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Finite element modeling and failure prediction of friction stir welded blanks

Amir Abbas Zadpoor [a,b,*], Jos Sinke [b], Rinze Benedictus [b]

[a] *Materials Innovation Institute (M2i), Mekelweg 2, Delft 2628CD, The Netherlands*
[b] *Faculty of Aerospace Engineering, Delft University of Technology (TU Delft), Kluyverweg 1, Delft 2629HS, The Netherlands*

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ABSTRACT

Finite element modeling of friction stir welded blanks needs a delicate compromise between accuracy and feasibility. On one hand, there are a number of zones with significantly different mechanical properties in a friction stir welded (FSW) Tailor-welded blank (TWB) whose mechanical and geometrical properties, if implemented, make the FEM models complicated and computationally expensive. One the other hand, the implementation of the different zones in the FEM model might make a significant contribution to the accuracy of the simulation results. In this paper, the effects of the implementation of the weld details on the accuracy of the failure prediction, strain distribution, and springback behavior of FSW TWBs are studied for two benchmark problems, namely the limiting dome height (LDH) test and the S-rail problem. The effects of the weld detail implementation on the simulation time are also considered. The Marciniak–Kuczynski (MK) theory is used for prediction of the forming limits diagrams (FLDs) of the different zones of the studied FSW TWBs. The MK imperfection parameters are obtained by fitting the theoretical FLDs to the experimental tensile test failure limits. It is shown that the implementation of the weld details results in more accurate strain field and springback predictions. Furthermore, the added computational cost caused by the implementation of the weld details is in many cases reasonable.

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1. Introduction

The highly competitive market of the end-products along with high energy prices and necessity to comply with the strict environmental standards are the driving forces for the industries to invest in the optimal design of the products and production processes. The necessity to optimize the material and processes has also justified the application of the so-called Tailor-welded blanks (TWBs) in the automotive and aircraft industries. The Tailor-welded blanks are sheet metal assemblies consisting of two or more sheets welded together prior to the forming. The sheets can be different in thickness, material, coating, etc. The possibility to have sheets with different thicknesses and/or materials in one assembly facilitates the optimal material distribution within the structural elements in the car bodies and aircraft structures. For a review of the Tailor-welded blanks technology see Ref. [1]. While the laser beam welding is mostly the first choice for steel sheets, it can not be used easily for aluminum alloys primarily because of the high welding temperatures it produces. The high welding temperatures of the laser beam welding can remove the pre-applied heat treatments of the high-strength aluminum alloys that are used, more than everywhere else, in the aircraft industry. In turn, the welding temperatures of the friction stir welding (FSW) are moderate and the effects of the welding temperatures on the mechanical properties of the aluminum alloys are minimal. Furthermore, the weld inspection is much easier for friction stir welding compared to the fusion welding processes. Roughly speaking, fusion welding averages one defect in each 8.4 m whereas there are some reports of 2.5 km continuous friction stir welding without any defect [2]. In addition, due to the high strength to weight ratios of aluminum alloys, the automotive industry is becoming more and more interested in aluminum alloys, see e.g. [3]. Some researchers have already studied the applications of the friction stir welded aluminum, specifically 5xxx and 6xxx series, for the automotive industry applications, see e.g. [4–7].

One of the important challenges of FEM modeling of TWBs is modeling the weld area because it needs a delicate compromise between accuracy and feasibility. On one hand, implementation of the mechanical properties of the different zones might significantly improve the accuracy of the finite elements model, but on the other hand, such implementation will add to the computational cost of the problem. For theoretical formability prediction, there is an additional complexity, because not only the mechanical properties but also the forming limit diagrams of the different zones are different. The first approach, to model the weld area accurately, has been adopted in several studies [8–18]. The second

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[*] Corresponding author. Address: Faculty of Aerospace Engineering, Delft University of Technology (TU Delft), Kluyverweg 1, Delft 2629HS, The Netherlands. Tel.: +31 (0)15 2784186; fax: +31 (0)15 2781151.

E-mail addresses: a.a.zadpoor@tudelft.nl (A.A. Zadpoor), z_amirabbas@yahoo.com (A.A. Zadpoor).

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approach, to exclude the weld properties and/or geometries from the FEM model, is also extensively used in the literature [9,13,19–23]. Many other papers, in which the procedure of numerical modeling is not sufficiently described, apparently have used the second approach. When the geometry and/or material properties of the weld area is excluded from the model, some kind of modeling technique is required to make the connection between the two different parts of the TWB. One may choose to use rigid links (spot welds) for making the connection [19,21]. As far as steel TWBs are considered, it seems reasonable to use this method. Because, due to the high strength of the weld metal in steel TWBs, the failure is more likely to happen in the base metals. Specifically, the method is more efficient while dealing with laser welded blanks, because the weld area in laser welding is very narrow (about 1–2 mm). However, this is not the case for other welding methods such as FSW, which form a relatively wide weld. Besides that, the method is not justified when aluminum TWBs are being modeled because the weld area in the aluminum TWBs is weaker than the base metal and the failure is more likely to happen in the weld area. Several techniques are already used for modeling of the weld area in Tailor-welded blanks. One of the methods is to use beam elements for representing the weld [12,24]. Beam elements limit the geometry that can be represented and the mesh refinement in the weld zone [8]. The second method uses shell elements for modeling of both the weld zone and base metal [9,17]. The third method is to model the weld zone by using the solid elements [9,17]. There is a high computational cost associated with the third method because several through-thickness solid elements are required for a good representation of the bending behavior [8].

