Experimental characterisation of multi-sheet, multi-material spot-welded assemblies under pure and combined loading conditions

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Résumé :

Une nouvelle génération d'assemblages trois tôles multi-matériaux soudés par point a été récemment introduite dans la conception de la caisse en blanc des véhicules automobiles, pour améliorer la sécurité et contribuer également à l'allégement structural. Malgré l'utilisation croissante de ces assemblages, leur comportement mécanique n'a pas encore été suffisamment étudié, notamment sous sollicitations multi-axiales. Dans ce contexte, ce papier propose une caractérisation expérimentale du comportement mécanique et de la rupture d'un assemblage trois tôles multi-matériaux soudé par point par résistance. L'assemblage étudié est constitué de deux tôles en acier Usibor 22MnB5 à très haute résistance et une tôle en acier doux DX54D. Un montage spécifique de type Arcan a été développé pour solliciter l'assemblage en chargements pûrs et combinés. Cinq angles de chargement ont été testés. Les résultats obtenus ont montré la grande influence de l'angle de chargement sur le comportement mécanique et le mode de rupture de l'assemblage soudé. L'effet de la qualité du noyau a été également mis en évidence en testant des assemblages possédant différentes tailles de noyau.

Abstract :

Resistance spot welding (RSW) of multiple sheets (more than two) and combining multiple materials (i.e. different steel grades) are increasingly employed with the growing demand of safety and lightweight vehicle structures. Despite that, the mechanical strength and rupture of such a new generation of RSW under multi-axial loading is not yet sufficiently studied. In this work it is proposed to study the mechanical strength and the failure of multi-sheet multi-steel grade spot-welded assemblies under pure and mixed loading conditions. An advanced experimental device has been developed, based on the Arcan test principle. The experimental study allows to characterize the mechanical strength and to understand failure mechanisms by varying the loading angle α. The effect of the nugget size was also investigated by testing three sets of assemblies with different nugget sizes.

Mots clefs : Spot weld, multi-sheet multi-steel grade assembly, experimental characterisation, Arcan tests, nugget size, failure.

1 Introduction

A new generation of multi-sheet multi-steel grade spot-welded assemblies has been recently introduced in the automotive industry, with the increase of the safety requirement. Meanwhile, lightweight automobile is the development trend in recent years, to reduce energy consumption and carbon emissions. In fact, the use of the High-Strength Steels (HSS) in these spot welded assemblies makes it possible to reduce weight by 30% to 50% compared to conventional steel grades (ArcelorMittal (2014)), while achieving the same crash performance. However, the mechanical behavior of this new generation of assemblies is not yet sufficiently studied. To the knowledge of the authors, most of published works for combined loadings concern two-sheet spot-welded assemblies (Lin and al. (2002); Langrand and Markiewicz (2010)). When three-sheet assemblies are considered, only few works relate the study of the mechanical strength under quasi-static loading using conventional tensile-shear specimens (Tavassolizadeh and al. (2011); Pouranvari and Marashi (2011); Wei and al. (2015)). In this context, this paper presents an experimental Arcan set up to investigate the mechanical behavior and the failure of the three-sheet multi-steel grade spot-welded assemblies in pure and combined loading conditions. The first section presents the studied spot welded assembly. The experimental tests are presented in the second section. The influence of the loading angle on the mechanical behavior of the three-sheet spot welded assembly are investigated and presented in the third section. Finally, the fourth section presents the effect of the nugget size.

2 Studied three-sheet spot welded assemblies

The studied specimen consists of a three-sheet assembly of various thicknesses and involving two steel grades : (P1) is 1.6 mm thick and made of an ultra-high steel 22MnB5, (P2) is 0.65 mm thick and made of mild steel DX54D and (P3) is 2 mm thick and made of 22MnB5 (Fig. 2a). The spot welding process was performed by our industrial partner 'Renault' according to his know-how. Three weld nugget sizes were manufactured according to internal quality rules : under size nugget ($D_1 = 3.7\ mm$), standard size nugget ($D_2 = 5.6\ mm$), and oversize nugget ($D_3 = 7.2\ mm$) (Fig. 1).

