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TIRÉ À PART

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Analyse de l'influence de la vitesse de déformation sur le comportement des matériaux affectés thermiquement d'un point soudé

par

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Résumé traduit :
L'histoire thermo-mechanique dans chaque ZAT est analysée à l'aide d'une simulation EF du procédé de soudage. La micro-structure de chaque ZAT est alors reproduite sur des échantillons de traction à l'aide d'un simulateur thermo-mécanique Gleeble. La micro-structure des ZAT ainsi simulées est comparée à celle des ZAT d'un point soudé afin de valider la procédure. Les échantillons sont testés en traction uniaxale à différentes vitesses de déplacement. Le comportement du métal de base et des matériaux affectés thermiquement s'avèrent dépendents de la vitesse de déformation alors que la déformation à rupture semble quant à elle insensible à la vitesse de déformation dans le cas de matériaux affectés thermiquement.

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Strain rate sensitivity analysis of spot-weld heat affected materials

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Abstract

The thermo-mechanical history in each HAZ is analysed by FE simulation of the welding process. The micro-structure of each HAZ material is then replicated on tensile sample using a Gleeble thermo-mechanical simulator. The micro-structure of the simulated HAZ materials was compared to the micro-structure of the HAZ materials in a spot weld to validate the procedure. Uni-axial tensile specimens are then tested at different displacement rates. The behaviour of the base metal and the HAZ materials are strain-rate dependents but the fracture strain is not strain rate sensitive for the HAZ materials.

Keywords: *Spot Weld, Heat affected zone, Dynamic testing, Material behaviour*

1. Introduction

In structural crashworthiness computations, explicit FE codes for fasteners commonly use a single element (e.g., a generalised spring, a beam, a spring type beam) connected to the shell elements by tied interfaces. The assembly's behaviour is a function of the welded point and the metal plate surrounding the joint. Local strains in the plate around the welded point contribute locally to the joint's observed non-linear macroscopic behaviour. It is thus necessary to integrate the local strains within a certain volume of the metal plate into the behaviour of the single macro element. In the model proposed by Combescure [1], the whole welded region is replaced by a single non-linear beam, which represents the region's homogenised behaviour. The main interest of this beam model is that it couples the loads in different directions, which is an improvement compared to previous solutions in which the joint models barely combined shear and tensile forces. The mechanical behaviour of the beam model is considered to be elastic-plastic, and a damage model is implemented in order to simulate the failure of the welded region. In its present version, the model does not consider strain-rate effects. Strain-rate dependence can be added to this model by introducing a material stress vs. strain curve depending on the strain rate (e.g., Johnson-Cook model) in the expression of the flow rule.

The authors have developed Arcan device for characterising the mechanical properties of joints in pure and combined modes I/II under quasi-static loading conditions [2]. The parameters of the elastic-plastic-damage joint model [1] were characterised using the pure opening and shear experimental results and validated using combined loading tests or pull-out, coach-peel and single-lap shear tests results [2]. This experimental procedure has been extended by the authors to dynamic loading conditions using hydraulic jack and Split Hopkinson Pressure Bars (SHPB) apparatus [3]. Experimental results have shown that the yielding, hardening and failure of spot welds were strain-rate dependent. However strains and strain rates are non-uniformed in the plate surrounding the nugget because strain and stress states are tri-axial and materials are heterogeneous (Base Material, Heat Affected Zone and Welded Nugget), making very challenging the improvement of the flow rule of the beam model for dynamic loadings with a strain rate dependent model.

The welded region is 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 work, the HAZ may be separated into four materials with different micro-structures (i.e., **G**rain **C**oarsened HAZ, **G**rain

Refined HAZ, **I**nter-**C**ritically HAZ and **S**ub-**C**ritically HAZ). Consequently their material properties are affected. To obtain a material specimen from each of these regions, large enough for tensile testing, is challenging knowing the size of the heat-affected zone. It is proposed to analyse the thermo-mechanical history in each HAZ by FE simulation of the welding process and then to replicate their micro-structure on tensile sample using a Gleeble thermo-mechanical simulator. Uni-axial tensile specimens are then tested at different displacement rates in order to study the strain-rate dependency of these materials.

