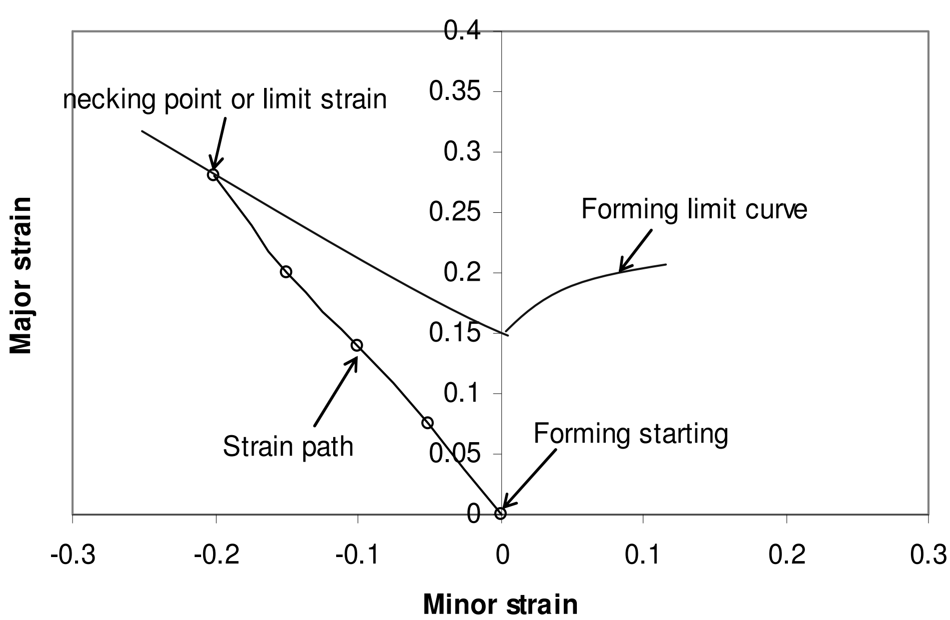


Fig. 11. Schematic representation of strain path with forming limit curve

The results of simulation showing the limit strain data for the 27 simulations are shown in Fig. 12. Though tensile test is simulated, most of the limit strains are close to plane-strain strain path (i.e., major strain axis) and not in tensile strain path. This is mainly because of the notch present in the tensile sample that is used for simulation for failure occurrence. Another important observation is that the strain path slope varies from 200.33 to 1.938. The lower slope values correspond to limit strain values that are away from plane-strain condition. The maximum limit strain is characterized by thickness ratio and strength ratio equal and occurs for a value of 1 and for longitudinal weld orientation. The failure location values for different experiments are shown in Fig. 13. The failure is expected to occur within the notch region, either in the base material or in the weld region depending on the weld width. It is clear from Fig. 13. that in almost all cases failure has occurred within the span, except in few cases wherein failure is seen just outside the notch region. The failure location is found to show significant effect on the minimum thickness achieved during TWB forming. Fig. 14. shows the variation of minimum thickness achieved for different experiments. The minimum thickness of 0.17 mm occurs in experiment 5, for which the failure location is at 65.93 mm, which is close to the notch edge AA in Fig. 13. (see inset).

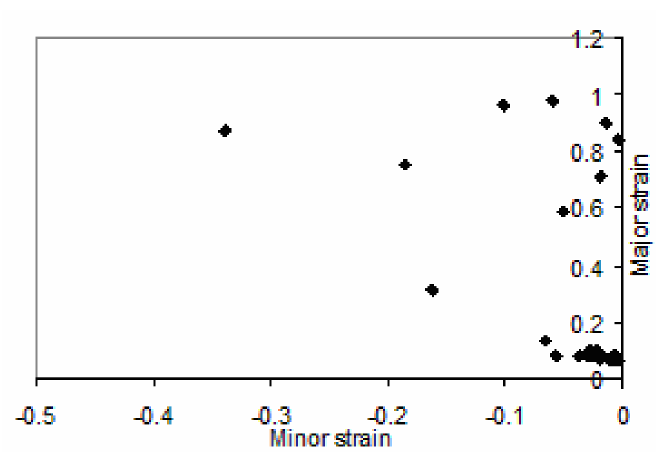


Fig. 12. Limit strain values for different TWB conditions (Abhishek et al., 2011)

