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Resistance spot welding of advanced high strength steels

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Summary

The safety of passenger cars and lorries is determined significantly by the performance of resistance spot welds (RSW) that keep the components of steel together. Advanced high strength steels (AHSS) are known to be more susceptible to weld failure than conventional mild steels. A key issue encountered in the current development of the AHSS and next-generation automotive steels is the catastrophic failure of the welds, accompanied by considerably reduced strengths and toughness. Problems arise mainly in the cross-tension tests of spot welds in AHSS steels of strength > 800 MPa, where welds are subjected to a mode I type loading.

The lowered cross-tension strength and poor failure mode of spot welds form a direct hurdle for a successful implementation of these new advanced steels in the automotive industry. Therefore, improvement of the mechanical performance of AHSS resistance spot welds is of vital importance to ensure the safety and crashworthiness of the cars. The present work aims at identifying the process-structure-property relationship in the RSW of dual phase (DP) steels and third generation AHSS steels. Special attention is paid to the microstructural evolution of the welds as a function of welding scheme and parameters.

The precise effect of the welding scheme (i.e. single and double pulse) on the microstructural evolution and mechanical response of DP1000 resistance spot welds were studied in *Chapter 3*. It was found that double pulse welding at the maximum welding current, fairly below the expulsion current, enhances the cross-tension strength of the welds significantly. It was shown that the second pulse in the double pulse scheme subdivides the initial fusion zone (FZ) of the first pulse into two zones. The inner part remains in the liquid form after the first pulse and is resolidified with a columnar structure after the second pulse, whereas the outer solidified layer becomes recrystallized during the second pulse leading to the formation of an equiaxed structure of prior austenite grains (PAGs) (named as Rex-zone). Orientation imaging microscopy characterization revealed that the Rex zone has a low fraction of high-angle grain boundaries and a coarser structure of so-called Bain groups compared to the FZ of single pulse weld. However, finer structure of PAGs, martensite packets and Bain groups are formed in the coarse grained heat affected zone (HAZ) of the double pulse welds. More severe softening of sub-critical HAZ, formation of equiaxed PAGs in the Rex zone and finer structure coarse grained HAZ in the double pulse weld led to the better mechanical properties in cross tension test.

Residual stress measurements in front of the pre-crack at the weld edge were the main objectives of *chapter 4*. As far as the correlations between residual stress

and mechanical properties of the welds are concerned the following important conclusions could be drawn: double pulse welding of DP1000 steels at low welding currents deteriorates the mechanical performance, whereas at higher currents double pulse welds outperform the welds produced by single pulse scheme. Local residual stress mapping using the slit milling method combined with digital image correlation revealed that the compressive residual stress perpendicular to the plane of the pre-crack decreases or is even fully released at the weld edge of double pulse welds. Diminished mechanical performance of double pulse welds produced at lower welding current is attributed to the lower compressive residual stress state normal to the plane of crack and the formation of martensitic structure in front of the pre-crack with a lower fraction of high-angle grain boundaries and coarser Bain groups, which lead to lower resistant against crack initiation and propagation.

RSW constitutes of complex microstructure gradients with a variety of mechanical responses in a confined space. It is of crucial importance to measure the local mechanical properties of the weld in order to make an accurate prediction of the failure mode and mechanical performance of the weld. *Chapter 5* mainly focuses on the methodology used to measure the local fracture toughness of RSW. Fracture toughness at micro-scale was measured using notched micro-cantilevers milled at different weld zones using focused ion beam. Due to large plastic yielding, linear elastic fracture mechanics were inapplicable. Instead cyclic loading was implemented to track the crack size and the conditional fracture toughness of weld zones was measured using crack tip opening displacement and J-integral methods.

Effect of chemical composition of DP1000 steel on the microstructural evolution and mechanical properties of resistance spot welds were investigated in *chapter 6*. It was shown that a higher carbon content of DP steel leads to the formation of martensitic microstructure in the weld nugget with smaller PAGs and finer block sizes. Furthermore, DP steel containing lower carbon content showed a stronger variant selection as the fraction of variants belonging to the same Bain group is higher for this particular steel. High carbon DP steel showed better tensile-shear properties, whereas low carbon DP steel showed higher maximum load in cross-tension testing. Nanoindentation and micro-cantilever bending techniques were utilized to determine the factors that govern the mechanical response of RSW during two different mechanical testing methods. It was shown that the tensile-shear properties are mainly determined by the strength/hardness of the weld nugget, whereas fracture toughness of the weld is the main factor governing the cross-tension performance of resistance spot welds.

The microstructural evolution and mechanical properties of the 3rd generation AHSS resistance spot welds were studied in *chapter 7*. It was demonstrated that the texture of the martensitic microstructure can be controlled via change in the weld scheme from single to double. It was shown that double pulse welding changes the texture of the single pulse weld from <001>//normal direction of sample reference frame (ND) to <011>//ND. The effect of texture and post heat treatment of the local fracture toughness of the welds was evaluated using micro-cantilever bending. It was revealed that the change in texture of martensite and also ε carbide precipitation during paint baking treatment enhance the fracture toughness of the weld in front of the pre-crack. A direct correlation was found between the fracture toughness of the weld edge and cross-tension properties. Using the combination of nanoindentation and micro-cantilever bending, critical weld nugget size was calculated to ensure pullout failure mode during cross-tension testing.