Assesment of Welding Current on Mechanical Properties and Microstructural Characterstics of Resistence Spot Welding

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Abstract : To increase the efficiency of the automotive vehicles, materials with high strength, good formability and crash resistance are required. The advanced high strength steels (AHSS) are widely used in automotive sectors due to their excellent formability and crash resistance characteristics. Dual phase (DP) steel is a family of AHSS which consists of ferrite matrix with martensite islands. Resistance Spot Welding (RSW) is one of the most prevalent and preferred welding processes for joining automotive body parts. RSW of DP steel has become a very important issue due to an increased number of application in auto-body structures. In this investigation, similar joints of DP600 steel in lap joint configuration were fabricated using RSW process. The process parameters were optimized using DOE (design of experiments) and the welds joints were fabricated using the obtained DOE matrix. The tensile shear fracture load (TSFL) of joints was evaluated using universal testing machine. An empirical relationship was developed to be predict load (Tensile shear fracture) carrying capability of RSW joints of DP600 steel Response Surface Methodology (RSM) was used to optimize the RSW parameter to attain maximum load carrying capability. From this investigation, it is understood that increase in welding current increases the nugget zone size as well as the higher degree of softening in HAZ. The tensile shear strength was found to be increased with increase in welding current up to a certain limit and then it decreases. The microhardness profile shows a peak hardness in nugget zone and the hardness is lower in the HAZ. The softening of HAZ is mainly attributed to inter-critical heating during welding**.**

***IndexTerms* – Dual phase steel, Resistance spot welding, Tensile shear fracture, Microstructures**

I. INTRODUCTION

Advanced high strength steel (AHSS) sheet has been introduced into auto body closures and suspension components resulting in a recent focus on the weldability of these alloys [1]. Resistance spot welding (RSW) is the primary sheet metal joining process in the manufacture of automotive assemblies. The microstructure of AHSS results in mechanical properties that are ideal for automotive applications with a high strength to weight ratio and good ductility; however, microstructural changes during RSW dramatically affect mechanical properties by transforming the base metal microstructure. To date, the microstructures and failure mechanisms of resistance spot welded AHSS have not been examined in sufficient detail. This is essential to the integration of AHSS sheet material in today's automobiles. For example, interfacial fracture, which is believed to have detrimental effects on the crashworthiness of vehicles, is a common occurrence when resistance spot welding AHSS [2]. Advanced high strength steels (AHSS) are engineering materials that combine higher strength (performance), good ductility (formability) and excellent energy absorption (crashworthiness). Amongst all AHSS viz. transformation-induced plasticity (TRIP), complex phase (CP), martensitic steel (MS), ferritic-bainitic (FB), twinning-induced plasticity (TWIP), dual-phase (DP) steel has met ample range of applications in the automobile industry [1]. DP steel is composed of a ferritic matrix with varied volume fractions of martensite phase (i.e. 15~50 %) and, in some cases, small additions of retained austenite, bainite and/or pearlite [1]. The amount of martensite phase is an essential factor governing the mechanical properties of dual-phase steel; for example, DP steel has a number of particular properties like: continuous yielding behaviour (no yield point), low yield strength (i.e. 0.2 percent offset), high tensile strength (up to 1000 MPa), high work-hardening rate, and usually high uniform and total elongation [2].In-service benefits like weight reduction (gas consumption) are realized when using DP steel, and because of the inherent mechanical properties; DP steel has become an attractive material for applications in the auto body construction. An increased number of automotive parts such as rails, bumpers, pillars, panels, etc. made with traditional high strength low alloy steel (HSLA), are being gradually replaced with DP steel [3].

