Scienxt Journal of Mechanical Engineering & Technology
Year-2023; Volume-1; Issue-2, pp. 51-68

Weldability and electrode life determination of resistance spot welding of secondary coated automotive interstitial free steel

Md. Tahsin Akhtar[1*]

Amrita Kundu[2]

[1, 2] Metallurgical and Material Engineering Dept.Jadavpur University, Kolkata, West Bengal, India

Soumyajit Koleyb[3]

Mahadev shomeb[4]

[3, 4]Research & Development, Tata Steel, Jamshedpur, Jharkhand, India

**Corresponding Author: Md. Tahsin Akhtar*

Email: *tahsin.akhtar@ternaengg.ac.in*

https://doi.org/10.5281/zenodo.10033153

Abstract:

Organosilane is a secondary coating applied over a primary coating of interstitial free (IF) galvannealed (GA) steel. It boosts corrosion resistance and is hence often used in automotive applications. In this investigation, the resistance spot welding of secondary coated GA-IF steel of 0.8 mm thickness has been studied. The effect on the mechanical properties such as: tension & cross tension strength, nugget diameter and the corresponding failure mode because of change in welding current and respective time was evaluated. In this way, the weld lobe was drawn and weldability of weldments were investigated. It has been found that the energy required to weld the nugget increased by 9 % after 1440 number of uninterrupted spot welds with uniformity in the weld nugget. This article also addresses the test protocol for estimating span of the welding electrodes. It has been perceived that, the electrodes can withstand up to 1440 number of uninterrupted welds without affecting the weld quality (in terms of the joint's strength). Nevertheless, the failure mode changes drastically after 600 number of welds due to expulsion during welding. The initial and final stereo images of truncated electrode which was usedin this experiment were reported to know the condition of electrode after 1440 number of continuous spot welds and found that the bottom electrode was more eroded than that of top electrode.

Keywords:

Organosilane coated GA-IF steel; resistance spot welding; tension test; failure modes; weldability lobe.

1. Introduction:

Interstitial free (IF) steels are essentially a single phase bcc steel, with very low amount of carbon and nitrogen due to which they are suitable for zinc coatings, which is required for automotive body works and are free from carbide precipitates at the grain boundaries (1). Theinterstitial free (IF) steels are made by adding titanium and/or niobium to the molten steel afterdegassing and this offers excellent drawability leads to extensively used for manufacturing carbodies and other different parts. Since IF steels are free from interstitial carbon and nitrogen, these steels possess excellent ductility and formability (2). In performance terms, these steels have to balance several conflicting requirements, i.e. deep-drawing capability, fatigue resistance, tensile strength, light weight and are likely to be subject to reserved cyclic loading in service (3). The coating on IF steels through zinc has resulted in severe welding problems due to its lower electrical resistance and melting temperature than that of steels, and accelerateddeterioration of welding electrode tips affects the productivity of process (4). Therefore, secondary coating in the form of organic compounds has been deposited to enhance the productivity and life of the electrode, termed as Organosilane based thin coated steel.

The effect of welding current and time on the joint strength and failure mode should be considered in the process of design of spot-welded structures. Quality and performance of resistance spot welds are very important for the determination of durability and safety design of the vehicles. Generally, there are three procedures for quality evaluation of spot welds: physical appearance, mechanical properties, and failure mode of the spot weld (5)(6). They can be classified as geometrical factors (weld nugget size, electrode indentation, sheet thick- ness,specimen width, etc.), loading mode (dominated by shear, by normal loading, or combined), and metallurgical factors related to welding thermal cycles and chemical composition of the steel (brittleness of the microstructure in the heat-affected zone (HAZ), presence of inclusions or porosities, etc.) (7)(8)(9). In current industrial practice, weld nugget geometry is consideredas one of the most important parameters for determining the weld quality. The relationship between the weld nugget geometry and tensile shear strength is successfully established (10)(11)(12)(13). Failure mode of RSWs is a qualitative measure for the joint quality. Failure mode can significantly affect load bearing capacity and energy absorption capability of RSWs.Generally, the pullout failure mode is the preferred failure mode due to higher plastic deformation and energy absorption associated with it (14), (15) because of the vehicle crashworthiness which is the main concern in the automotive design, can be dramatically reduced if spot welds fail via the interfacial mode (16). The critical weld nugget geometry for nugget pullout depends on the mechanical properties of base metal, the physical properties of the weld nugget zone and heat-affected zone, as well as the weld coupon geometry (17). The common norm according to the American Welding society for the minimum nugget diameter is equal to or larger than 4√t (t defined as material thickness in mm) (18). However, accordingto Sun et al. (19), a fusion zone size of 4√t cannot produce nugget with a pullout failure modefor both DP800 and TRIP800 spot welds under lap shear loading. In dual phase steels for sheetthickness less than 1.5 mm, Kumar Pal and Bhowmick (18) showed that the average weld nugget diameter should be equal to or larger than 4√t for nugget pull out failure mode.

Resistance spot welding (RSW) process is defined as the joining process in which coalescenceof a metal is produced at the faying surface by the heat generated due to contact resistance andjoule effect when an electric current is passed through the work piece. Electrode force is alwaysapplied before, during and after the application of current so that problem of arcing/expulsionat faying surface is prevented. Major parameters that control RSW process are welding current,weld time, electrode force (20), (21). Dependence of above mentioned parameters leads to the interaction of electrical, thermal, mechanical and metallurgical phenomena, made the process very complicated. Due to such interaction, heterogeneous structure is developed in and aroundfusion zone which are categorically distinct into three zones: 1) Fusion zone or nugget (first melted and then recrystallized), 2) Heat affected zone (HAZ), a region which is not melted butrecrystallized due to heat dissipated from the faying zone. 3) Base metal (BM), a region whichis neither melted nor recrystallized during the process of welding, also called as work piece (see Fig.1.1).

