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Experimental Research on Tensile-shear Behavior of Spot-welded Lap Joints of Ultra-high Strength Steel

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Abstract. The ultra-high strength quenched 22MnB5 steel is researched in this paper, the intermediate frequency inverter & electric servo welding gun system is used to weld the sheets, experiments included of tensile-shear with synchronous electrical testing, microstructure of the material and fractures analysis and the Vickers-Hardness testing. The results point out that the maximum hardness is located at weld nugget, and the minimum hardness is appeared in heat affected zone (HAZ). Fracture is formed under the combined effects of shear stress and normal stress, the shear stress contributes to interfacial fracture, and leads to rupture. Non-uniformity of the microstructure caused by spot welding, changed the property of the material in nugget, stress-strain relationship of this area is nonlinear. The results also show that the conventional weld size guidance of $4\sqrt{t}$ is not sufficient to produce nugget pullout failure mode for 22MnB5 UHSS spot welds.

Introduction

Nowadays, the rapid expansion of automotive has brought more convenience to people, at the same time, the problems of energy consumption and environmental pollution are increasingly serious, so lightweight becomes the inevitable trend of development of the automotive [1]. Ultra-high strength steel can balance the contradiction between weight and cost, which makes ultra-high strength steel become one of the most popular lightweight materials in automobile manufacture [2]. Statistics suggest that there are about 3000~5000 spot-welds in a typical car uni-body structure in average, to some extent, the integral performance of the car is determined by the quality of these spot-welds.

Numerical simulation based on some assumptions is the common method to research mechanical properties of spot welding joints under tensile-shear load, Baohua Chang [3] has established a computational model that consists of nugget, HAZ and base metal for the single point spot welded lap joints, and the whole stress distribution in the joints is obtained, the results show that high stress concentration around the spot weld edge may be the determinable factor for initializing and propagating of the high cycle fatigue crack. Xingxing Xie [4, 5] adopts the local stress analysis method to study the nonlinear mechanical properties of the welded spots in a tensile-shear spot-welding lap structure, the nonlinear finite element model is established under the condition of elastic-plasticity, to analyze the strain-stress distribution rules under various loads, the conclusion indicates that the shear stresses should be the main criterion for the safety evaluation on the spot-welded structures. Yarong Wang [6] has developed a three-dimensional elastoplastic finite element model to get stress-strain feature of welding joint in resistance spot welding of Mg alloy. On the basis of the experiments, such as tensile-shear test with electrical measure, hardness testing and the fracture morphology microscopic observation, the mechanical property of tensile-shear spot-welding lap structure of 22MnB5 UHSS is studied in this paper.

Heat Treatment and Spot Welding Technology

The 22MnB5 steel, low-carbon alloyed steel, is one of the common hot-punching steel in automobile industry, some alloy elements, Mn, Si, Cr and B, can increase hardenability of the steel, the chemical constituents are shown in Table 1. The yield strength and ultimate strength of 22MnB5

are only about 400MPa and 600Mpa before heat treatment. In hot stamping, the blank is put under the combination of reheating temperature 880~950℃ and holding time 5~10 minutes to fully austenitizing, then moved quickly (5~7 seconds) to punching machine and stamped under temperature 600~800, and finally quenched with a rapid cooling rate >30℃/s to ensure the microstructure becomes single martensite, all these measures help the yield strength and ultimate strength of the steel increase to about 1000MPa and 1500MPa, and make the original steel become ultra-high strength steel [7].

Table 1 Chemical composition of 22MnB5 [%]

ω(C)	ω(Mn)	ω(Si)	ω(Cr)	ω(Ti)	ω(B)	ω(S)	ω(P)
0.230	1.500	0.450	0.190	0.023	0.002	0.012	0.010

As indicated in literature [8], the intermediate frequency inverter & electric servo welding technology has a better performance in spot welding of ultra-high strength martensitic steels. In this paper, the spot-weld joints of specimen were made under the above technology, some important parameters of welding process are shown as follow, welding current 6.5KA, welding time 400ms, welding pressure 4200N, forging force 6500N after welding.