2. Simulated HAZ materials

A finite element model is developed with the Sysweld FE code to study the thermo-mechanical history in the spot weld. The FE analysis of the welding process was performed by the industrial partner of this project using his own methods and input data. The force and the intensity were defined by the automotive manufacturers and the metallurgy industry. The welding FE simulation was validated by comparing the temperature of the electrodes and the size of the welded nugget observed after one or several welding cycles. Nugget formation kinetics were validated for the case of two-sheets, as well as three-sheets joining. The predicted and the measured thermal histories were in a good accordance for the magnitude of the temperature even if a slight discrepancy in the heating and the cooling rates could have been observed [4]. Figure 1 presents the temperature distribution given by Sysweld at the end of the welding process. From the welding process FE simulation, the thermal transformation has been analysed in the different nodal positions from the centre of the nugget to the HAZ. The thermal transformation in the different HAZ of interest has been interpolated based on the numerical results of the FEA of welding process. Results in Table 1a are used as input data of a thermo-mechanical simulator in order to reconstruct the micro-structure in these HAZ materials.

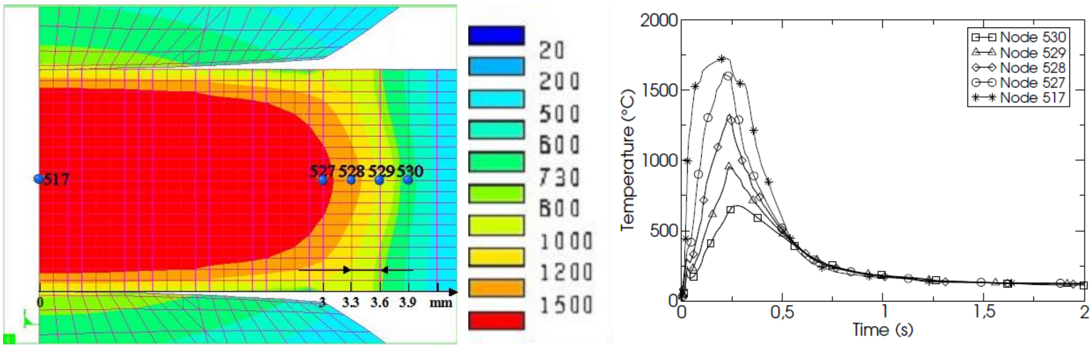

Figure 1: Temperature distribution and time histories in the spot weld. Contours are given in °C.

Table 1: Thermal transformation of the welding process. Temperature is given in °C and rates in °C/s.

HAZ	(a) from the FEA			(b) by the Gleeble		
	Max. Temp.	Heating rate	Cooling rate	Max. Temp.	Heating rate	Cooling rate
GC	1250	4833	2754	1260	3608	258
GR	1100	4421	2283	1096	3545	267
IC	900	3743	1654	902	3155	233
SC	750	3005	1183	745	2801	237

A thermo-mechanical simulator Gleeble 3500 has been used to affect the mild-steel material. Copper alloy electrodes deliver an electric discharge in the specimen. The temperature was measured by three thermocouples in order to verify the temperature homogeneity during the heat. The heating and cooling rates depend on the size of the specimen. The specimen is a tip of sheet metal plate (1.16mm thick) with the overall length and width equal to 120mm and 12mm respectively. Once heat affected, these tips will be machined with electro-erosion-machining to produce the tensile specimens to be tested at high rate of strain. First tests were conducted with the inter-electrode distance of 60mm. Heating rate up to 3000°C/s was measured, but the cooling rate was 25°C/s only. Reducing the inter-electrode distance to 30mm has made it possible to increase the heating rate to values close to those given in Table 1a but the cooling rate was 100°C/s only. It was not possible to decrease again the distance between the electrodes (it won't be possible to machine tensile specimen with an homogeneous material between the griping areas) and a water hardening system was unavailable; so a air quenching system has been developed to increase the cooling rate to 250°C/s.