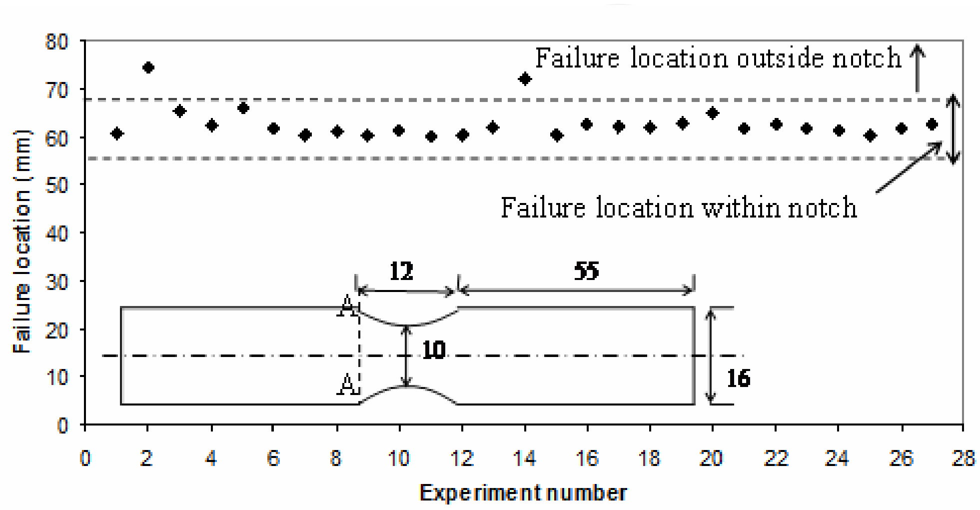


Fig. 13. Failure location in aluminium TWB (Abhishek et al., 2011)

4.4 Modelling simulation of deep drawing test for welded blanks

For the simulation of deep drawing a square cup deep drawing simulation set up constructed as per the NUMISHEET '93 benchmark specifications (Makinouchi et al., 1993) is used (Fig. 15.). CAD models of the tools (like die, punch, blank holder) in deep drawing are generated in Pro-E® and imported into PAM-STAMP 2G® for pre-processing, performing simulations and post processing. The meshing and material assignment are followed as discussed for the tensile simulations. Two shims are used to compensate the thickness difference in TWB, and these shims are exactly positioned above and below the thinner sheet. The shims are compressible with properties same as the stronger base metal. The friction coefficient between contact surfaces is taken as 0.12 as this approximates all forming conditions. The blank holding force is optimized during simulation to avoid wrinkling and extra thinning. Downward stroke is given to the punch with a velocity of 0.5 mm/min. The solution is mapped in such a way that the punch force is monitored for each unit of progression of the punch.

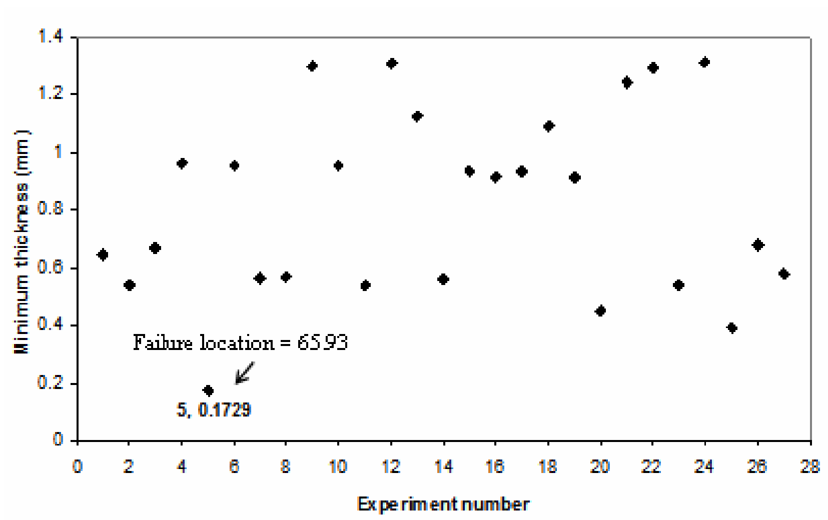


Fig. 14. Minimum thickness achieved for different simulation trials (Abhishek et al., 2011)