II. DUAL PHASE STEEL

2.1 Introduction

Automotive steels are classified in three different ways considering: the metallurgical designation, the strength, and various mechanical properties or forming parameters. The metallurgical designation includes: the low-strength steels, i.e. interstitial-free and mild steels; conventional high strength steels (HSS), i.e. carbon-manganese, bake hardenable, high-strength interstitial-free; and high-strength low-alloy steels (HSLA); and the relatively newer types of AHSS, i.e. dual-phase, transformation-induced plasticity, complex phase, and martensitic steels. Additional higher strength steels for the automotive market include ferrite bainitic, twinning-induced plasticity, Nano, hot-formed, and post-forming heat treated steels. The second classification related to the strength defines High-Strength Steels (HSS) as tensile strengths from 210–550 MPa, while Ultra-High-Strength Steels (UHSS) steels have tensile strengths greater than 550 MPa. Various mechanical properties or forming parameters of different steels, such as total elongation, work hardening exponent n, or hole expansion ratio define the third classification. For example, the "banana" curve from Fig. 1 compares total elongations – a steel property related to formability – for the different metallurgical types of steel [1].

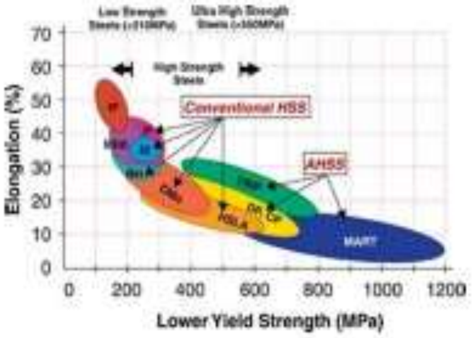


Fig. 1 Schematic of automotive steels [1]

The term “dual-phase” refers to the predominance of two phases that consist of a soft, ductile, polygonal ferrite matrix with hard martensite islands (Fig. 2), and in some cases a small amount of retained austenite, bainite and/or pearlite [44]. Dual-phase (DP) steel is produced either by controlling the transformation of austenite after hot rolling or by inter-critical annealing after cold rolling [45].

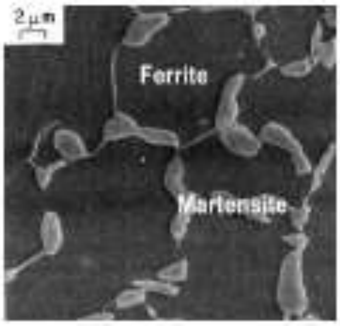


Fig. 2 Ferrite-martensite microstructure of dual-phase steel [2]

DP steel typically exhibits a low yield point and a high strain-hardening coefficient. T Strength- ductility balance is controlled first by the volume fraction of martensite (typically in a range between 7-50%) and secondly on the dispersion of this hard phase. The physical metallurgy of DP steel is complex, mainly due to presence of carbon and additions of manganese. Essentially, carbon enables the formation of martensite at practical cooling rates due to carbon segregation into austenite during the inter-critical annealing treatment. The addition of Mn further promotes the formation of austenite during inter-critic processing. Increasing the Mn content increases the tensile strength and the fracture elongation due to the finer dispersion of the hard martensite phase [46]. Other alloying elements like chromium, molybdenum, vanadium and nickel can also be present within the steel. The inter-critical annealing treatment, the cooling rates and the material determine in high degree the final microstructure of the DP steel.

III. INTER CRITICAL ANNEALING

The dual-phase microstructure is produced by inter-critical annealing (generally in a tenuous annealing line) followed by a critical cooling rate (usually within the range of 15 ~50 °C/s) which promotes the required amount of fine well dispersed martensite necessary to obtain the desired dual-phase mechanical properties [47].The aim of the inter-critical annealing is to form austenite/ferrite mixture by reheating the material up to the inter-critical region. The formation of austenite is basically carried out by the nucleation and growth from ferrite-cementite aggregates. For instance, the formation of austenite is explained by separating the process into various steps [48]. Nucleation of austenite at the ferrite-pearlite interface and further rapid growth of austenite into pearlite. The higher the temperature the faster the completion of dissolution of pearlite: after dissolution of pearlite, further growth of austenite into ferrite occurs. The growth of austenite is controlled by carbon diffusion at high temperatures and shorter times, however if lower temperatures are used, then longer times are required and the growth is controlled by Mn diffusion into ferrite. Final equilibration of Mn content of the austenite and ferrite phases is controlled by Mn diffusion in the austenite which is much slower process than Mn diffusion in ferrite. The times for completion of this process are extraordinarily long. The carbon content of the austenite is governed by the inter-critical temperature. Basically, the hardenability of the austenite phase varies with the inter-critical temperature, for instance, at low temperatures the carbon content of the austenite is high and the hardenability is high. Similarly, at high temperatures the carbon content of the austenite is low, hence the hardenability is low [2].