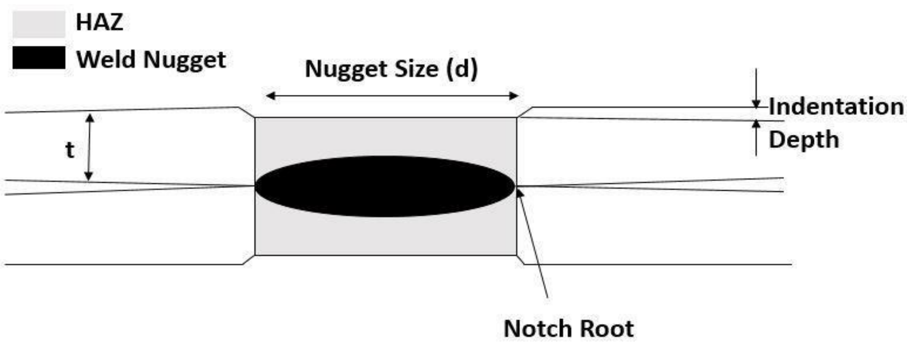


Figure. 1.1: Schematic of spot weld microstructure

2. Experimental:

2.1. Materials:

Commercially synthesized secondary coated interstitial free (IF) steel sheets of 0.8 mm thick were considered for the present investigation. This steel was conventional galvannealed (Zn- 12%Fe alloy coated known as GA coating) steels. The galvannealed layer was 6±2 µm thick corresponding to 70 gm/m^2 of Zn-Fe deposition on either side. A non-metallic organosilane based secondary coating was applied on top of primary GA coating by a commercial roll coater maintaining thickness between 1-3 µm. The chemical composition and mechanical properties are listed in Table. 1. The ensemble of different coatings on the steel substrate and schematic of electrode has been schematically shown in Fig. 1 (a) and 1 (b) respectively.

Table. 1: Chemical composition (in wt. %) and mechanical properties of the steels used in the investigation

C	Mn	Si	P	S	Nb	Ti	N	Tensile strength (MPa)	Yield stress (MPa)	Elongation(%)
0.002	0.067	0.005	0.015	0.009	0.012	0.028	0.0025	280	140	47

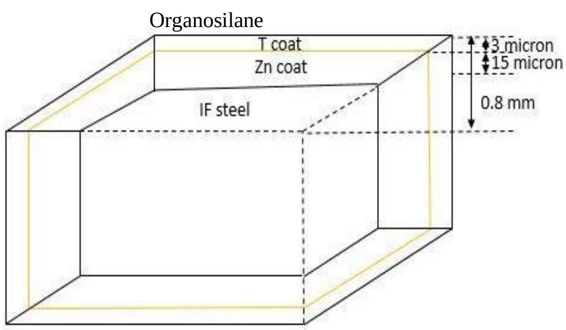


Figure. 1(a): organosilane-based coated GA-IF steel

Figure. 1(b): Cross sectional view of electrode

2.2. Methodology:

The spot welding was performed using a 120 kVA AC pedestal-type resistance spot-welding machine operating at 50 Hz, controlled by a programmable logic controller (PLC). The welding was conducted using a 45-degree truncated-cone Resistance Welder Manufacturers Association (RWMA) Class-2 electrode with a 5 mm face diameter. The composition of electrode was Cu-Cr-Zr having less than 1% is chromium and less than 0.1 is zirconium manufactured by Ador Company. Rectangular pieces (150 X 50 mm) of steel sheets were welded in lap configuration. Welding parameters such as welding current and welding time were varied systematically between 5-8.8 kA and 150 – 300 ms respectively at a constant electrode pressure of 2.2 KN. A Miyachi weld-checker, measured the weld current and voltageduring particular spot welding on the cross tension sample to determine dynamic contact resistance and heat input in Joule. After welding, both the sheets were peeled off to note the modes of failure based on which the weldability lobe was constructed.

Table. 2: Welding parameters for electrode endurance test

Welding current (kA)	Electrode Force (KN)	Weld Time (ms)	Upslope Time (ms)	DwellTime (s)	Electrode Type	Electrode Diameter (mm)
(I)Exp-0.2	2.2	250	20	83	Truncated dome Cu-Cr-Zr	5

Static Contact Resistance (SCR) across the electrode-steel sheet ensemble was measured usinga set-up schematically described in Fig. 2(a). The magnitude of the current was decided as 0.5 kA which was well below the welding current. However, the apparently small current would ensure no heating of the steel specimen and thus the measured resistance would be without any influence of temperature. The instantaneous voltage difference between the electrodes and the passing current were measured using the Miyachi weld-checker.

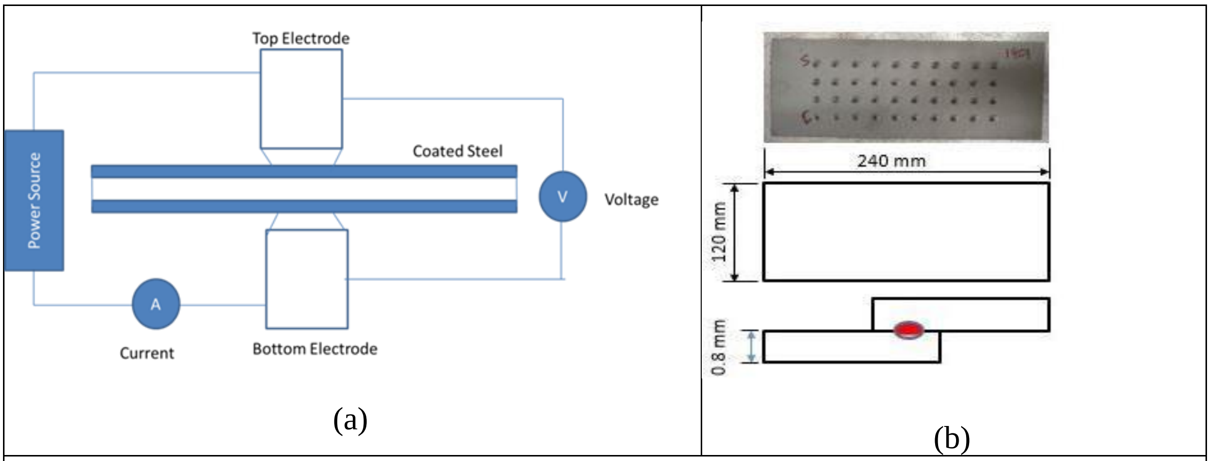


Figure. 2: Schematic description of static contact resistance measurement setup and (b) design of specimen used for continuous welding study

Electrode life was evaluated by measuring the number of spot weld up to which the quality of weld is acceptable. For this test, welding was continuously carried out for 1440 number of welds on a specially designed test specimen (Fig.2 (b)) applying a fixed set of welding parameters (Table. 2). After every 120 continuous spot welds three specimens such as Tensile shear (TS) test, Cross tension (CT) test and Coach Peel (CP) test specimens were prepared andtested in an Instron 5582 machine under a constant crosshead velocity of 3 mm/min. The dimension of TS, CT and CP samples are shown in fig. 4 (a), 4 (b), and 4 (c) respectively. Images of electrode faces were captured by using Olympus stereo microscope to assess any surface changes on the top and bottom of electrodes. Metallography was done on the transversesections of welds by two step etching using 4% picral and 2% nital solution respectively. Optical microscopy was carried out under a

Leica (LEICA DM 6000 M) microscope and scanning electron microscopy was done using a Gemini Supra 25 type SEM. For microstructural analysis eight samples were selected at the welding time of 150, 200, 250, and300 ms with a weld current of 6 and 8 kA through the Vickers micro hardness (X) measurementacross the weld nugget, the heat affected zone (HAZ), and the base metal at a 300 gf of load atan interval of 350 micro meter.