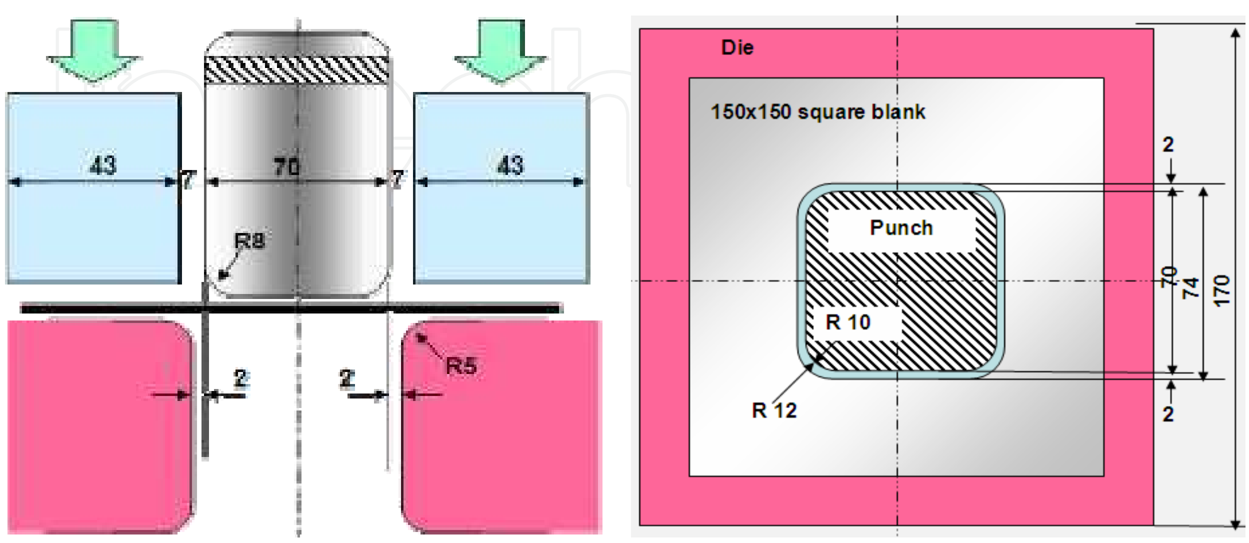


Fig. 15. Square cup deep drawing set up used for simulations (Makinouchi et al., 1993)

Hollomon's power law is used to describe the strain-hardening behaviour of base material and weld region, and Hill's 1948 isotropic hardening yield criterion is used as the plasticity model as before. The output deep drawing parameters monitored are maximum punch force, maximum weld line movement, draw depth and draw-in profile. The maximum punch force was obtained from force-progression data during deep drawing simulation. Draw depth was obtained after cup failure is witnessed. Fig. 16. shows that the draw-in profile of deep drawn TWB cup and was quantified by the dimensions DX, DY and DD. The draw-in profile is important and can be related to anisotropic sheet properties and earing behaviour of sheet metal. In order to include the impact of weld and base material conditions only, plastic strain ratios of base metal was kept constant throughout the work. Maximum weld line movement as observed is also represented in Fig. 16. This weld line movement is of practical importance as weld region should ideally be located in the safe region of the drawn cup. Similar procedure was followed for all the 27 deep drawing simulation trials for TWBs.