The introduction of DP steel in auto-body constructions makes resistance spot welding the favoured process for joining this steel. Resistance spot welding (RSW) is a joining method that consists of pressing two or more overlapped metals together while a current is passed through a localized contact area in order to heat the metal to adequate temperature and form the weld nugget [4]. The resistance spot weldability [5,6] of DP steel is however narrower when compared to typical HSLA steel because of the multiphase structure characteristic and the relatively higher alloying level in the former. For instance, it is well established that the tensile performance of spot weldments is highly dependent on the geometric characteristics (size) of the weld nugget [7,8]; however, phase transformations occurring at the fusion zone (FZ) and/or heat affected zone (HAZ) have strong influence on the tensile properties of resistance spot welded dual-phase (RSW-DP) steel [9].

IV. HAZ - SOFTENING

One interesting issue is the reduction in hardness with respect to base metal (softening)Occurring in the HAZ of welded DP steels. For example, softening has been observed upon Different welding processes such as gas metal arc welding [10], laser welding [11], and flash Welding [12], and resistance spot welding [13]. Moreover, HAZ-softening has been reported to be responsible for diminished mechanical properties of welded DP steel; for instance, it has been found that HAZ-softening affects the uniaxial tensile properties of laser butt welded DP steel by strain localization and earlier fractures [14]. Recent reports have shown that formability of welded DP steel is significantly reduced due to formation of soft zones in the outer HAZ [15]. Numerical simulations and experimental results have confirmed that a local decrease in strength in the softened HAZ is responsible in the overall strength and ductility of the tested specimens [16]. In laser welding of various DP steels; both martensite content and heat input have been found to strongly influence the HAZ-softening behaviour; in this regard, it has been observed that softening is proportional to martensite content and the heat input controls the completion of softening [11].

On the other hand, HAZ-softening in resistance spot welding of DP steel (RSW-DP) has been reported several times in literature [13-1 1 19]. It has been observed that softening modifies the lap-shear tensile properties and the failure mode of RSW-DP steel [19,20]. Moreover, it is believed that softening region is weaker in comparison to that of the base material and hence is more susceptible to failure initiation [13]. Interestingly, HAZ-softening in RSW-DP steel has been essentially attributed to the tempering of martensite phase but no details have been provided about this metallurgical issue [9,19]. It is noteworthy to mention that there is a lack of information in the literature regarding to the tempering of martensite subjected to rapid thermal cycles of heating and cooling and with extremely short times at peak temperature (non- isothermal) such as those developed by welding processes, particularly, in the HAZ**.**