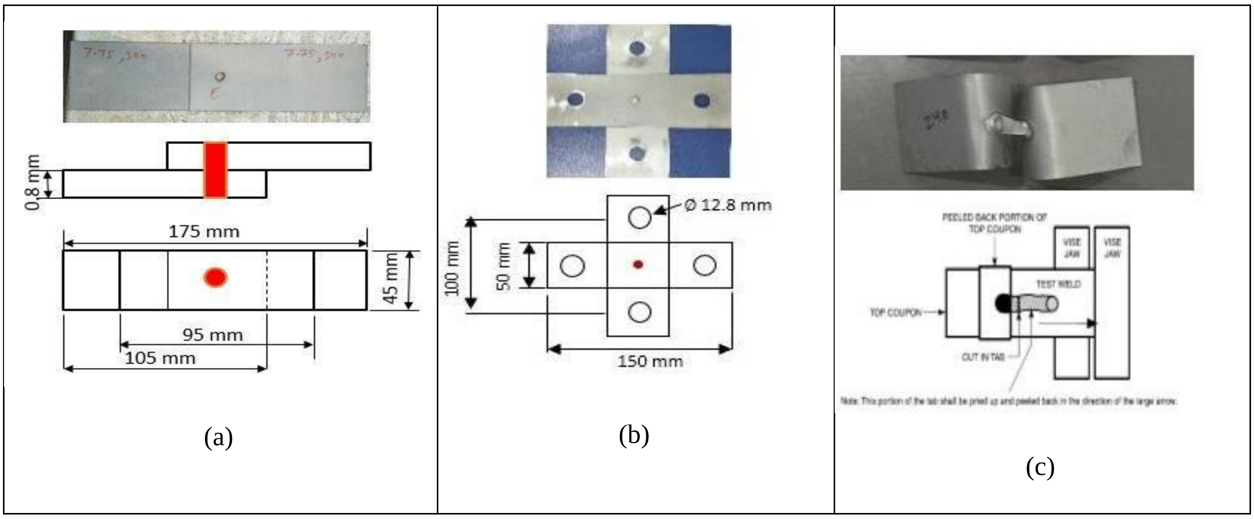


Figure. 3: The schematic diagram of (a) Tensile shear test sample (175*45), (b) Cross tension test sample (150*50) and peel test sample (55*30) (All dimensions in mm).

3. Results and Discussion:

3.1. Weldability Lobe:

Weldability lobe diagram is plotted to identify the range under which welding is to be done sothat it gives optimum result (22), (23). It provides an indication of good quality joining and the tolerance of the weld parameters. Typical weldability lobe consists of weld time and weld current with all other parameters remain constant divides the welding time and the welding current with all other welding parameter remains constant in to different classes depends on the boundary condition. In this study, failure mode (interfacial (IF)/partial interfacial failure (PIF) to pull out failure (PF)) during peel test condition decides the lower boundary of weldability lobe. The crack originates from the weld nuggets is defined as IF mode whereas the crack initiate from the base metal is known as PF mode while in case of PIF, some portionbreaks through IF and remaining through PF. Upper boundary of the weldability is defined bythe minimum welding current and time at which the expulsion initiates (22). The expulsion during the welding leads to hamper the weld quality to the meagre which should be avoided. In fact, it causes more detrimental effects on the service life of the electrode. In this investigation, different welding parameters are available i.e., welding current, welding time, electrode force, dwell time, hold time, squeeze time. In spite of considering all such parameters,only two parameters were consistently varied (such as welding time and welding current) withconstant electrode force of 2.2 KN. The welding current, welding time and the electrode forceare the most important parameters in spot welding (24). As it is rather difficult to change the electrode force in the same rate as the electrodes are "truncated dome shaped," accordingly BS1140:1993 standard, targeted value is 2.2 KN for 0.8 mm thick steel (25).

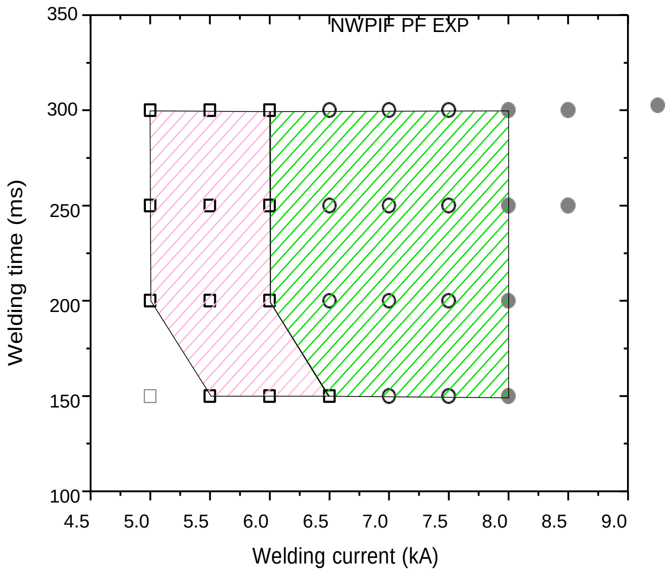


Figure. 4: Weld Lobe at constant electrode force of 2.2 KN.

As shown in Fig. 4, the weld lobe of T-coated IF steel based on welding current and weldingtime gives an indication of good welding parameters and the tolerance of the weld schedule in manufacturing environment (26), (27). The left limit of weld lobe resulting in undersize, weaker nuggets seems like no weld condition particularly between 5.0 to 6.5 kA at 150 to 300 milliseconds. The right limit of weld lobe was established as the nugget diameter is relatively large within the acceptable limit (expulsion region), resulting in severe expulsion which decreases the weld strength. When the welding parameters such as welding current and welding time are high, the spot weld will also have intensive heat. This will affect the nugget size and strength of the weld joint (17), (28). The selection of the left limit of the weld lobe will be determined by the specific demand of automakers. In the present study, weld strength will be used as a criterion to assess the weld quality. It can be seen from the test results that when expulsion takes place and no weld condition, low tensile strength, low cross tension strength and low nugget size will be achieved.

