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A methodology for the viscoplastic behaviour characterisation of spot-weld heat affected materials

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ABSTRACT

The material behaviour of all zones of a spot-welded assembly needs to be known to build the finite element (FE) model of its fast dynamics strength. A methodology employing a thermomechanical simulator is thus proposed to replicate the micro-structure of different HAZ materials in a spot-weld. The obtained replicated HAZ materials are characterised through tensile testing at different strain rates. This methodology can be applied to many types of weldments. A spot-weld made of two XES (mild-steel) sheet metal plates is chosen for application. The behaviour of these HAZ materials appears to be sensitive to the strain rate. The yield and ultimate stresses have increased with the strain rate, while the fracture stress has decreased; the strain to fracture being more or less strain rate independent. The influence of the strain rate is more important on the material behaviour of the base metal. The heat affected materials have higher yield, ultimate, and fracture stresses than the base material. The strain to fracture has contrary decreased because of the heat treatment. The parameters of the modified Krupkowsky viscoplastic model are identified for the base metal and the HAZ materials. This methodology will be helpful to supply a meso-scale FE model of spot-welded assemblies and to analyse the plastic strain location which leads to different fracture modes experimentally observed.

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1. Introduction

In structural crashworthiness computations, explicit finite element (FE) codes commonly use a single element connected to the shell elements by tied interfaces for fasteners. The literature survey shows that several spot weld FE macroscopic models exist. Langrand et al. (2001) developed a generalised spring element with non-linear behaviours for tensile and shear loads. Combescure et al. (2003) developed a beam element to model the weld nugget that joins the sheets. Shepperd and Strange (1992) proposed to combine numerous bars to model the assembly. Various architectures combining beams and/or springs can be found in other models. Vivio (2009) proposed that type of model to formulate an element for spot welds and Petrinic et al. (2004) for rivets. Radaj et al. (1990) represented the weld nugget with a more complicated (and more realistic) approach based on a FE solid element. However this approach is not as suited as the previous ones to structural computations, due to the fine mesh employed in the nugget area.

Under loading, local strains develop in the plate around the welded point. These local strains are not accounted for in the structural computations because of the imposed size of the shell elements used for each component. Thus, the local strains within a certain volume of the metal plate must be integrated into the behaviour of a single macro scale element. Consequently, the mechanical behaviour of the numerical model of the assembly has to depend on the physical properties of the spot weld and of the metal plate surrounding the joint.

Combescure et al. (2003) proposed to model the whole welded region by a single non-linear beam. In fact, the beam described the region's homogenised behaviour. The flow rule of the beam element coupled the loads in all directions, which improved the previous solutions proposed by Langrand et al. (2002) in particular for shear and tensile forces combination. The beam model of Combescure et al. (2003) featured elastic, plastic and damage descriptions. The damage model was used to represent the whole welded region failure. In this implementation, the beam model was strain-rate insensitive. A description of the stress that depends on the strain

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rate (e.g. the model proposed by Johnson and Cook (1983) which is available in most FE solvers used for crashworthiness) could be introduced to make it become sensitive to the strain rate.

Arcan et al. (1978) test devices dedicated to the characterisation of the mechanical properties of assemblies in pure and combined modes I/II under quasi-static loading conditions were proposed by some of the authors. Patronelli et al. (1999) developed this procedure for rivets and Langrand and Combescure (2004) for spot welds. It made possible the identification of the elasto-plastic-damage model of Combescure et al. (2003) thanks to experimental pure opening and shear results. The model parameters were validated first using combined loading results and then using single-lap shear, coach-peel, and pull-out tests results (Langrand and Combescure, 2004).

Langrand and Markiewicz (2010) extended the Arcan experimental procedure to dynamic loading and tested spot welds with a hydraulic jack and a Split Hopkinson Pressure Bars (SHPB) apparatus. The analysis of the experiments revealed that for spot welds the yielding force, non-linear behaviour, and failure were sensitive to the strain-rate. The dependence of parameters to the strain-rate of a commonly used failure criterion, given by Bruhn (1973), which couples tensile and shear strength, was studied. The results analysis highlighted that the coupling parameters used to combine loads in the criterion were relatively strain-rate independent, while the other parameters (ultimate pure opening and pure shear loads) were strain-rate dependent.

However strains and strain rates are non-uniform in the plate surrounding the nugget because strain and stress states are tri-axial and materials are heterogeneous (base material (BM), heat affected zone (HAZ) and welded nugget), making the improvement of the flow rule of the beam model Combescure et al. (2003) to predict loads with a strain rate dependent model very challenging.