V. TEMPERING OF MARTENSITE

Existent literature regarding to the tempering of iron-martensite has been mostly addressed to fully martensitic steels upon isothermal heat treatments [21]. Basically, the tempering of martensite occurs at temperatures below the lower critical (Ac) [24] and during isothermal heat treatments is highly dependent on the maximum peak temperature, the time at peak temperature, the prior microstructure and the alloying level [26]. The process of tempering is developed in series of overlapped stages which can be outlined as: (a) the precipitation and coarsening of carbides, (b) the decomposition of retained austenite, and (c) the recovery or recrystallization of the martensitic sub-structure [21]. Furthermore, there exists little research regarding to tempering of martensite phase in dual-phase steels [32-3 3 3 3 3 38]. Most of these studies have related conventional isothermal tempering heat treatment at various peak temperatures to mechanical behaviour. For instance, it has been found that the tensile strength decreases when increasing the tempering temperature. Moreover, a more complex phenomena occurs with the yield strength as it first increases with temperature but decreases as tempering temperature increases, this was attributed to a number of factors such as carbon segregation, transition from continuous to discontinuous yielding behaviour, and the relief of residual stresses [32].On the other hand, few details have been provided regarding the microstructural characteristics and the kinetics of tempering of martensite phase in DP steel. In this regard; it has been observed that the carbon content within the martensite structure plays an important role on the tempering mechanism. For example, high-carbon martensite are more susceptible to form low-temperature carbides (i.e. e-carbide) [37,35], whereas rod plate-shape cementite was certainly promoted on low-carbon martensite [36]. It is not clear, however the influence of the martensitic sub-structure on the formation of carbides. Interestingly, the tempering of martensite in dual-phase steel when subjected to non-isothermal transformations upon fast heating and fast cooling conditions lacks serious attention, to date; this subject has not been studied.

VI. LITERATURE REVIEW

6.1 Resistance Spot Welding

Resistance spot welding (RSW) is a joining method carried out by pressing two or more overlapped metals together by means of a pair of electrodes through which current is passed thus heating the localized contact area and creating localized melting to form the weld nugget [4]. RSW is one of the oldest processes and the predominant method for joining steel sheets in automotive manufacturing and is the preferred welding process for auto-body construction because it is fast, easily automated, economical, clean and no additional material is required [39]. Amongst the automotive welding processes, RSW is characterized by providing rapid thermal cycles; for instance, very fast heating (i.e. well above 2000 °C/s), extremely short holding times (i.e. few milliseconds) at peak temperature, followed by very rapid cooling rates [40]. The rapid thermal cycle in RSW is accomplished by quick generation of heat at the sheet/sheet interface owing to the high resistance to the welding current flow, which in fact results in formation of molten material first at that interface. Furthermore, once the current flow has been cut off, the electrodes remain in contact with the sheet surface (holding time) for a controlled period of time. During the holding time, the molten material solidifies and the water-cooled electrodes assist in heat removal from the weld zone. Thus, the thermal cycle (RSW) is completed in few seconds and is characterized as providing clearly non-equilibrium conditions within the material. Even though time-temperature-transformation (TTT) and continuous cooling transformation (CCT) diagrams are available for making interpretation of the dynamic nature and kinetics of phase transformations, they are basically material chemistry dependent. Since most AHSS involve relatively novel and proprietary compositions for which CCT data are not available, there is a serious lack of information regarding the metallurgical transformations occurring during the rapid thermal cycles in RSW [41].

VII. RESULTS AND DISCUSSION

6.1 Macrostructure

The macrograph of the weldment is shown in Table 1, produced using a current of 40 kA shows minor nugget formation so the joint was separated after welding. At a current of 45 kA, the thermal energy produced through the electrode is not sufficient to plasticize the material. This insufficient heat resulted in poor weld between the mating surfaces. A uniform nugget formation was noticed in the joint made using a current of 45 kA. The macrograph clearly reveals the uniform nugget formation with weak joint in the top right side of the weldment. The current of 45 kA is approximately sufficient to plasticize the mating surfaces, but the produced heat is not uniform across the width. So, the joint shows defect on the lower side with non-uniform flash formation. The joint fabricated using the current of 50 kA results in sound joint. The macrograph of the weldment.

It reveals the increased current increased weld nugget zone which is attributed to the variation in electrode pressure. From the photograph, it is also evident that the joint is slightly mismatched from its equilibrium position. The macrograph reveals sound joint and the nugget formation. The joint produced using the current of 55 kA resulted in zero defects that is evident from both photograph and macrograph. The nugget formation is also uniform on both the sides and the extent of the weld nugget (WN) zone is wider than the joint produced using 50kA. The photograph of the joint produced using the current of 60 kA yielded a defect at the middle of the joint. This was due to the excess heat formation between the mating surfaces. From the macrograph observations, it is understood that the joints produced using the current of 50 kA and 55 kA exhibited zero defect joints with the appreciable nugget formation. For further analysis and characterization these joints alone utilized.