Experiments

In this paper, the specimens are made of two UHSS sheets by spot welding, researchers used to research the characteristic of the spot-weld lap joints by using the model [9] shown in Fig.1, which makes the center of the nugget and the load not collinear. According to the standard of BS EN ISO 14273-2001, a modified tensile-shear model that contains two shims with the same thickness shown in Fig.2, is applied in this paper, to ensure the center of the nugget and the load collinear.

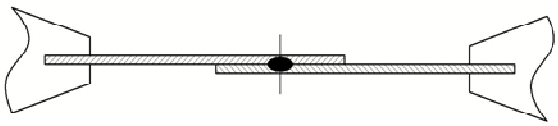


Fig. 1 Common structure of tensile-shear

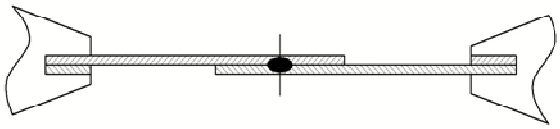


Fig. 2 Modified structure of tensile-shear

There are two methods in tensile-shear experiment, the difference is testing together with electric measure or not. The size of specimens and the position of the strain gauges are separately shown in Fig.3 and Fig.4.

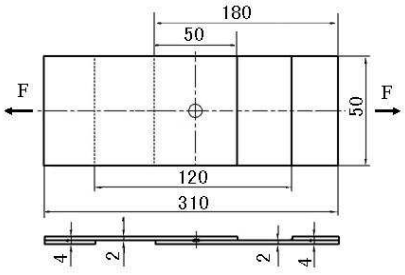


Fig. 3 Size of the specimen

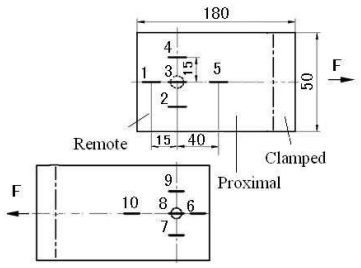


Fig. 4 Strain gauge distribution

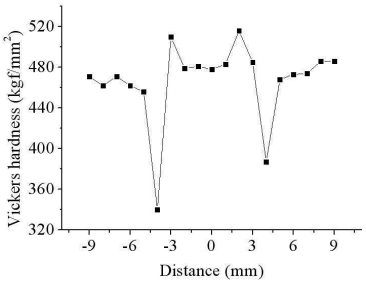


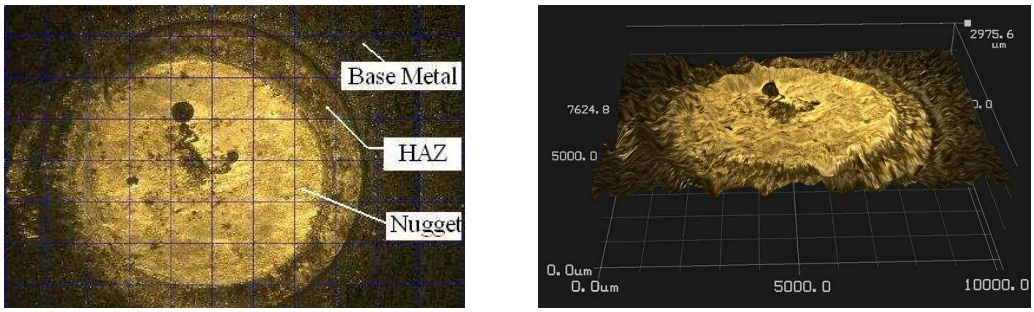
Fig. 5 Vickers hardness

Results of the Experiment and Analysis

Result analysis of Vickers hardness. The high temperature changed the original property of the material, and contributed the area around nugget to complex characteristics. The Vickers hardness around the nugget is tested along line from one side to the other side through the nugget center, there are twenty indentation points spaced one millimeter each other, and 10kgf in each load. The test results are shown in Fig.5, hardness of nugget is close to 500kgf/mm^2, the result reduces with increasing distance at HAZ with a magnitude about 100kgf/mm^2, then hardness rebounds to 450kgf/mm^2 at the base metal region.

Because the center of the nugget and the base metal are composed of different types of martensite, the hardness of nugget is slightly higher than base metal region. The peak hardness locates at the edge of the nugget, which consists of fine martensite. Moreover, the valley appears at HAZ with heterogeneous micro-structure.