In order to predict the non-uniform local stress, strain, and strain rate fields developing in the Arcan type specimen under quasi-static and dynamic loading conditions, a solution is to develop a refined FE model at the meso-scale. Such a model, which is not addressed in this paper, will be helpful to analyse plastic strain location which leads to the different fracture modes experimentally observed and to enrich a spot-weld macro-scale element for structural crashworthiness computation. However, the strain-rate dependence of the heterogeneous materials constituting a spot-weld (Zuniga and Sheppard, 1995) has first to be studied and characterised before setting-up such a FE model.

Langrand et al. (2009) extracted small specimens in the fusion zone, HAZ and BM of a weld joint. The specimens were tested with a hydraulic jack and a SHPB apparatus to study the strain rate dependence of these materials. The dynamic tests were also performed at different temperatures. Zhu and Xuan (2015) performed micro-tensile tests based on small-scale specimens to characterise strain hardening behaviour along a steel welded joint. Obtaining (by machining process) a material specimen large enough for tensile testing from each of these regions is challenging knowing the size of the heat-affected zone in a spot weld (Markiewicz et al., 2001).

Indentation tests can be used to characterise the material properties. Dao et al. (2001) derived analytical expressions to relate indentation data to elasto-plastic properties of various metal using elasto-plastic finite element computations. Cao and Lu (2004) extended the idea of Dao et al. to spherical indentation. Sakai (2004) used analytical approaches for the simultaneous estimate of the elastic modulus and the true hardness. Ma et al. (2003) presented a methodology for evaluating the yield strength and hardening behaviour of metallic materials by spherical indentation. Poon et al. (2008) analysed the extraction of material properties using nano-indentation for linearly elastic and elastic–plastic materials. Zhang et al. (2013) proposed a procedure to derive the elasto-plastic properties of metallic materials from the Vickers and the Knoop hardness measurements. The indentation tests were also applied to determine the material yield stress and the material hardening using the Finite Element Updating method. Inverse method was used by Cao and Lu (2005) to calculate the material parameters from given load penetration depth curves. Casals and Alcalá (2005) developed a methodology for extracting yield strength, Young's modulus, strain hardening exponent and hardness from Vickers and Berkovich instrumented indentation experiments.

Table 1
Mild-steel XES nominal chemical composition (measured in wt%).

C	S	N	Mn	P	Si	Al	Ni	Cr
0.0268	0.0175	0.006	0.202	0.007	0.007	0.07	0.018	0.036

Cu	Mo	Sn	Nb	V	Ti	B	Ca
0.014	0.002	0.004	0.001	0.002	0.002	<0.0003	<0.0003

Since the indentation method needs a small amount of material volume, it can be applied to materials with high gradients on their properties, such as in weldments (Zarzour et al., 1996). Kong et al. (2008) applied inverse methods to characterise the material properties of the various weld zones by combining hardness tests and shear single lap or pull-out tensile tests. Knowing that the HAZ is a heterogeneous medium (Zuniga and Sheppard, 1995) and when failure and strain-rate dependency analyses are of concern, these approaches are quickly limited by the growing complexity of the optimisation problem (non-uniqueness of the solution) and the computation time increases with the number of material zones to identify, as highlighted by Markiewicz et al. (2001) for single lap shear specimens.

The work presented in this paper aims at alleviating these difficulties by proposing a methodology for the direct characterisation of the material constitutive models of the HAZ. The thermal cycles which affect the base material during the spot-welding process were simulated and validated by one of the authors in a previous study (Dupuy and Srikunwong, 2004). These thermal cycles were used in a Gleeble thermomechanical simulator to replicate the material micro-structure of several areas of the HAZ. It was applied in particular to the characterisation of the HAZ visco-plastic constitutive models of a mild-steel base material. The strain-rate dependence of the heterogeneous materials constituting the spot-weld was studied using uni-axial tensile specimens made of the replicated HAZ materials.

The paper is organised as follows. In Section 2, the methodology employed to replicate the HAZ materials is presented. It consists of obtaining the thermal cycles in the spot weld, applying the thermal cycles to samples, and finally controlling the materials micro-structure. In Section 3, uni-axial tensile experiments are performed on the heated specimens and the influence of the thermal cycle in several HAZ is analysed with the increase of the strain rate. The parameters of a visco-plastic model are identified based on the experimental results in Section 4. Finally, results are discussed in Section 5 and conclusions are drawn in Section 6.

2. Replicated HAZ materials

The spot welding process consists in joining contacting sheet metal plates by a heat obtained from resistance to electric current. Forcing a large current, in a very short time (approximately 10 ms), through the spot melts the metal and forms the weld. The welded region is consequently a very complex zone for which the actual material properties are complex and highly variable from point to point. For mild-steel (XES) considered in this paper (Table 1), the welded nugget consists of martensite and bainite, while the HAZ around the nugget has a mixed micro-structure consisting of

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