3.2. Tensile shear (TS) and cross tension (CT) performance of the weldability parameter:

The effects of the welding parameters such as welding current and welding time on the, nugget diameter, tensile shear strength and failure mode of the nugget were investigated. As the welding current increases, plug or nugget diameter increases due to higher heat generation. The tensile shear strength of the weldment improves by increasing the heat input associated with the welding current and the welding time as seen in fig. 5.

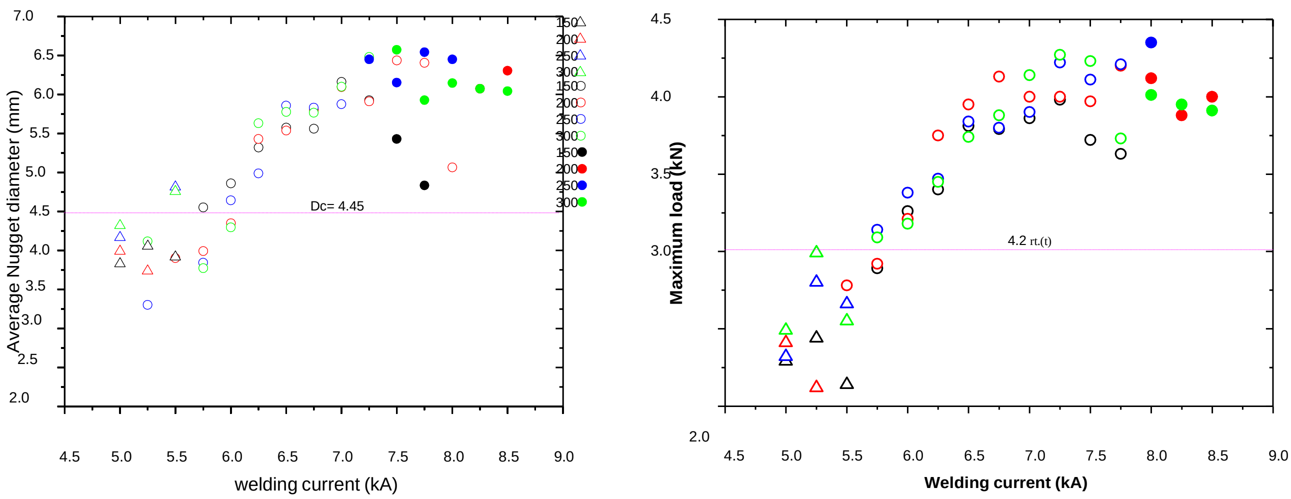


Figure. 5: Variation of Nugget diameter and the tensile strength as the function of welding current and timeat constant electrode force of 3.2 KN

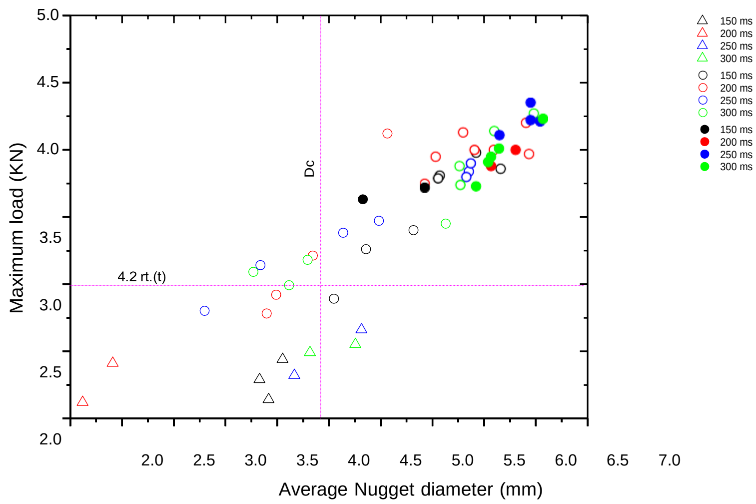


Figure. 6: Variation of maximum tensile strength as the function of average nugget diameter at constant electrode force of 3.2 KN by varying welding current and time

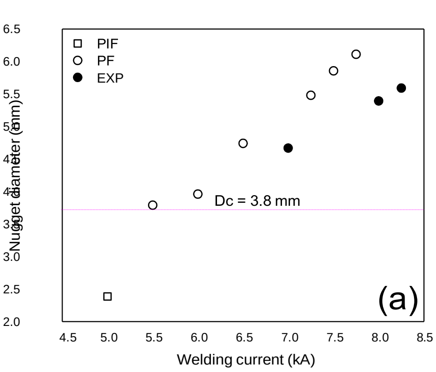
The maximum tensile shearstrength for the welded sample 4.35 KN at the welding current of 8 kA and welding time of 250 ms. Kocabekir et. al (29) also found that tensile shear strength increases with increasing heat input because of enlargement in nugget size. However, it resulted in expulsion (with indication of arcing during welding). The acceptable maximum tensile strength was therefore being 4.27 KN with welding current of 7.25 kA and welding time of 250 m.

The failure modesof the test samples were examined. An interfacial failure mode was assessed till 5.5 kA weldingcurrent for all welding times (Figure 5 and Figure 6). The interfacial fracture mode can be avoided by either reducing the fusion zone hardness or alternatively increasing the nugget diameter for a given sheet thickness (30). Increasing the heat input, enabled a joining of larger area resulting in a desired pullout failure mode. An expulsion was evaluated with welding current of 8 to 8.5 kA for all welding times due to high heat input. There is a critical heat inputwhich results in a PIF type failure (31). In between IF and PIF mode, the PF mode is assessedwith the range of welding currents of 5.5 to 7.75 kA. With the increase of the welding current,the mode of failure changes. This is due to the increase in the nugget diameter (32). The nugget diameter for IF mode was 4.8 mm (tensile load: 2.67 KN). The maximum nugget diameter in which expulsion was started is 6.45 mm (tensile load: 4.35 KN).