Simulated HAZ materials samples were produced at least with the thermal properties summarised in Table 1b. As already explain, the cooling rate was about 250°C/s. The maximum temperatures reached in the simulated HAZ materials were close to those observed in the welding simulation (Table 1a). There is a more or less important deviation between heating rate depending on the HAZ considered due to the size of the specimen that remains too large to reach upper values. It has been verified first that the micro-structure of the simulated HAZ materials was homogeneous along the effective length (30mm) of the heated samples. Then, the micro-structure of the simulated HAZ materials was compared to the micro-structure of the HAZ materials in a spot weld. No difference can be observed between both micro-structures of SC-HAZ material. The shape and the size of the grains in this HAZ are close to those of the base material. The micro-structure of the simulated IC-HAZ material is in a good agreement with the IC-HAZ of the spot weld. The geometry and the dimensions of the grains are very close. They are typically representative of a fine-grained micro-structure. Little difference can be observed on the micro-structure of the GR-HAZ materials. The grain size in the spot weld is a little finer than the simulated GR-HAZ material. The morphology and the size of the grains in the GC-HAZ differ slightly in both the simulated and the spot weld materials. The simulated GC-HAZ material has a coarse-grained micro-structure, such as the material in the spot weld. The number of grains is however more important and batten-shaped grains can be observed. Moreover, needle-shaped micro-structure (Widmanstäetten) is missing in the simulated material.

3. Strain-rate dependence of HAZ materials behaviour

The strain rate sensitivity of the HAZ materials and Base Metal behaviour is studied with the uni-axial tensile specimens shown in Figure 2. The specimen was subjected to uni-axial stress loading at different rates of strain, using a hydraulic jack and the experimental device, shown in Figure 2. Tests were performed at 5mm/mn (0.008/s), 0.01m/s (0.8/s) and 1m/s (90/s).

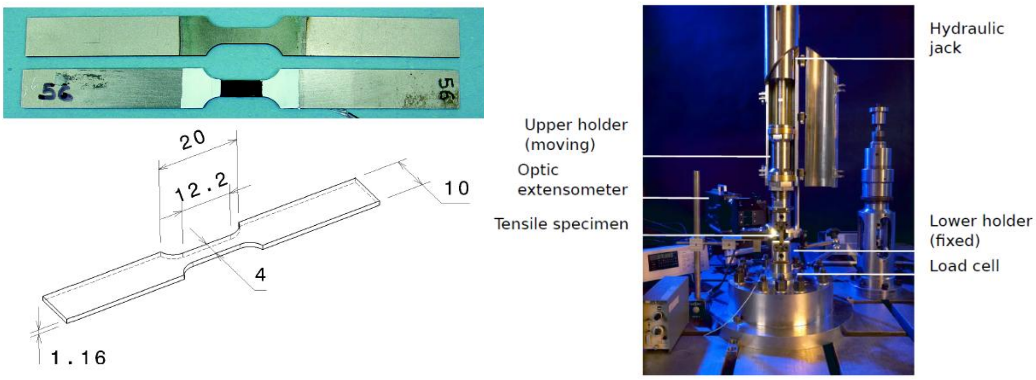

Figure 2: Uni-axial specimen and experimental device for tensile tests at high rate of strain.

Engineering stress vs. nominal strain curves obtained from tensile tests on HAZ materials in Figure 3 have exhibited inhomogeneous yielding between the elastic region to plastic deformation, known as Piobert-Lüders bands that form and propagate across the length of the sample. These P-L bands are common for mild steels when subjected to aging mechanisms, here thermal heating and cooling.

The Engng. stress vs. Engng. strain responses in Figure 3 has a notably dependence to the strain rate whatever the materials. The yield and ultimate stresses have increased with the strain rate. The yield stress is however more influenced by the strain rate than the ultimate stress. The material behaviour evolves consequently to rigid plastic behaviour at high rate of strain.

The fracture stress and fracture strain are used to compare the materials under uni-axial loading (triaxiality is equal to 0.33). These properties are affected by the strain rate in the case of the base metal. The fracture strains are gradually reduced with the strain rate: 0.61 at 5mm/mn and 0.50 at 1m/s. Similar fracture stresses were observed at 5mm/mn and 0.01m/s (150MPa), but the fracture stresses have increased more significantly to 175MPa at 1m/s displacement rate. The fracture stress and fracture strain are on the contrary not influenced by the strain rate for the heat affected materials.