Fracture analysis of the tensile-shear spot weld. The morphology of the fractured specimen is shown in Fig.6.



a) Two-dimensional fracture b) Three-dimensional fracture

Fig. 6 Fracture surface

As shown in Fig.6, the sharp of the fracture fits ellipse not a circular, and the joint comprises of three regions: the nugget, heat affected zone and the base metal zone, shrinkage porosity and shrinkage cavity appear around the center of the nugget. As can be seen from Fig.7 and Fig.8, because of the effects of the bending stress from pulling, there is a convex hull on surface of the part far from the power, on the contrary, depression on surface of the nearby part. The obvious grains from proximal side to remote side indicate the direction of the force transferring, and the shear stress from axial force on this interface results in collapse.

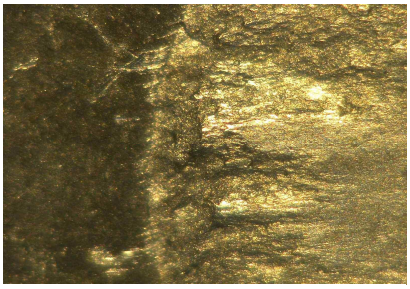


Fig. 7 Partial enlargement of fracture of power remote

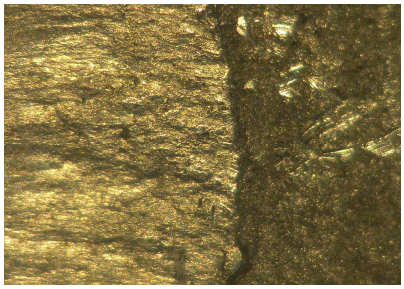


Fig. 8 Partial enlargement of fracture of power proximal

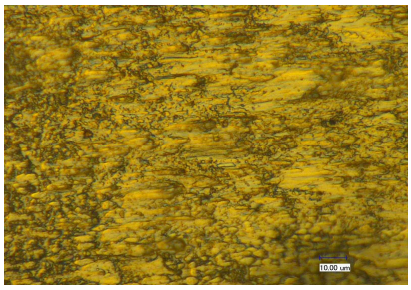


Fig. 9 Partial enlargement of fracture of nugget

As shown in Fig.9, some tiny jagged units in microstructure of the nugget turn into elongated dimples because of the effects of shear stress [10]. Fractured surfaces show that the fragment occurred in the interface between nugget and board for a major stress concentration.

Table 2 The results of tensile-shear testing

Number	F_m [KN]	Diameter of nugget [mm]	Shear strength [MPa]	Failure mode
1	20.6	5.54	855	Interfacial fracture
2	22.32	6.0	789	Interfacial fracture
Average	21.46	5.77	822	---

Result analysis of tensile-shear experiment. Table 2 provides the maximum load of the spot weld specimens, shear strength, nugget diameter and failure modes, Fig.10 shows the tensile curves measures in test, it can be seen that the stress-strain relationship is nearly linear.

As shown in Table 2, the shear stress of spot weld specimen of ultra-high strength steel is more higher than ordinary steel and high strength steel, this is because the weld nugget consists of lath martensite, which belongs to single-phase supersaturated interstitial, leading to serious distortion of

lattice and higher dislocation density, so the microstructure of lath martensite can make the spot weld higher plasticity deformation resistance and shear stress. In Fig.10, the load-displacement curves is linear, and turns vertical when reaching peak load, which indicates that the crack grows rapidly almost without strain. The average diameter of the nugget (5.77mm) is larger than $4\sqrt{t}$ (nearly 5.6566mm), but the failure mode of interfacial fracture is different from nugget pullout failure mode in literature [11, 12].

The variation trend of the strain gauges is shown in Fig.10, the strain of No5 and 10 are positive, and others are negative strain. As shown in the fitted curve, the results of symmetrical pairs are similar to each other, such as No2 and No7, No4 and No9.