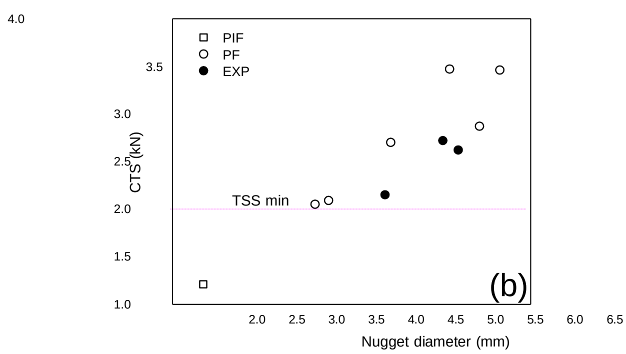
In case of CT performance (fig. 7(a)), as the welding current increases, the nugget diameter increases to 6.5 mm at 7.75 kA and then due to expulsion, nugget diameter start decreasing because of arcing in the form of molten metal due to maximum heat generated and due to which some portion of molted metal get eroded. The maximum cross tension load also increases withthe increase in nugget diameter. The failure mode initially PIF, then PF having maximum CT and TS strength and then expulsion with decreasing trends. As shown in figure 7 (b), maximumcross tension strength is 3.47 at 5.48 mm of nugget diameter when welding current 7.75 kA was made associated with the pullout failure. Expulsion actually started from 8 kA as justifiedby TSS test too. A transition occurred from interfacial fracture to plug fracture as the nugget diameter increased, and the CTS also tended to increase (33).

As seen in fig.7, minimum critical diameter where nugget fails via pull out failure is 3.75 under cross tension test at 5.5 kA. The failure mechanism for pullout failure is proportional tothe ratio of the tensile strength of the FZ to the shear strength of the HAZ (34). The critical diameter in cross tension test decreases as compared to the tensile shear test.

Figure. 7: Effect of welding current and nugget diameter on the cross-tension strength of the spot weld.



6KA and 200ms



8KA and 200m

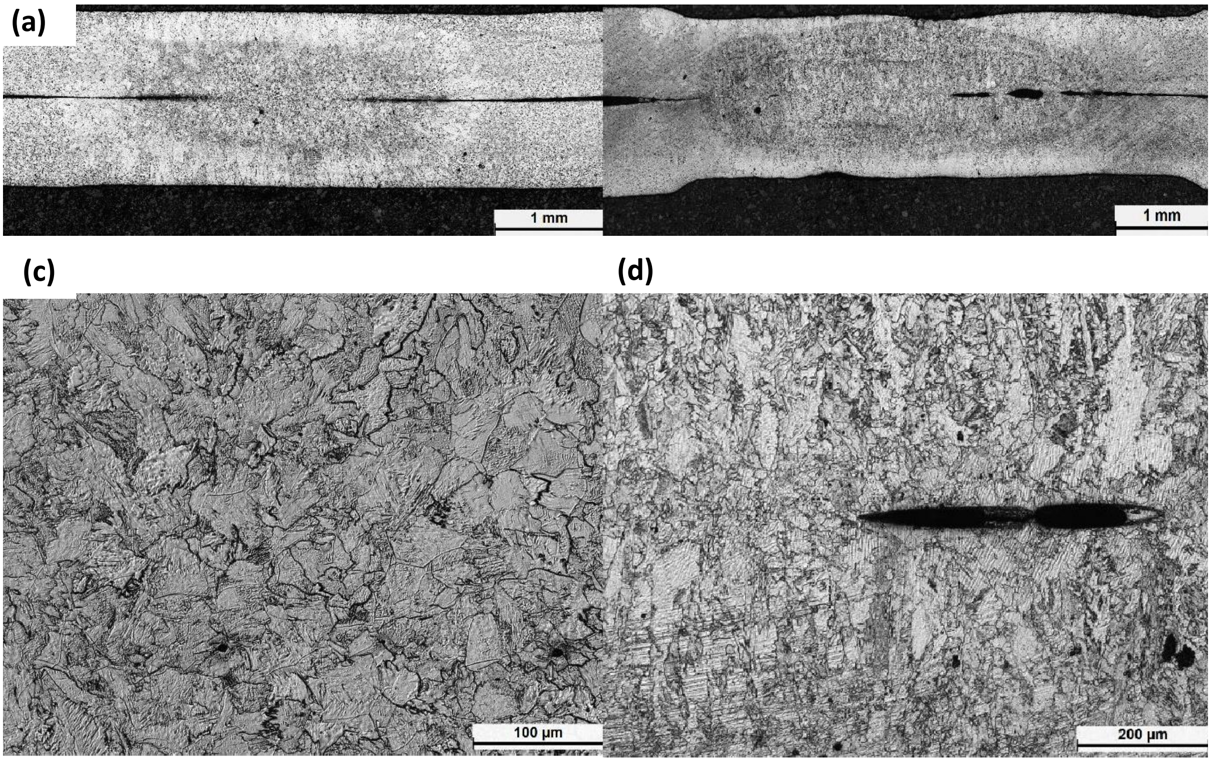


Figure. 8: Etched macrostructure as seen under optical microscope of the weld cross-section of a joint welded with: (a) 6 kA current, 200 ms time and (b) 8 kA current, 200 ms time with constant electrode force of 2.2 KN; weld cross section of the same weld showing (c, d) FZ. The red arrows in (d) indicate presence of defects in FZ during expulsion of welds.

3.3. Endurance test:

3.3.1. Effect of Heat input on number of spot weld:

Nugget diameter shows almost constant trends with all the diameter above $4\sqrt{t}$ and $5\sqrt{t}$ as described by AWS and Japanese standard (Figure 8). The energy was calculated using the equation (1):

Energy input per spot = $\int v(t).I(t).dt$ ....(1)

Where it is the welding time required to complete cycle in ms, v is voltage in v and I is the current in kA. These data were directly taken from the Miyachi instrument during welding. The dynamic contact resistance as seen from fig. 9 (a) with the help of Miyachi instrument can be varied in decreasing order of curve as the number of spot welds increases from initial condition to the 1440 number of spot welds except at 240 and 480 number of spot welds. This may be because of stabilization of electrode with respect to the welding current and origination of expulsion due to less initial contact resistance

As seen from figure 9 (b), the average energyrequired to produce an average nugget of 5.36mm was 2.35 KJ with the fluctuation of ± 0.2 KJbetween 120 numbers of spot welds. As the energy required to produce nugget was higher, thesize of nugget will be lower (35).