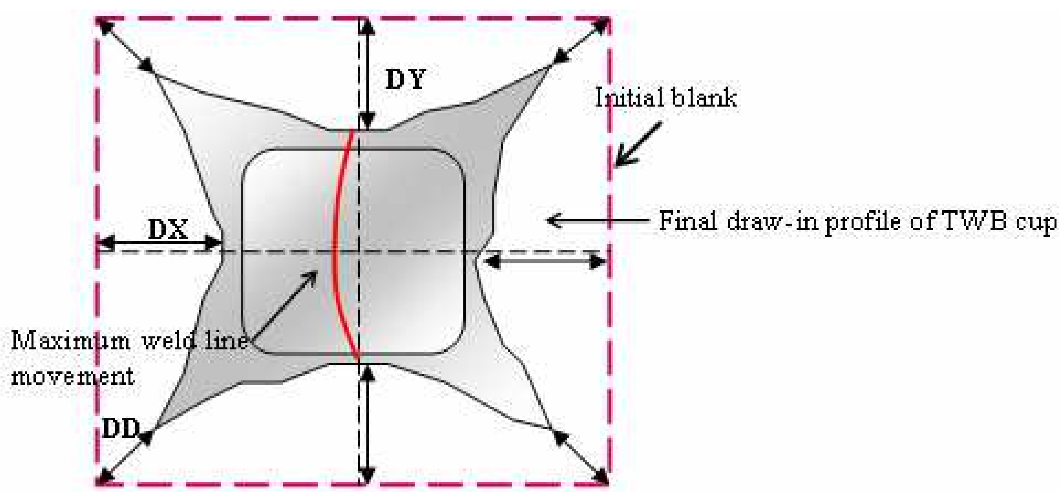


Fig. 16. Weld line movement and draw-in profile during deep drawing of TWB

The simulation of deep drawing test of aluminium TWBs show that with increase in initial weld line position, weld line movement is found to increase. The results are consistent with the results obtained from Heo et al. (2001). Fig. 17. presents the failure location during the deep drawing of square cup TWB. It is seen that necking always occurs in the thinner or weaker base material parallel to the weld region. This is consistent with the experimental and simulation results shown in Ahmetoglu et al. (1995). It is interesting to note that unlike un-welded blanks (or homogeneous blanks), draw-in profile of welded blanks are un-symmetrical as shown in Fig. 18a. This is because of thickness, strength differences in base materials that are welded and weld line movement during deep drawing. Because of these heterogeneities, different regions of the cup undergo different levels of plastic deformation resulting in un-symmetric draw-in profile. Hence it is also expected that earing behaviour during deep drawing will also be un-symmetrical in nature. It is also interesting to note that a stronger weld region at some angle and thicker (or stronger) base material introduce more resistance to drawing and hence minimum draw-in is seen in these regions of the drawn cup, while thinner (or weaker) base material show maximum draw-in as presented in Fig. 18b.

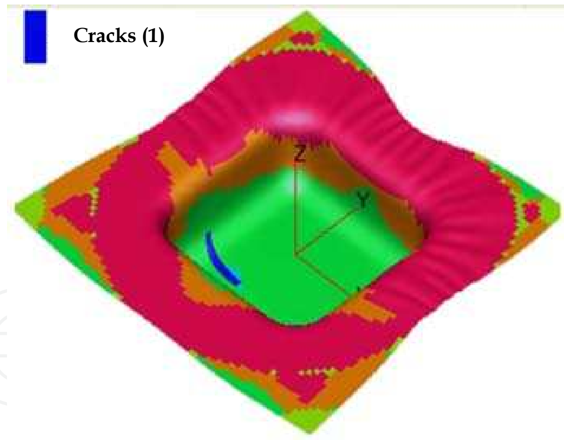
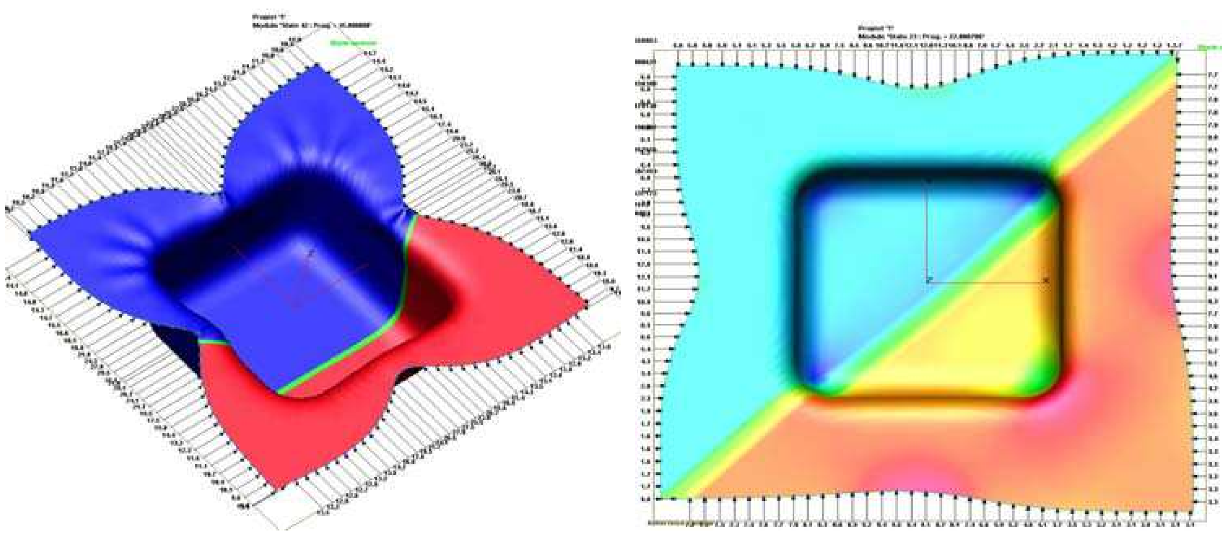


