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Determination of mechanical properties of the weld line by combining micro-indentation with inverse modeling

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ABSTRACT

This paper provides a comprehensive study on determination of mechanical parameters in the weld zone and heat affected zone (HAZ) by using the micro-indentation and inverse modeling techniques. In order to improve the simulation accuracy of finite element (FE) modeling for such complex welded structures as tailed-weld blanks (TWBs), it is critical to characterize the detailed mechanical properties of the weld line. Majority of existing works however took uniform properties of weld line, which could lead to insufficient simulation accuracy for the welded structures. In this study, the weld line will be divided into several different zones, including weld zone and heat affected zones (HAZs) according to their hardness measured. In the characterization process, the relationship of force versus depth in different weld zones is obtained from micro-indentation tests using the Vickers sharp indenter. Then, an axisymmetric two-dimensional (2D) FE model is constructed based on the power law constitutive model to simulate the elastoplastic response of each corresponding zone. Finally, the mechanical parameters in different zone are identified by using genetic algorithm (GA) to minimize the discrepancy between the experimental data and simulation results. To verify the presented method, the modeling results are compared with the experimental data obtained through both uniaxial tensile test and digital image correlation (DIC) of welded specimens. The results demonstrate that the obtained mechanical properties allow well correlating the simulation to the experiment with better accuracy than other methods reported in literatures.

1. Introduction

In recent years, ever-increasing attention has been paid to reduction of the vehicular weight in response to such environmental issues as air pollution, fuel economy and high energy cost. To achieve a list of demanding goals, optimizing the usage of materials has been one of the main strategies. In this respect, various tailored methods and welding technologies e.g. laser-welding, metal active gas (MAG), tungsten inert gas (TIG), electrical resistance spot (ERS) welding are becoming prevalent [1–4]. Of these welding techniques, laser-welding has proven particularly effective for fabricating advanced high strength steel materials [5,6], which allows producing the laser tailor welded blanks (TWBs). As a promising alternative, TWBs technique can more flexibly optimize the usage of different materials and more appreciably achieve the abovementioned objectives. For this reason, many automotive companies have been widely utilizing the laser tailored-weld blanks (TWBs) made of various advanced materials such as aluminum alloy and high strength steel [7–9].

The laser TWBs can be manufactured by welding two or more sheets of metal with dissimilar material grades and/or thickness into a single blank through the laser-welding process. Except for different strengths and/or thicknesses, other major difference between general steel blanks and TWBs is existence of weld line. The importance of weld line has been emphasized by numerous researchers [10–14]. For example, Wang et al. [12] investigated the effects of the weld line on blank formability and performed a numerical study on the weld line behavior of the TWB deep drawing. These above works were focused largely on the influence of the weld line movement on sheet forming process rather than identifying the mechanical properties. In many studies, base sheets were connected by using coincident node models which ignore the specific mechanical properties around the weld line. As a result, there existed a certain mismatch between modeling and experimental results. To address this issue, some researchers treated the weld line region as a special yet homogeneous material with uniform mechanical properties [14,15]. Although such an approach somewhat improved the modeling accuracy, the error still existed and may affect a final design. For this reason, these two modeling strategies of either using coincident nodes or homogeneous properties should not be widely applied into detailed design stage in engineering practice.

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To precisely model the formability and performance (e.g. mechanical response and crashworthiness) of TWB components, it is significant to obtain the detailed mechanical properties near and in the weld line, since this special zone is made of two or more different base materials with distinctive mechanical properties induced by high welding heat and coupled thermal–mechanical effects [7]. In reality, the weld line is often divided into several different zones, e.g. welded zone and heat affected zones (HAZs) in line with their hardness. Understanding such detailed properties in different zones is critical to precisely predict the effects of some important design and manufacturing parameters, such as the sheet thickness and weld size, on the resulted mechanical performance [16]. For example, the effects of softness and HAZ size on fracture behavior and tensile performance were investigated, which showed the necessity of determining detailed local mechanical properties [17,18].

To characterize the mechanical properties of the weld zone and heat effect zone, Kim et al. [19] applied the standard and nonconventional uniaxial tensile tests to obtain the specific mechanical properties from weld-only specimens and HAZ-only specimens, respectively. The mechanical performance of weld zone by means of a mixture rule was evaluated based on the assumption that this special seam was uniform in the longitudinal or cross section [14,15]. In essence, such testing techniques allowed determining only the overall/average properties of the specimens and failed to distinguish the materials inhomogeneity inside the specimen. According to hardness test in real weld line, the values were, however, largely non-uniform, indicating strong heterogeneous mechanical properties near the weld zone concerned.