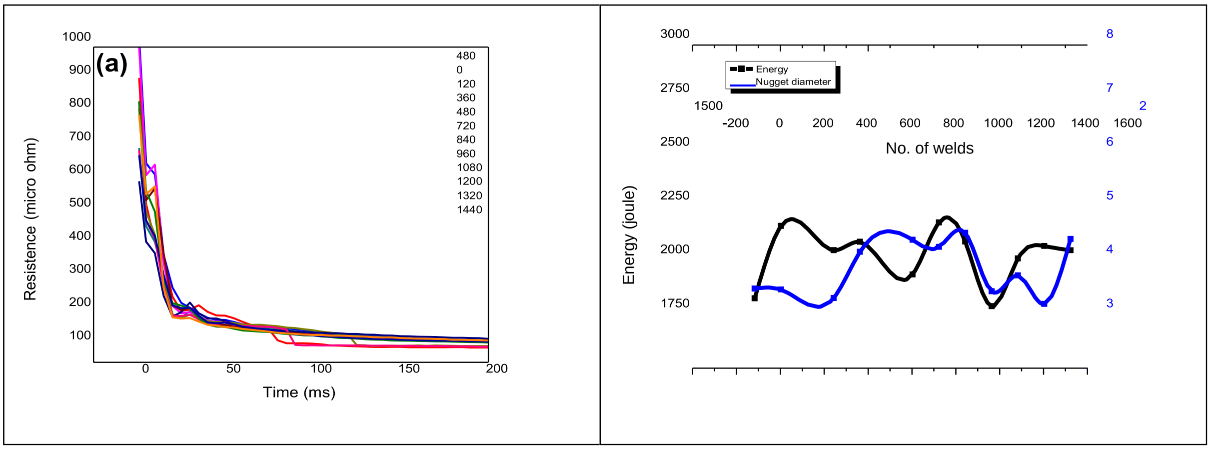


Figure. 9: Variation of: (a) resistance and (b) energy with the number of welds under cross tension test andthe effect of the number of spot welds on nugget diameter.

3.3.2. Effect of mechanical performance on number of continuous spotwelds:

Maximum load and extension at maximum load decrease with the increase in number of continuous spot welds. It is above the minimum tensile load according to AWS and Japanese and NES standard of 3.0 KN at the 1440 number of continuous welds. The maximum tensile strength and extension at maximum load are 4.38 KN and 2.83 mm (Figure 10 (a, b)) at 120 number of spot weld. This was not accepted due to expulsion evaluated at this position. The acceptable maximum tensile strength and extension at maximum load are 4.21 KN and 2.63mm at 480 continuous spot welds and the failure mode was PF. Since spot welding is designedon the basis of maximum crash worthiness for automotive application made PF failure highly preferred because of high weldability due to wide range of plastic deformation and energy absorption (36). As the number of spot welded increases, the mode of failure of the nuggets was first expulsion then pullout failure followed by partial interfacial failure with the decreasing strength of the welded nuggets. Under cross tension test as shown in figure 10 (c, d), the minimum cross tension strength is 1.9 KN and the minimum extension at the maximumload is 26 mm. The trend shows that it is almost constant over the entire number of welds (1440).

As shown in fig. 10 (c, d), the cross-tension strength of the initial weld and the final weld (1440 number of continuous spot welds) remains approximately same. The maximum cross tension strength and extension at the maximum load is 3.22 KN at 600 number of spot weld and 30.13 mm at 480 number of spot weld respectively. The strength and extension at the maximum load was evaluated in the form of PF with some sort of expulsion. Moreover, with the lapse of number of spot welds, the cross-tension strength first showed an increase up to 600number of continuous welds and then drops rapidly to 2.51 KN at 960 continuous welds. Thishappened because during expulsion the mode of failure was pullout failure but at 720 continuous welds, the mode of failure was partial interfacial failure with no expulsion.

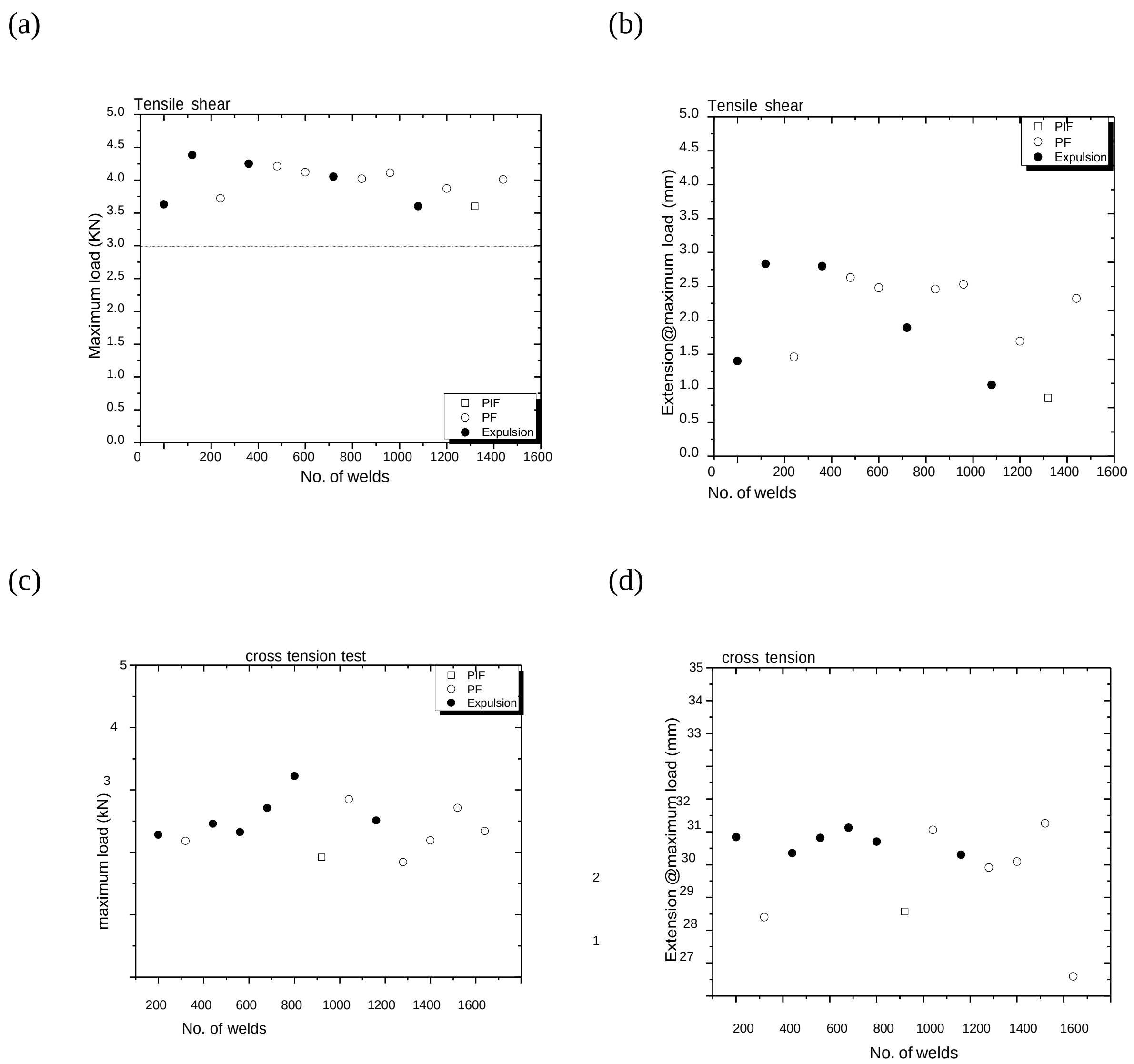
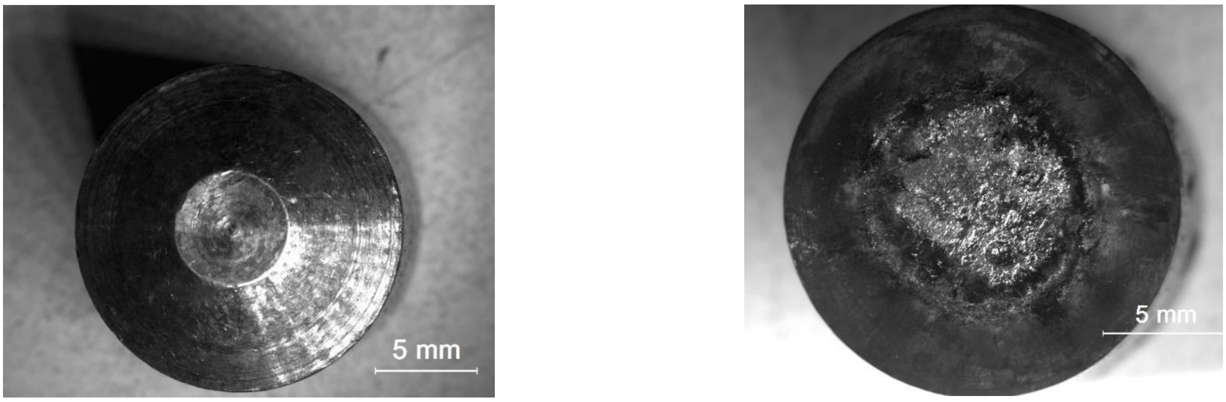