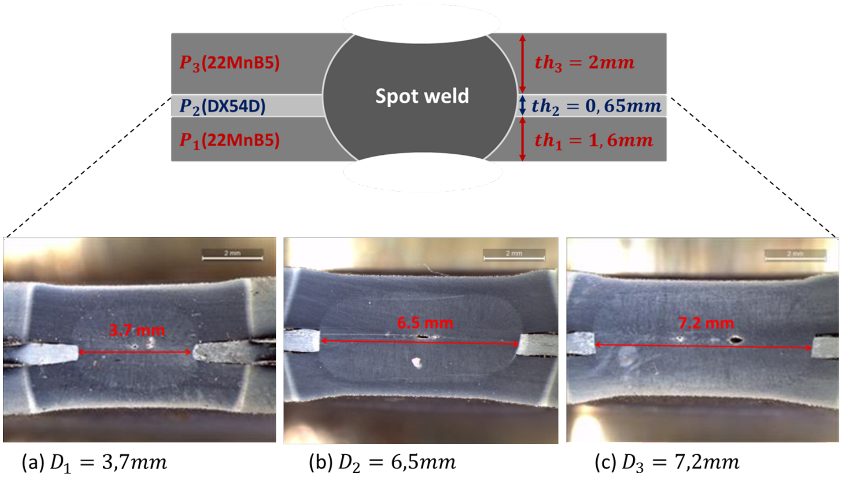


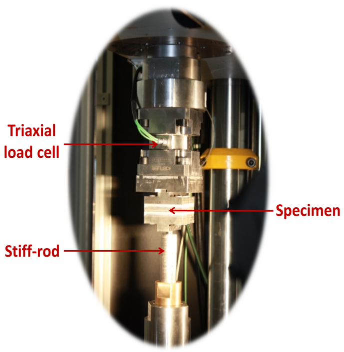
FIGURE 1 – Spot welds qualities according to the nugget size

3 Experimental Arcan tests

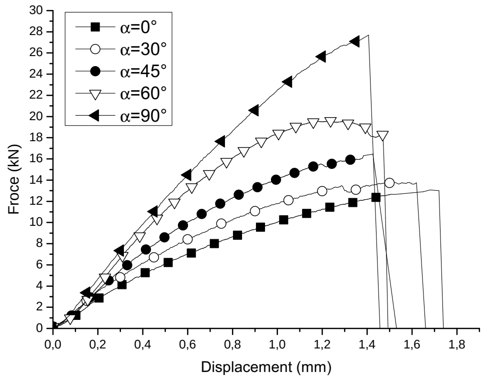
The tests are carried out on a high speed hydraulic machine (INSTRON VHS 65/20). The forces along the three main directions of the machine ($F_x,\ F_y\ and\ F_z$) are measured during the tests, using a triaxial load cell (Kistler 9367C) (Fig. 2a). The displacement is obtained by a LVDT sensor.

A specific set up, based on Arcan principle, has been developed to link the specimen to the tensile machine. The loading modes are therefore combined and well controlled, with a reduced contribution of the plates strength surrounding the weld nugget in the macroscopic response. The angular position α between the loading directions (the vertical axis) and the normal to the surface of the specimen defines the tensile/shear ratio (Fig. 2a). Note that an adequate test device is especially designed for each angular position.

The experimental tests are performed such that the loading is applied on the two external plates of the specimen, at a loading velocity equal to $V = 1\,mm/s$. Three specimens are tested for each angle. Figure 2b shows the average experimental results of force versus displacement under different loading angles. The different forces versus elongation responses have the same shape.



(a) Experimental Arcan set up



(b) Average forces versus displacement responses

FIGURE 2 – Experimental Arcan test

4 Loading angle influence

Thanks to the proposed Arcan device, five loading angles are tested ($\alpha = [0°, 30°, 45°, 60°, 90°]$). The analysis of the experimental results, allowed to study the influence of the loading angle on the mechanical behavior and the failure of the studied three-sheet spot welded assembly. Table 1 presents the exponential evolution shape of the peak load function of the loading angle. In fact, for $0° \leq \alpha \leq 30°$ the peak load increases slowly. Then, for $\alpha = 45°$, it increases rapidly until it reaches its maximum value $F_{max} = 27.71\,kN$ for pure shear ($\alpha = 90°$). However, the displacement at failure decreases progressively when the loading angle increases (Tab. 1). The displacement at failure is maximum in pure tensile ($\alpha = 0°$), with $U_{rup} = 1.74\,mm$.