Unlike standard tensile test, the indentation test allows characterizing the localized material behaviors in the indented region. Because of this feature, it has been extensively used in determining mechanical properties of inhomogeneous materials [4,20–24]. According to the previous indentation studies [24], the material properties of weld line (including weld nugget and heat-affected zones) can differ significantly from those of the base materials. In this situation, the indentation test was particularly suitable for characterizing localized mechanical properties in weld line [25].

Over the years, the depth-sensing instrumented indentation test has been developed as a common technique to measure mechanical properties near surface, in which the indenting load is monitored as a function of the indentation depth in the loading/unloading processes [20–23,26–28]. Ghosh et al. [29] studied the effect of post-weld heat treatment on the mechanical properties of a high strength low alloy (HSLA) steel by employing ball indentation technique. Zhan et al. [14] obtained constitutive models of the weld bead and heat-affected zone (HAZ) metal based on a mixed material tensile test and micro-indentation by considering variation in flow stress across HAZ. Ye et al. [30] carried out a series of experiments including low-cycle fatigue tests, indentation tests, optical microscopy examinations in order to study the local mechanical properties and microstructures for 304L SS welded joints in both as-welded and cyclic straining conditions. Charitidis and Dragatogiannis [31] extracted equivalent stress–strain curves for base metal and welded zone of a friction stir welded aluminum alloy by using Berkovich nanoindentation.

Table 1
Nominal chemical composition (in wt%) of the base steels (DP600/DP980) [33].

Composition	C	Si	Mn	Cr	Mo	S	P
DP600	0.09	0.36	1.84	0.02	0.010	0.005	0.01
DP980	0.15	0.31	1.50	0.01	0.006	0.006	0.01

This paper aims to characterize the mechanical properties of weld line with different materials (DP600/DP980) but the same thickness by combining the indentation and inverse computational modeling techniques. Section 2 introduces physical experiments including the uniaxial tensile, indentation, and digital image correlation (DIC) tests. Section 3 constructs an axisymmetric FE model with a power law constitutive relationship to simulate elastoplastic response in different zones. Section 4 presents the computational procedure for determining the constitutive parameters, where the genetic algorithm (GA) is used for solving the inverse problem. Section 5 shows the results and discussion, and finally the new finding is concluded.

2. Experiments

The materials used in the present study are two typical dual phase high strength steel sheets (DP600/DP980), whose thickness is the same (2 mm). The chemical compositions of the base steels are listed in Table 1. The welding of these two steels with different yield stresses and ultimate strengths leads to complex and inhomogeneous material properties. As pointed out in the literature [32], the weld zone consists of martensite and bainitic phasea, while the HAZs around the weld zone have a more complex and mixed microstructure comprising of martensite, bainitic, ferrite and pearlite. It is these discrepant microstructures that give rise to distinct material performance and behaviors. This section introduces physical experiments such as the uniaxial tensile, indentation, and DIC tests.

2.1. Uniaxial tensile test

The welded specimens for the uni-axial tensile test are prepared in line with the standard as illustrated in Fig. 1. Since necking and rupture of specimens do not normally occur in the weld line for transverse specimens (weld direction is parallel to tensile direction), but rather in the weaker base material, in which the appears on the thinner or weaker part of the tailor-weld tensile specimens [4,34], the longitudinal specimens (weld direction is parallel to tensile direction) would be studied here as seen in Fig. 1(b). Fig. 2 presents a photo of the real specimen that includes the base materials and weld line, in which the weld line is divided into two different zones: weld zone and HAZ (Fig. 2(c)).

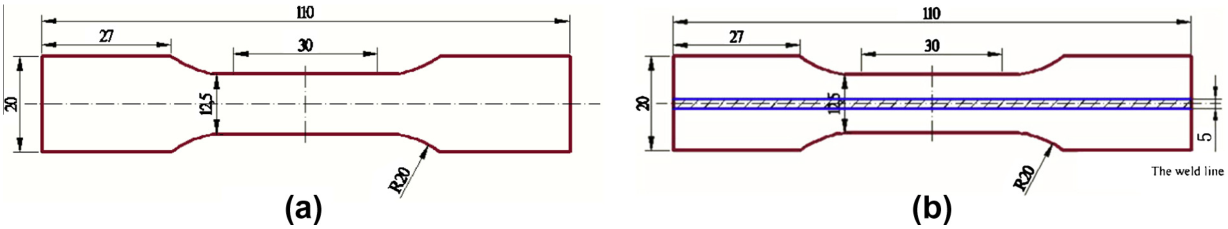

Fig. 1. Schematic showing the geometry and dimensions of the DP steel specimens for uniaxial tension (unit: mm): (a) the specimen of base material and (b) a typical laser-welding specimen along the longitudinal direction.