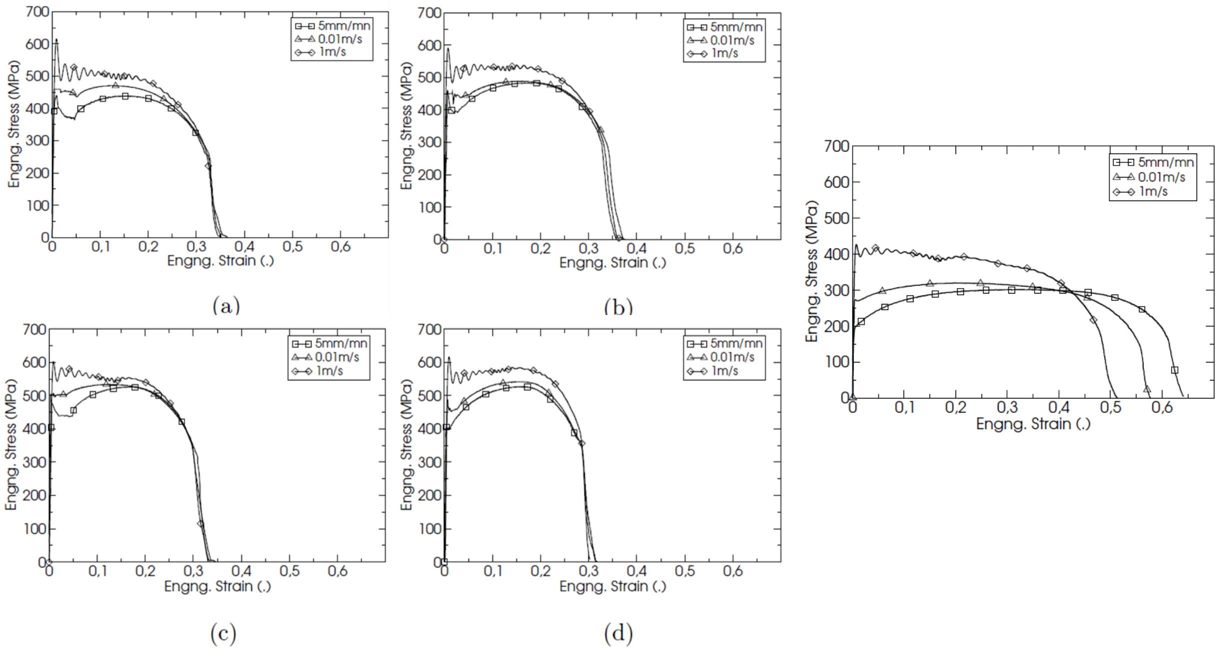

Figure 3: Engng. Stress vs. Engng. Strain diagrams at different strain rates (0.008, 0.8 and 90s^{-1}). (a) SC-HAZ, (b) IC-HAZ, (c) GR-HAZ, (d) GC-HAZ (right), Base Metal.

4. Conclusions

In this paper, the thermo-mechanical history in each HAZ is analysed by FE simulation of the welding process. The micro-structure of each HAZ material is then replicated on tensile sample using a Gleeble thermo-mechanical simulator. The micro-structure of the simulated HAZ materials is compared to those of the HAZ materials in a spot weld. Apart for the GR-HAZ material which differs slightly the procedure to simulate HAZ materials is validated. Uni-axial tensile specimens are tested at different displacement rates. The behaviour of the base metal and the HAZ materials are strain-rate dependents but the fracture strain is observed to be not strain rate sensitive for the heat affected materials.

The parameters of viscoplastic plastic model can now be identified using the true stress vs. true strain diagrams from the experimental data. Finally, a refined FE model of the Arcan specimens can be set-up to make it possible the prediction of the non-uniformed local stress, strain and strain rate fields developing under quasi-static and dynamic loading conditions. Based on these FEA results, the flow rule of the beam model with a strain rate dependent model will be developed.

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