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Effect of holding time on microstructure and mechanical properties of resistance spot welds between low carbon steel and advanced high strength steel

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ABSTRACT

The effect of holding time on microstructure, hardness and mechanical properties of unequal thickness weld joints between low carbon steel and advanced high strength steel is investigated in the present work. The microstructures in the regions of weld nugget, heat affect zone and base metal are obviously different. The hardness of fusion zone both at low carbon steel and advanced high strength steel sides shows a slight variation and it is much higher than that of base metal. The peak load and failure mode of the weld joints are carried out via tensile shear test and finite element analysis. The test result demonstrates that the peak load and failure mode depend on the resistance force generated via the failure zone. For a given fusion size, the increase of holding time raises the hardness of fusion zone, and affects the peak load and failure mode of weld joints via enhancing the interfacial resistance capability. The increase of holding time reduces the welding efficiency, thus, a suggestion based on the test result is proposed that the holding time should be less than 15 cycles to ensure the manufacturing efficiency. A nonlinear finite element analysis is applied to simulate the tensile test procedure. The simulation demonstrates the necking phenomenon and failure process at interfacial or base metal around the weld nugget.

1. Introduction

Due to the recent legislations by the governments to reduce greenhouse gas emissions and fuel consumptions for environment preservation, the automotive industry is currently facing enormous challenges to develop more fuel efficient vehicles. The industry is constantly seeking efficient methods to manufacture vehicles via lighter or higher strength and ductility materials to reduce the vehicle weight while guaranteeing improved occupant safety and durability [1]. The dual phase (*DP*) steels have the properties of higher strength, lower yield rate, higher working hardening rate, higher strain energy absorbing and other more excellent forming characteristics than the conventional high-strength low alloy steels with similar strength [2,3]. As a result, the *DP* steels are widely used in automotive manufacturing industries.

However, conventional low carbon steels are dominant in complex shaped products of car bodies because of their lower cost and higher forming ductility properties. A *dissimilar combination* of materials and sheets thickness is frequently specified to tailor materials for local design requirements. As a result, the resistance spot welding (RSW) joints of unequal thickness and dissimilar materials are frequently involved in manufacturing of body-in-white (BIW). Compared to the equal thickness and similar materials weld joints, the unequal thickness and dissimilar metals RSWs are particularly characterized by compositional gradients and micro-structural changes and yield large variations in physical and mechanical properties at the weld joints [4–7]. In the past decades, extensive investigations about similar resistance spot weld have been carried out. However, there are limited literatures about the investigation of dissimilar resistance spot welds. Marashi et al. [8] investigated the overload failure behavior of dissimilar thickness RSWs, and stated that final solidification line moves from interface to the geometrical center of the total thickness of the joints and reduces the tendency of failure in the mode of interfacial failure (IF) during the tensile-shear test. Khan et al. [9] stated that the fatigue performance of RSW joints welded with dissimilar materials *HSLA350/DP590* is similar to that of *HSLA350/HSLA350*.

Literatures demonstrate that the welding parameters, e.g., welding current, welding time, electrode pressure affect the microstructures, mechanical properties and failure mode of weld

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joints. Table 1 provides a synoptic view of recent progresses in the investigation of welding parameters effect on the weld joints. Sketches of the literatures are simplified summarized as follows:

(i) The increase of welding current and welding time raises the peak load and diameter of the weld joints by means of increasing the welding heat [10–16].
(ii) The rise of electrode force reduces the peak load and diameter of the weld joints via reducing the electrical resistance of the welding sheets [10,12,14,16,17].
(iii) The welding parameter of holding time dose not effect on the welding heat and the diameter of weld nugget, but it affects the cooling rate of welding process, thus, affects the microstructures and hardness of the weld nugget [14,15].

Peak load and failure mode are typical properties studied in tensile shear test, which is one of the most general methods used to estimate the mechanical properties of spot weld joints. Literatures stated that, the failure mode of spot weld joints are dominant in the types of interfacial failure (IF) and button pullout failure (PF) in tensile shear test [18,19]. To simplify this problem, the weld nugget is schematically simplified as a cylinder to analyze the load bearing capability of spot weld joints (see Fig. 1a). The welded joint experiences the shear stress when a tensile shear load is suffered, and then, a rotation is generated and enlarged with the increase of deformation via the increase of tensile shear load.