Fig. 17. Failure location seen in thinner sheet near weld line during deep drawing



a) b)

Fig. 18. Simulation of deep drawn cup showing un-symmetric draw-in for different weld orientations; (a) 90° weld region, (b) Angular weld region

5. TWB formability prediction using ANNs

The set of tensile and deep drawing characteristics of TWB from the simulation trials are used for ANN modelling and expert system development. The ANN is trained to learn arbitrary nonlinear relationships between input and output parameters of TWB. The ANNs are inspired by biological neurons and have shown credible results in learning the arbitrary and complex relationships between the inputs that govern the outputs of an system. ANN consists of several layers of highly interconnected neurons which are the basic computing. The various architectural parameters of an ANN are number of hidden layers, neurons, and transfer functions which are optimized based on many trials to predict the outputs within certain errors that can be tolerated in an given application. In the present study a normalized error limit of 10^{-4} is taken. Using the simulation data obtained ANN with various network structures with one and two hidden layers with varying number of neurons in each layer and different transfer functions were examined. Optimized ANN architecture are found to model the tensile behaviour from the two sets of tensile simulation as well as the deep drawing behaviour. In all these cases, the ANN architecture consists of input layer with 6 input neurons (corresponding to 6 factors), and one / two hidden layers and output neurons corresponding to the number of outputs to be predicted. A feed forward back propagation algorithm is selected to train the network in Matlab® programming environment (Mathworks Inc., 2008). Here the scaled conjugate gradient algorithm (Mathworks Inc., 2008) is used to minimize the error. For each of the simulation trials based on the L_{27} orthogonal design of experiments, 27 data sets were used to train and two intermediate data sets were utilized for testing. The TWB tensile behaviour or deep drawing behaviour from FE simulations and ANN modelling for chosen two intermediate test sets or trials are compared to validate the accuracy of ANN predictions in each case. As an example, the ANN architecture used to predict the tensile behaviour without pre-existing defect based on the first set of tensile simulation data is shown in Fig. 19. Similar ANNs were trained for the other tensile simulation test for limit strain prediction as well as deep drawing simulation. The salient observations on the prediction of TWB tensile and deep drawing behaviour are described further.