Figure. 10: Effect of the maximum load and extension at the maximum load on the number of spot welds subjected to TSS and CT

3.3.3. Electrode condition:

During endurance test, the electrode gets eroded as the number of continuous spot welds increases as shown by stereo images in figure 11. After 1440 number of continuous welds, thecentre portion of face of truncated electrode get eroded because of the heat generated during continuous spot welds were constant made the electrode life not degradation first otherwise they may have fail to develop the standard nugget diameter. Formation of brass on the top faceof electrode (reaction of zinc coating with that of cu electrode at the elevated temperature ~1700^{o}c). The width of top face of electrode increases leads to the lower energy density madethe spot undersized. Since Cu electrode is softer than that of zinc metal, therefore after repetition of spot welding, electrode get eroded as seen in figure 11, the initial and final condition of electrode. As compare to mushrooming effect on the electrode, degradation is thedominating phenomenon because of secondary coated IF steel (37). The minimum height of new fresh electrode was ~2209.04 µm at the horizontal distance of 6000 µm and height of topelectrode was ~1995.10 µm and bottom electrode was ~1449.590 µm at the same horizontal distance after 1440 number of spot welds as shown in figure 12. The more deterioration of bottom electrode may be due to the action of more pressure on the fixed support bottom electrode as top one was movable in nature.



(a) Initial condition ***(b) Final condition***

Figure. 11: Stereo image of the electrode in (a) initial condition and (b) after 1440 number of spot welds.

3.3.4. Tensile shear performance

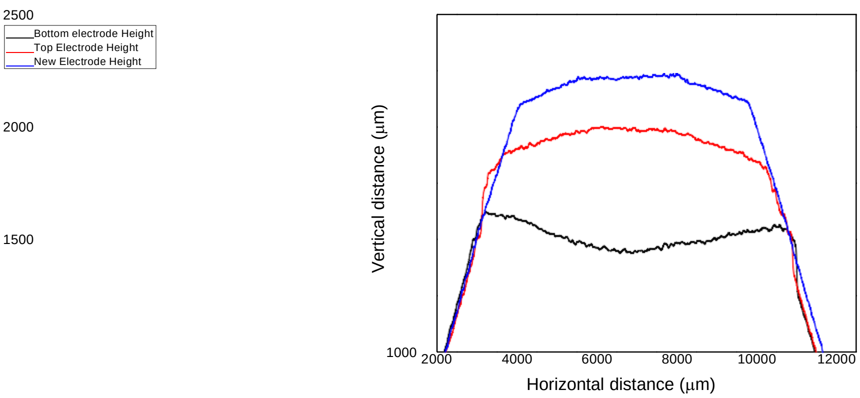


Figure. 12: Electrode condition before and after 1440 number of spot welds.

4. Conclusion:

Based on existing weldability window, endurance test was carried at 7.75 kA of welding current, 300 ms of weld time and 3.2 KN of electrode force in an automated zig assisted weldingmachine. It was found that ~ 1440 spots were welded with no significant deterioration of weldquality. The weld nugget diameter (was higher than 4.25√t condition) with satisfactory TSS and CTS value.

The energy input per welding was calculated from dynamic contact resistance (DCR) and was found to be consistent at ~2.4±0.12 kJ. Consequently, the nugget diameter was at ~ 5.4±0.5 mm for all the spot weld. The maximum load bearing capacity of the welds were at 4±0.25 KNwhich is mare to an acceptable. Formation of brass on the top face of electrode (reaction of zinc coating with that of cu electrodeat the elevated temperature ~1700^{o}c). The width of top face of electrode increases leads to thelower energy density made the spot undersized.

5. References:

(1) "Feliu Jr S, Perez-Revenga ML. Effect of alloying elements (Ti, Nb, Mn and P) and the water vapour content in the annealing atmosphere on the surface composition of interstitial free steels at the galvanizing temperature. Appl Surf Sci 2004; 229:112–23."

(2) "Narayanasamy R, Sathiya Narayanan C. Forming limit diagram for interstitial free steels supplied by Ford India Motors. Mater Des 2007; 28:16–35."

(3) "James MN. Intergranular crack paths during fatigue in interstitial-free steels. Eng Fract Mech 2009;77:1998–2007."

(4) "Chen Zheng, Zhou Y. Surface modification of resistance welding electrodes by electro-spark deposited composite coatings. Part II. Metallurgical behavior during welding. Surf Coat Technol 2006;201:2419–30."