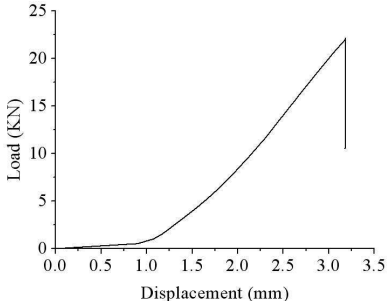


Fig. 10 Load-displacement curves

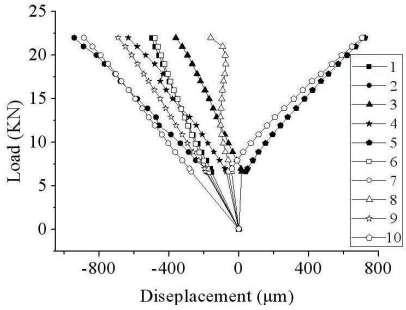
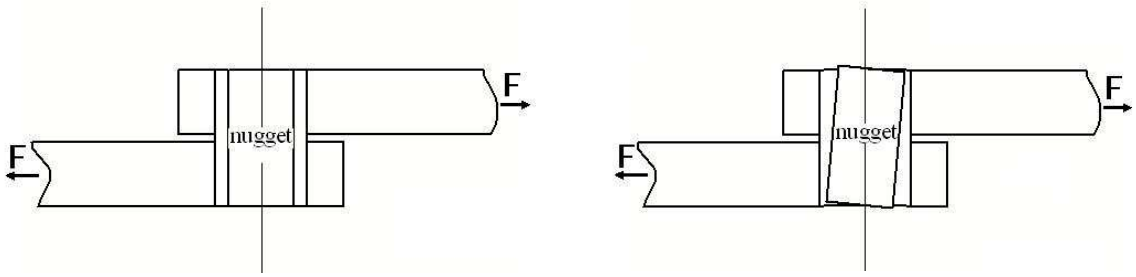


Fig. 11 Fitted curve of the strain gauges

Based on above results and analysis about ultra-high strength found that, the high temperature in spot welding makes the zone around nugget into three regions with different microstructures, the nugget composed of lath martensite has the highest hardness, the HAZ consisting ferrite, pearlite, and a small quantity of martensites has the lowest hardness, and the hardness of base metal zone is between nugget and HAZ. During the tensile-shear process, the nugget connecting two sheets transmits the force by bending effects, the force makes nugget from vertical state to inclined state by extruding HAZ as shown in Fig.12, the rotation of the nugget makes pressure on HAZ and the base metal, all of these lead the whole specimen under the combined effected of shear stress and normal stress. Pressure stress from bending is larger than tensile pressure in the area around the weld nugget, so the strain gauges of No2, 4, 7, 9 show negative strain, the bending effects decrease with increasing distance to nugget, No1, 6 are smaller negative strain. At the proximal-force part, the primary stress turns into tensile stress, No5, 10 show the positive strains. From the center to the edge of the nugget, the microstructure with poor homogeneity contains shrinkage, which makes the local material nonlinear, that is the why No3, 8 exhibit a nonlinear feature.



a) Original status b) Status of tensile testing

Fig. 12 Deformation of the region around nugget

The strength and hardness of HAZ are lowest in the structure, so the maximum stress occurs in HAZ, which leads to a problem of stress concentration. On the microscopic level, HAZ is transitional region from ferrite and pearlite to fine martensite, all of these lead this region become crack origin.

Conclusions

By means of experiment, including tensile-shear testing, hardness testing and morphology observation, this paper makes a research on the mechanical properties of spot welding structure of ultra-strength steel, conclusions are drawn as follows:

(1) The results of Vickers hardness testing indicate that the maximum hardness of the structure is located at weld nugget, and the minimum hardness appears in heat affected zone. Especially, the hardness of nugget is a little different from the base metal area. That is one of the obvious differences between UHSS and ordinary steel.

(2) The microscopic morphology of Fracture shows that fracture is formed under the combined effects of shear stress and normal stress, separately, the normal stress makes the fracture surface uneven, and the shear stress contributes to tearing the interface, so the later one is the major factor leading to rupture.

(3) The tensile-shear experiment results of electrical measurement indicate that stress-strain relationship of the base metal region is linear, and the stress distribution is mainly tensile stress in the area away from weld nugget for less effect from the weld nugget. The stress of region around the nugget is different from the former, the pressure stress from the nugget leads to a compressive stain. In nugget area, non-uniformity of the structure changed the property of material, so stress-strain relationship of this area is nonlinear.

(4) The strength of HUSS is much better than ordinary steel and high strength steel, furthermore, the conventional weld size guidance of $4\sqrt{t}$ is not sufficient to produce nugget pullout failure mode for 22MnB5 UHSS spot welds.

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