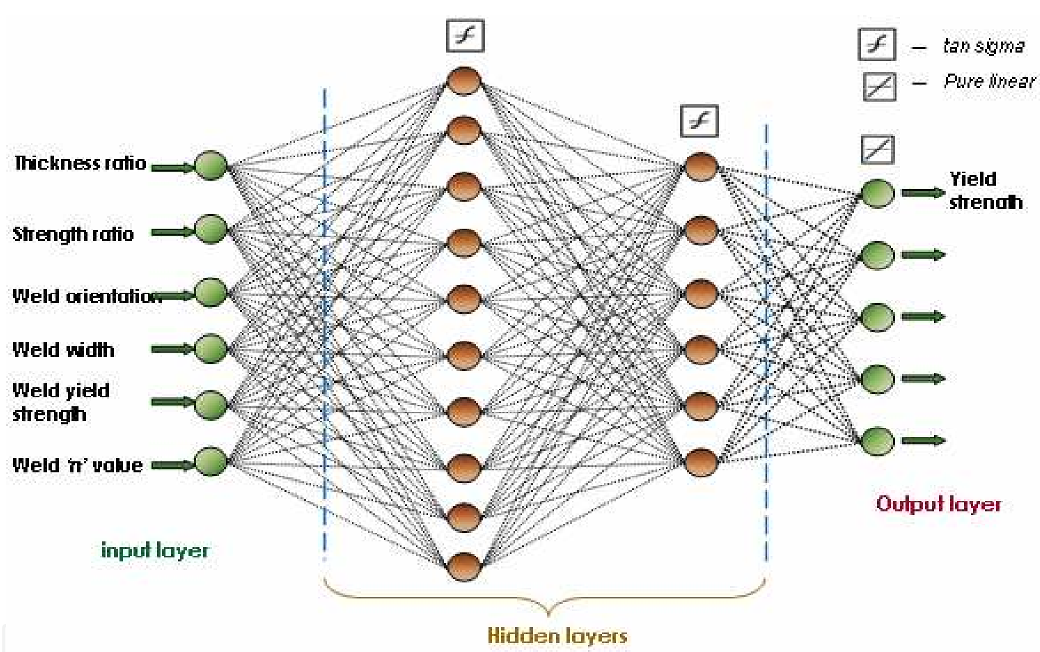


Fig. 19. Neural network architecture for TWB tensile behaviour prediction in safe region

The first set of 27 tensile simulation data (for the safe region of progression) was used to train an ANN and true stress-strain response, yield strength, ultimate tensile strength, uniform elongation, strain-hardening exponent and strength coefficient of welded blanks were predicted and validated with FE simulation results for two intermediate input levels. The comparison between ANN predicted true stress-strain behaviour and simulation results are shown in Fig. 20. The strain-hardening exponent (n) and strength coefficient (K) values obtained from ANN models were incorporated into Hollomon's equation ($\sigma = K\,\varepsilon^n$) for TWB made aluminium alloy base materials and true stress-strain curves were obtained. It should be noted that even though Hollomon's strain-hardening law is not accurate to predict the tensile behaviour of aluminium alloy base material, ANN predictions are quite accurate in predicting the same.

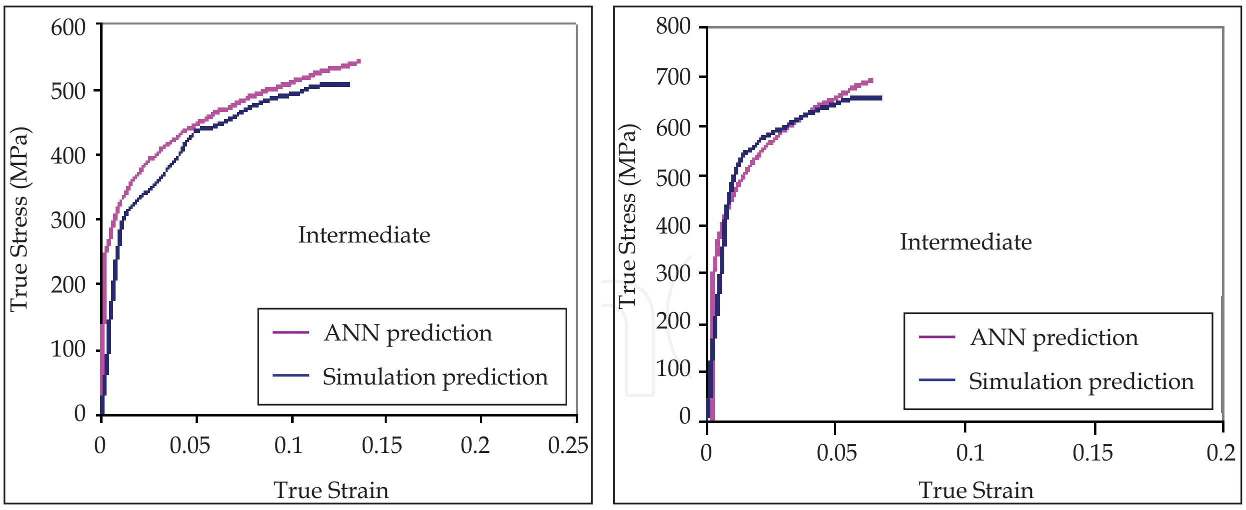


Fig. 20. Validating the true stress - strain behaviour predicted by ANN with FE simulation for two test data (Veerababu et al., 2009)