The cross section of the weld joint (see Fig. 1b) shows that the interface suffers a shear stress and the half circles of the cylindrical regions A/D and B/C suffer compressive and tensile stress, respectively. Correspondingly, the maximum resistance forces generated by the shear stress and tensile stress at interface and tensile regions B/C are simplified as shown in Eqs. (1) and (2).

$$F_{s\,\max} = f_1 A_{FZ} \tau_{FZ} \quad (1)$$

$$F_{t\,\max} = f_2 A_{FL} \sigma_{FL} \quad (2)$$

f_1 and f_2 are the material dependence coefficient, A_{FZ} denotes the area of fusion zone, τ_{FZ} represents the maximum shear stress of weld nugget, A_{FL} is the area of failure zone, and σ_{FL} represents the tensile strength of the metal at failure zone. Logically, if the maximum shear resistance force supplied via the interface of the weld nugget exceeds the maximum tensile resistance force supplied by the tensile cylindrical regions, the failure mode exhibits a tendency of button pullout; otherwise, it *turns* a tendency of interfacial failure.

The equations of maximum resistance force bridge the geometrical and mechanical properties of the weld joints via failure area, shear strength and tensile strength of the failure zone. The maximum resistance force suffered by the weld joints depends on the failure area and mechanical properties of the failure zone. Electrode holding time on solidifying welding metals does not affect the input heat of the welding process, and thus, weld nugget size does not change according to the variation of the holding time [14]. For a given sheet thickness and weld size, the failure area virtually keeps constant, thus, the failure mode depends on the material strength of failure zones. The mechanical properties of base metal, heat-affected zone (HAZ) and fusion zone (FZ) are quite different from each other, because the welding process changes the microstructures of these regions. Meanwhile, the increasing holding time enhances the material properties by means of increasing the hardness of weld nugget. Pouranvari et al. [14] gave a similar statement that, for a given sheet thickness, the decreasing of hardness ratio of weld nugget and failure zone increases interfacial failure mode tendency. It was concluded by the same author that in the pullout failure mode, the strength of the spot welds dose not affected by the strength of fusion zone, and fusion zone size is proved to be the most important controlling factor for spot welds' mechanical properties in terms of peak load and energy absorption [15].

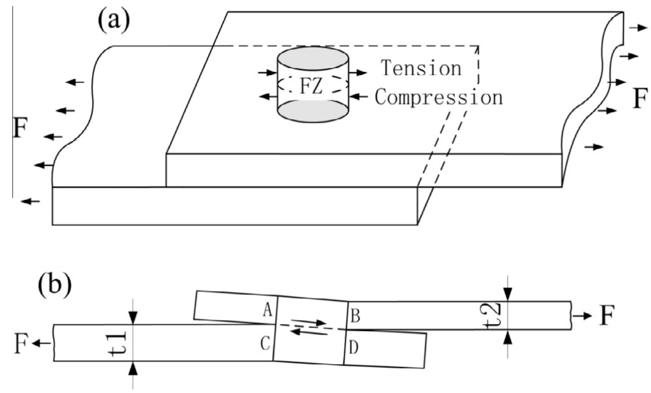

Fig. 1. The simplified model of the welded joint shows the shear and tension or compression stress suffered at the interface and cylindrical regions A/D or B/C, respectively.

Dissimilar resistance spot welds of low carbon steels and advanced high strength steels are widely employed to join sheet metals in automotive bodies. There are limited investigations about the welding parameters of dissimilar resistance spot welds of low carbon steels and advanced high strength steels. This work presents an extensive investigation about the effect of holding time to the failure mode and peak load of dissimilar and unequal thickness spot weld joints. Microstructures and hardness are characterized to study the material properties of the weld joints. Meanwhile, tensile–shear tests accompanying with nonlinear finite element

Table 1
Synoptic view of reports on weld parameters.

Author	Base metal			Thickness (mm)	The welding parameters are studied
	Grade	σ_y (MPa)	UTS (MPa)		
Aslanlar [10,11]	Alloyed	–	540	1.2–1.2 0.8–1.0	Weld current, weld time, electrode force
Zhao [17]	DP600	350(i)	600(ii)	1.7–1.7	Electrode force
Kahraman [16]	Ti	280	340	1.5–1.5	Electrode force, welding time and environment
Bouyousfi [12]	304L	275(iii)	525(iv)	1.0–1.0	Electrode force, welding current, welding time
Özyürek [13]	304L	275(iii)	525(iv)	1.0–1.0	Weld current, environment
Pouranvari [14,15]	Low C	180	330	0.8–0.8 2.0–2.0	Weld current, hold time, electrode force
Present work	Low C DP590	240 455	342 678	1.2 1.5	Hold time

*The datum marked (i, ii, iii, iv) are estimated from relative literatures.
*Low C: low carbon steel.