Table 1 Multi model Controller parameters

Current (kA)	Photograph of Nugget surface	Macrograph of nugget cross -section	Observation
40			Not welded
45			Welded but defect are present
50			Proper penetration
55			Due to current undercut has been taken place
60			Due to high current metal deformation has been taken place

6.2 Microstructural Characteristics of RSW Joint

Microstructure of Nugget Zone (NZ), IF and HAZ are illustrated in Figs. 3 and 4. Both NZ and HAZ shows martensitic microstructure in which Nugget Zone exhibited columnar microstructure. This is attributed to the thermal cycle of these zones experienced during welding. The temperature regime of NZ resulted in melting of this zone whereas the temperature of the HAZ was just above A1 temperature. The high cooling rate of these zones resulted in the formation of martensite. Cooling rate >400 deg C/s have been reported for NZ and HAZ during RSW. The melting and re-solidification of fusion zone or NZ during the process has yielded columnar grains in this one which is a characteristic of cast structure whereas, the thermal cycle undergone by the HAZ has led to the microstructural transformation. Microstructure of NZ and HAZ are illustrated in Fig. 3. Both NZ and HAZ exhibited a martensitic microstructure, and columnar grains in NZ.

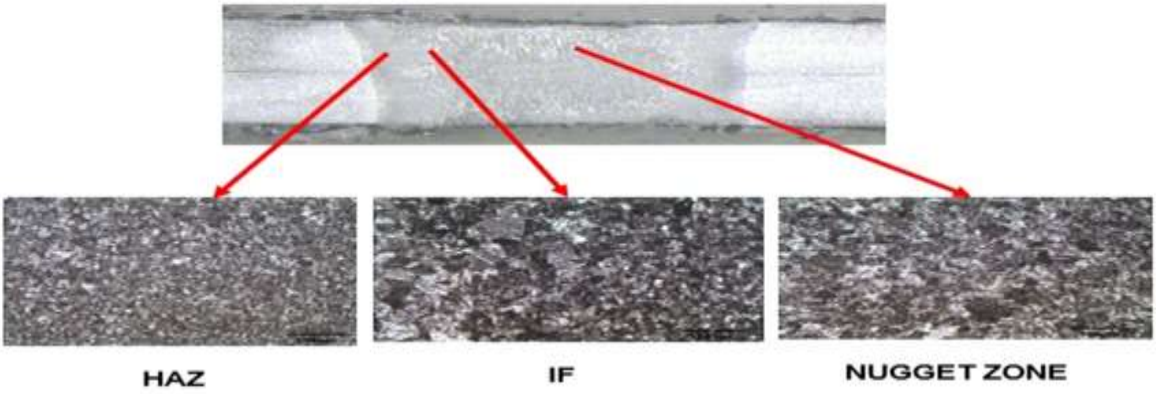


Fig. 3 Microstructural features of joint made using 50 kA

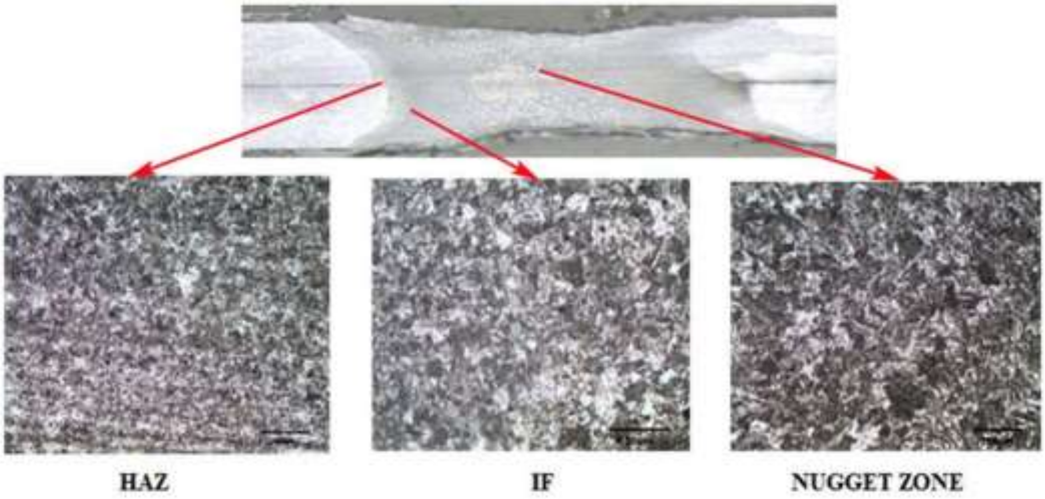


Fig. 4 Microstructural features of joint made using 55 kA

This is related to the heat cycle of both NZ and HAZ during welding. The high cooling rate of NZ and HAZ after attaining A1 temperature has led to the formation of martensite in these zones. It is well established by the researchers that the cooling rate of these zones are >400 oC/s for RSW. The level of cooling rate for RSW is very high when compared to other processes. For DP steels, the rate of cooling for the formation of martensite is approximately 40-120 °C/s) [27-28]. Hence, the observed cooling rate for RSW process is much higher when compared to the actual cooling rate of martensite formation. The diffusion of carbon at such sharp cooling rates is irrational due to the limited time and will assist the formation of martensite at an appreciable amount in the NZ and HAZ. The microstructure for 50 kA depict regular martensite at the middle of the NZ and away from NZ it shows two regions of heat affected zone upper critical (UC) and sub-critical (SC) HAZ.