Saunders reported that additional costs associated with the implementation of the weld area is not justified [25,26]. Zhao et al. compared three models: one not implementing the weld are and two including the weld area [9]. They found that the solid model with the HAZ and the shell model with the HAZ increase the reaction forces by 25% and 7%, respectively. However, implementation of the HAZ had a little effect on the springback. The CPU time was increased from 0.615 h for the simplest model to 16.26 h for the 3D solid element model (orientation of the weld line parallel to bending moment). Kampus and Balic used two different models one excluding the weld area and one accounting for hardening caused by the MIG welding [13]. They found that while the differences between the forming forces are minimal, the second model could give a better approximation of the actual shape of the deformed part. Raymond et al. concluded that though there are a number of differences between models with the weld area and models without the weld area [8], the differences are subtle. Roque et al. examined four different models: shell element model without HAZ, shell element model with HAZ, solid element model without HAZ, and solid element model with HAZ [17]. They showed that only the solid element with the HAZ could provide validated thickness distributions. Buste et al. used the rigid links for making connections between adjacent nodes of the thick and thin sheets, and found that the model is lacking accuracy in predicting the strain distribution near the weld line [21]. It seems that whether the weld area should be implemented in the model is highly dependent on the welding method and the welded materials on one hand and the geometry of the problem on the other hand. Roughly speaking, the errors caused by excluding the weld area from the model are minimal when the FEM model are used for steel TWBs or the weld line is located in the low strain regions. Limited information about the FEM modeling of FSW TWBs is available in the literature. This paper tries to provide answers for the questions regarding the FEM modeling of the weld zone in FSW TWBs. Two different problems, namely limiting dome height (LDH) test and the S-rail problem, are used as study cases. The LDH and S-rails problems are, respectively, good examples of the cases in which accurate prediction of the strain field and springback are important. In this paper, some FEM models of these two problems are validated by using the NUMISHEET 96 benchmark data. After validating the models, the monolithic sheets are replaced with two friction stir welded blanks. The Marciniak–Kuczynski theory is used to determine the FLDs of the base metal, weld nugget, and heat-affected zone based on the imperfection parameters obtained by fitting the theoretical FLDs to the results of the tensile tests. Six different models as specified in Table 1 are built, simulated, and compared. First three models are related to the LDH test and the last three ones are related to the S-rail problem. From degree-of-heterogeneity viewpoint, the above-mentioned models can be categorized as completely heterogeneous models (models no. 3 and 6) in which the mechanical properties of both the weld nugget and heat-affected zones are implemented, moderately heterogeneous models (models no. 2 and 5) in which only the mechanical and geometrical properties of the weld nugget are implemented, and homogenous models (models no. 1 and 4) in which no weld detail is implemented and the blank is considered to be monolithic. The effects of asymmetry of the weld nugget and heat-affected zones around the centerline on the strain distribution and springback behavior of the blanks are also studied. Simulation results and computational time are compared between different models.

Table 1
The specifications of models used in this paper to study the LDH test and S-rail problem

Model no.	Case of study	WN	HAZ
1	LDH test	No	No
2	LDH test	Yes	No
3	LDH test	Yes	Yes
4	S-rail	No	No
5	S-rail	Yes	No
6	S-rail	Yes	Yes

WN: weld nugget.
HAZ: heat-affected zones.

2. Limiting dome height test

The limiting dome height test is one of the most commonly used formability tests. In this test, a 101.6 mm (4 in) diameter hemispherical punch is used to form some rectangular blanks with a common length and varying widths. The punch's travel at the onset of the failure is recorded as the dome height. Different widths are used to generate different strain ratios. The minimum value of the dome height is called limiting dome height (LDH) and is deployed as a measure of formability. The clamping of the blanks during the forming should be carefully controlled by means of a large blank holding force (BHF) and/or drawbeads. For a detailed description of the test and reporting procedures see ASTM standard E2218 or ISO standard 12004.

The limiting dome height test was assigned as one of the benchmark problems of the NUMISHEET 96 conference. A detailed description of the problem was provided by the organizers [27]. In this paper, we use exactly the same geometry, material, and parameters as of the NUMISHEET 96 benchmark problem. Drawings of the blank and die-set geometries are shown in Fig. 1. A constant length of 180 mm and width of 100 mm is used for all simulations. The thickness of the blank is 1 mm. The blank is made of draw quality mild steel (IF). The material properties of the IF steel are given in the NUMISHEET 96 documents. The origin of the coordinate system is supposed to be coincident with the intersection point of the blank's diagonals. As specified by the NUMISHEET 96 documents, the friction coefficient for the contact between the punch and the blank is 0.11.

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