TABLE 1 – Evolution of the peak load F_{peak} and the displacement at failure $U_{failure}$ for the different loading angles

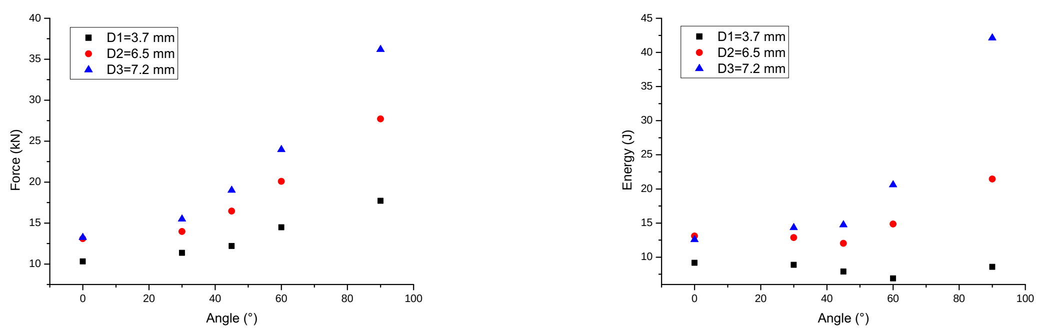
	$\alpha = 0°$	$\alpha = 30°$	$\alpha = 45°$	$\alpha = 60°$	$\alpha = 90°$
F_{peak}, $Mean\ (kN)$	13.09	13.97	16.46	27.60	27.71
$U_{failure}$, $Mean\ (mm)$	1.74	$1,66$	$1,53$	$1,49$	1.46

The increase of the peak load with the loading angle can be explained by the failure mode associated for each solicitation. Indeed, the pure tensile is characterized by a pull out failure. The rupture is thus localized in the affected zone. However, the pure shear test is characterized by an interfacial failure. The rupture is thus localized in the nugget at interface of two plates.

5 Nugget size influence

Many parameters of RSW process can influence the quality of the spot welds. That's why, it is very important to investigate the influence of the nugget size on the mechanical behavior of the spot welded assembly. Three sets of specimen with different weld nugget sizes ($D_1 = 3.7\ mm$, $D_2 = 6.5\ mm$, and $D_1 = 7.2\ mm$) are tested for the five loading angles. The obtained results show that the peak load and the dissipated energy increase with the nugget size of the spot. This is because, when the nugget size increases, the resistant area increases.

Moreover, Figure 3a shows that when the nugget size increases from $D_1 = 3.7\ mm$ to $D_3 = 7.2\ mm$, the peak load increases of about 30% for pure tensile ($\alpha = 0°$), and of about 120% pure shear ($\alpha = 90°$). Therefore, the influence of the nugget size is much more important in the pure shear test characterized by an interfacial failure mode. In fact, the interfacial failure section $S_{interfacial} = \pi * \dfrac{D^2}{4}$ depends on the square of the diameter D of the spot weld. However, for the pure tensile test, characterized by a pull out failure mode, the pull-out failure section $S_{pull-out} = 2 * \pi \dfrac{D}{2} * e$ depends on the diameter of the spot weld and the thickness of the broken plate e.



(a) Evolution of the peak load

(b) Evolution of dissipated energy

FIGURE 3 – Effect of the nugget size

6 conclusion

An experimental procedure has been proposed in order to investigate the mechanical behavior of multi-materials multi-sheets spot welded assemblies in pure and combined opening/shear modes. A proportional evolution of the peak load with the loading angle is observed for this assembly. The evolution of the peak load and the displacement at failure with the loading angle is highlighted. Two principal failure modes are also identified. Three nugget size are tested. The obtained results show that the peak load and the absorbed energy increase with the nugget size of the spot welds especially for the pure shear test characterized by an interfacial failure mode.

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