6.3 Mechanical Properties

The mechanical properties such as tensile shear test and cross tensile test were performed, and the results are furnished. The failure mode is depicted in Figure 6 which is of pull-out type, and also the crack has commenced from the periphery of the weld NZ. The microstructure of the fractured area possesses martensitic structure which is depicted in the above microstructural characteristics. The periphery of the weld nugget zone is the region from which the crack has initiated. The crack initiation is due to the electrode force during welding which emerged as a stress concentration area in the NZ. It is well known that the martensite is a non-deformable phase as a consequence it is not expected to fail in ductile mode. The tensile specimens were failed in heat affected zone which is away from the weld nugget zone. The weld joints exhibited lower ductility when compared to the base metal. The tensile shear test and cross-tensile test results were furnished as load-displacement graph which is depicted in Fig. 5.

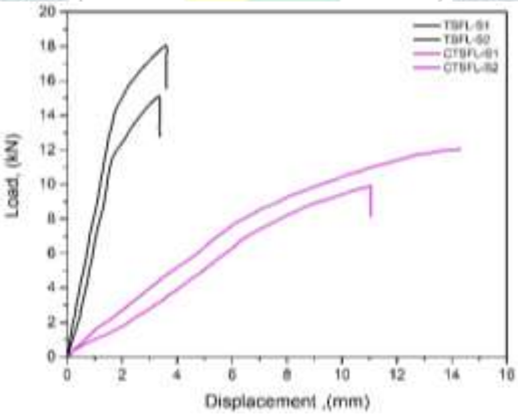


Fig. 5 Load-displacement curves relating to tensile-shear and cross-tensile tests of the studied weldment

The mean load for failure for the cross-tensile samples of 50 kA and 55 kA is 10.02 kN and 7.5 kN receptively while the mean displacement is 15 mm and 11mm. The mean load for tensile shear test samples of 50 kA and 55 kA is 18 kN and 15 kN and the respective mean displacement are 3.5mm and 3 mm. In the present investigation the diameter of the nugget is approximately 7.28 mm and 6.21 mm

6.4 Hardness

The transverse hardness across the weldment is illustrated in Fig. 6. The hardness value of Nugget Zone and BM were observed as 497 and 252 for 50 kA and 449 and 281 for 55 kA respectively. The hardness values of martensite and bainite phases are approximately 450-500 HV and 300-350 HV respectively. The hardness value <300 HV shows the presence of ferrite phase. The high cooling rate in the heat affected zone leads to formation of martensitic structure and the base metal contains ferrite phase which is well established in the microstructural analysis of the weldment.