The TWB tensile properties from FE simulations and ANN modelling for chosen two intermediate trials were compared to validate the accuracy of ANN prediction. Table 3 summarizes the average error statistics pertaining to ANN prediction for training and testing with two intermediate test data not used for training. In the industrial application error range of 10-12% is considered acceptable and the same has been taken as a bench mark. It can be seen that almost all the output parameters are predicted within acceptable error limits. It is seen that only strain-hardening exponent (*n*) value of aluminium alloy TWB shows unacceptable error percentage (14.35%). This is possibly due to the smaller values of strain-hardening exponent which gives large percentage difference even if varied within small range (Veerababu et al., 2009). Similarly, the second set of tensile simulation with notched sample was used to train an ANN in a similar way. The limit strain (major and minor strain), failure location, minimum thickness, strain path were predicted using the trained ANN and validated with FE simulation results for two intermediate input levels. The prediction of failure location showed a higher level of prediction error (6.52 %) (Table 4). All other parameters show better prediction level with acceptable error range (Abhishek et al., 2011).

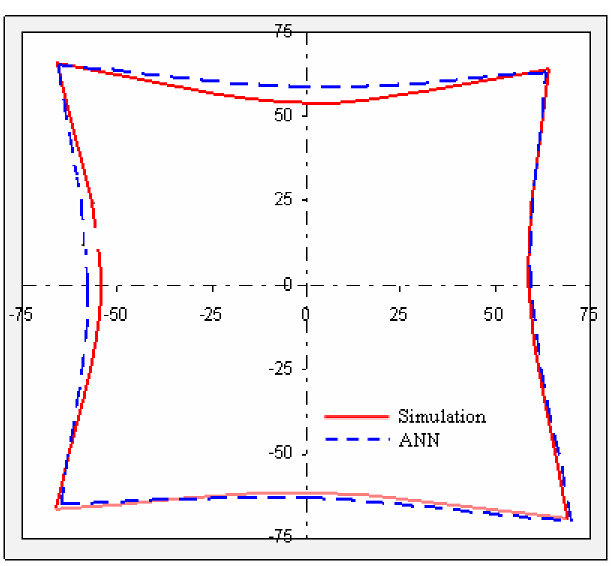
Output	**Training**		**Testing**	
	% error	**SD in error**	**% error**	**SD in error**
Yield strength (MPa)	0.18	7.08	11.91	50.04
Ultimate tensile strength (MPa)	0.05	13.71	5.03	35.63
Uniform elongation (mm)	0.09	0.10	4.45	1.41
Strain-hardening exponent '*n*'	0.01	0.01	*14.35*	0.01
Strength coefficient '*K*' (MPa)	0.01	13.01	10.49	36.04

Table 3. Validation of ANN model for tensile test simulation within safe progression limits

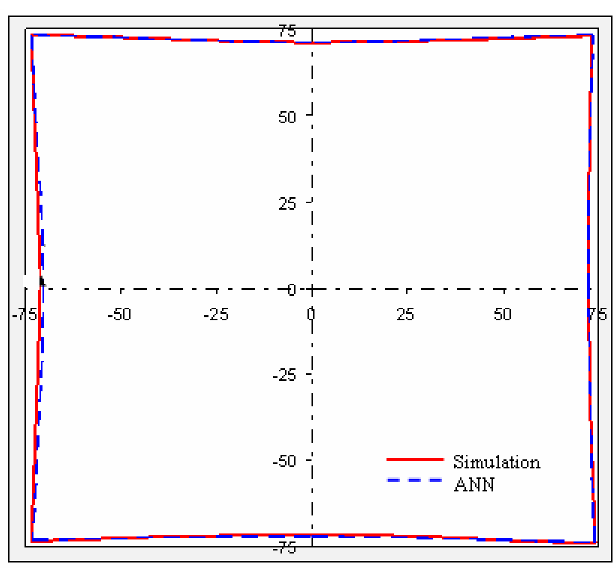
Output	Training		Testing	
	% error	SD in error	% error	SD in error
Major strain	0.007	0.23	5.23	3.51
Minor strain	0.067	0.92	2.79	0.87
Failure location	0.071	0.76	6.52	1.82
Minimum thickness	0.003	0.03	4.28	2.64
Strain path slope	0.052	0.42	3.91	0.36