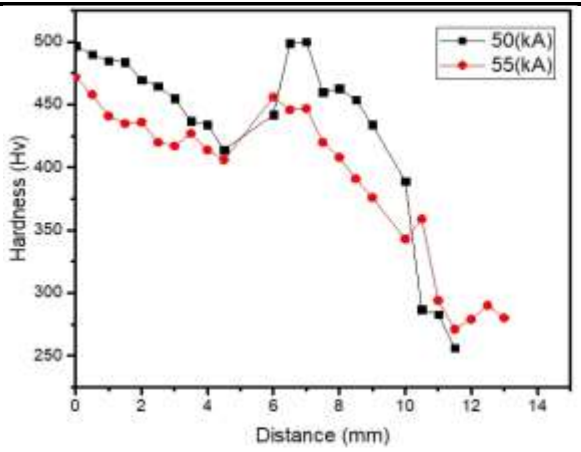
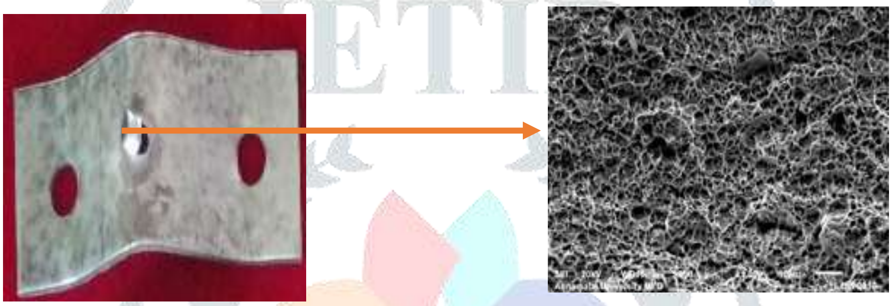


Fig. 6 Load-displacement curves relating to tensile-shear and cross-tensile tests of the studied weldment

The high elastic distortion in the grains of NZ alters the crystal volume thereby lowering the hardness of the heat affected zone when compared to NZ. The formation of martensite is attributed to the shear deformation of the crystal that result in forming elastic distortion as well as dislocations thereby enhancing the hardness. The study on the effect of microstructural characteristics during RSW, hardness survey of the weldment is eminent. This hardness map is correlated with the different zones of the weldment and the mechanical properties of the different zones are studied. In addition to that the hardness survey is instrumental for the assessment of the micromechanical properties of the different zones.

6.5 The Fracture Surface (SEM analysis)



A B

Fig. 7 Fracture surface of the RSW DP600 steel after cross-tensile test (a); detailed appearance of the fracture surface shown in (b)

VIII. CONCLUSIONS

- As the welding current increases depth of the nugget zone also increases thereby increasing weld strength.
- The nugget zone consists of a hard-martensitic columnar microstructure with hardness of497 HV.
- HAZ consist of martensite, and other areas had a BM feature microstructure. The base metal (near HAZ) shows the presence of some carbide phases distributed in ferrite matrix, as a result of tempering.
- Nugget Pull-out failure mode was the characteristic of fractured specimens, while the initial cracks were initiated from the periphery points around the weld region.
- Fracturesurfaceanalysisofthebrokenshear-tensileandcross-tensilespecimensindicated mainly brittle fracture surface; however, the presence of few dimples was also observed in fracture surface.

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