Table 4. Validation of prediction by ANN for tensile simulation with necking induced failure

The deep drawing simulation data was used to train ANN to predict global TWB deep drawing behaviour viz., maximum weld line movement, draw depth, maximum punch force, draw-in profile for the chosen range of thickness and strength combinations, weld properties, orientation, and location. Two intermediate level data were taken for testing and validating the results as shown in Table 5. Fig. 21 presents the comparison between ANN and simulation results of draw-in profile of deep drawn cup. At different TWB conditions, the draw-in profile predicted by ANN model is well matched with the simulation results. All output parameters are predicted within acceptable error limits, except maximum weld line movement. Average error in this case is approximately 15% which is unacceptable. This possibly can be improved by using different strain-hardening laws and yield theories more suitable for aluminium alloy base materials. It is observed from Fig. 21a that the draw-in profiles are un-symmetric in shape. Minimum draw-in is seen along the angular weld region and in thicker material side, while thinner material shows maximum draw-in.



a) Test sample-1



b) Test sample-2

Fig. 21. Comparison of draw-in profile between ANN prediction and FE simulation for two deep drawing test simulation of aluminium alloy TWB

Parameters	**Test Data 1**	**Test Data 2**
Thickness ratio (T_1/T_2), T_1 mm	0.6, 0.9	0.7, 1.05
Strength ratio (YS_1/YS_2), YS_1 MPa	0.7, 210	0.6, 180
Weld orientation (°)	35	55
Weld location, mm	14	7
Weld yield strength (YS_W), MPa,	250	325

Table 5. Input properties for validating the ANN deep drawing behaviour prediction of TWB

6. Conclusion

This chapter presented some studies on tensile and deep drawing behaviour of aluminium tailor-welded blanks. A finite element based numerical simulation method is used to understand the behaviour. The presence of thickness, strength heterogeneities and weld region deteriorates the formability of aluminium welded blanks in most of the cases. Designing TWB for a typical application will be successful only by knowing the appropriate thickness, strength combinations, weld line location and profile, number of welds, weld orientation and weld zone properties. Predicting these TWB parameters in advance will be helpful in determining the formability of TWB part in comparison to that of un-welded base materials. In order to fulfil this requirement, one has to perform lot of simulation trials separately for each of the cases which is time consuming and resource intensive. Automotive sheet forming designers will be greatly benefited if an 'expert system' is available for TWBs that can deliver its forming behaviour for varied weld and blank conditions. A artificial neural network based expert system is described which is being developed by the authors. The expert system is envisaged to be expanded with industrial applications also. For example, a sheet forming engineer who wants to develop expert system for some industrial TWB sheet part can just make it as part of existing system framework in the same line of thought, without introducing new rules and conditions. The relations between TWB inputs and outputs are non-linear in nature and hence it is complex to explicitly state rules for making expert system. But these complex relationships can be captured by artificial neural networks. The expert system proposed is a continuous learning system as the field problems solved by the system can also become a part of training sample. Though the expert system can not reason out the decisions/results unlike rule based systems, one can interpret the results by comparing the outputs of two different input conditions quantitatively with minimum knowledge in TWB forming behaviour.

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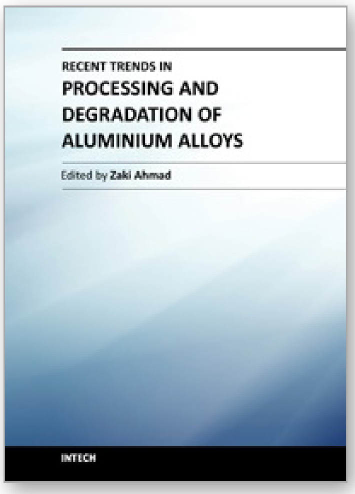

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In the recent decade a quantum leap has been made in production of aluminum alloys and new techniques of casting, forming, welding and surface modification have been evolved to improve the structural integrity of aluminum alloys. This book covers the essential need for the industrial and academic communities for update information. It would also be useful for entrepreneurs technocrats and all those interested in the production and the application of aluminum alloys and strategic structures. It would also help the instructors at senior and graduate level to support their text.