(5) "Goodarzi M, Marashi SPH, Pouranvari M, Mater J (2009) Dependence of overload performance on weld attributes for resis- tance spot welded galvanized low carbon steel. Process Technol 209:4379–4384."

(6) "Pouranvari M, Mousavizadeh SM, Marashi SPH, Goodarzi M, Ghorbani M (2011) Influence offusion zone size and failure mode on mechanical performance of dissimilar resistance spot welds of AISI 1008 low carbon steel and DP600 advanced high strength steel. Mat."

(7) "Williams N, Jones T (1979) Spot weld size and fracture mode in low carbon mild steel. Met Constr 11:541–546."

(8) "Gould J, Workman D (1998) Fracture morphologies of resistance spot welds exhibiting hold time sensitivity behavior. Sheet Metal Welding Conference VIII, Michigan Papers 14-16."

(9) "Dancette S, Fabregue D, Massardier V, Merlin J, Dupuy T, Bouzekri M (2011) Experimental and modeling investigation of the failure resistance of advanced high strength steel spot welds. Eng Fract Mech 78:2259–2272 12."

(10) "Zhang US, Zhang XY, Lai XM, Chen GL (2007) Online quality inspection of resistance spot welded joint based on electrode indentation using servo gun. Sci Technol Weld Join 12:449–454."

(11) "Wu KC (1968) Electrode indentation criterion for resistance spot welding. Weld J 10:472–478."

(12) "ZhouM, Zhang H, Hu SJ (2003) Relationships between quality and attributes of spot welds. Weld J 77:72–77."

(13) "Heuschkel J (1952) The expression of spot weld properties. Weld J 31:931–943."

(14) *X. Sun, E.V. Stephens, M.A. Khaleel, Eng. Failure Anal. 15 (2008) 356–367.* .

(15) "P. Marashi, M. Pouranvari, S. Amirabdollahian, A. Abedi, M. Goodarzi, Mater. Sci. Eng. A 480 (2008) 175–180."

(16) "M.I. Khan, M.L. Kuntz, Y. Zhou, Sci. Technol. Weld. Joining 13 (2008) 294–304."

(17) "Aslanlar S, Ogur A, Ozsarac U (2008) Welding time effect on mechanical properties of automotive sheets in electrical resistance spot welding. Mater Des 29:1427–1431."

(18) A. D8, "Recommended practices for test methods and evaluation the resistance spot welding behavior of automotive sheet steels," pp. 9–97, 1997.

(19) "Sun X, Stephens EV, Khaleel MA (2008) Effects of fusion zone size and failure mode on peak load and energy absorption of advanced high strength steel spot welds under lap shear loading conditions. Eng Fail Anal 15:356–367."

(20) C. L. Jenney, A. O'Brien, and Welding Handbook Committee., *Welding handbook. Volume 1, Welding science and technology*.

(21) *"Handbook for resistance spot welding", 2005, Miller Electric Manufacturing Co.,*

Appleton, WI.

(22) "Emre, H. E. and Kaçar, R., Development of weld lobe for resistance spot-welded TRIP800 steel and evaluation of fracture mode of its weldment. Int. J. Adv. Manuf. Technol. 2016, 83, 1737–1747."

(23) "Cho, Y., Li, W., Hu, S. J., Design of experiment analysis and weld lobe estimation for aluminum Resistance spot welding. Welding Journal, 2006. 85: p. 45-51."

(24) "Tumuluru M (2010) Resistance spot weld performance and weld failure modes for dual phase and TRIP steels. Failure Mechanisms of Advanced Welding Processes A, In: Woodhead Publishing Series in Welding and Other Joining Technologies, Edited by: X.Sun, ISBN."

(25) "Aslanlar S (2006) The effect of nucleus size on mechanical properties in electrical resistance spot welding of sheets used in automotive industry. Mater Des 27:125–131."

(26) "Ruuki part of SSAB, http://www.ruukki.com/~/media/Files/Steel- products/Cold- rolled-metal-colour-coated-instructions/Ruukki- Resistance-welding-manual.pdf."

(27) "Xinmin L, Xiaoyun Z, Yansong Z, Guanlong C (2007) Weld quality inspection based on online measured indentation from servo encoder in resistance spot welding. IEEE Trans Instrum Meas 56:1501–1505."

(28) "Satonaka KK, Okamoto S (2004) Prediction of tensile-shear strength of spot welds based on fracture modes. Weld World 48: 39–45."

(29) F. Hayat, "An effect of heat input, weld atmosphere and weld cooling conditions on the resistance spot weldability of 316L austenitic stainless steel an effect of heat input, weld atmosphere and weld cooling conditions on the resistance spot weldability of 316L au," *J. Mater. Process. Technol.* ·, vol. 195, no. January, pp. 327–335, 2008.

(30) "TECHNIQUES FOR IMPROVING THE WELDABILITY OF TRIP STEEL USING RESISTANCE SPOT WELDING G Shi and S A Westgate TWI Ltd, Cambridge, United Kingdom."

(31) U. T. Steels, "Resistance Spot Weldability of Galvanize Coated and Uncoated TRIP Steels," 2016.

(32) M. Pouranvari, S. P. H. Marashi, M. Pouranvari, and S. P. H. Marashi, "Factors affecting mechanical properties of resistance spot welds Factors affecting mechanical properties of resistance spot welds," vol. 0836, 2013.

(33) G. Watanabe, T. Amago, Y. Ishii, H. Takao, T. Yasui, and M. Fukumoto, "Improvementof cross-tension strength using concave electrode in resistance spot welding of high- strength steel sheets," *AIP Conf. Proc.*, vol. 1709, no. February, 2016.

(34) P. Marashi *et al.*, "Relationship between failure behaviour and weld fusion zone attributesof austenitic stainless steel resistance spot welds Relationship between failure behaviour and weld fusion zone attributes of austenitic stainless steel resistance spot welds," vol. 0836, 2013.

(35) X. Sun, E. V. Stephens, and M. A. Khaleel, "Effects of fusion zone size and failure mode on peak load and energy absorption of advanced high strength steel spot welds under lap shear loading conditions," *Eng. Fail. Anal.*, vol. 15, no. 4, pp. 356–367, 2008.

Cite as

Md. Tahsin Akhtar, Amrita Kundu, & Soumyajit Koleyb, Mahadev shomeb. (2023). Weldability and electrode life determination of resistance spot welding of secondary coated automotive interstitial free steel. In Scienxt Journal of Mechanical Engineering & Technology (Vol. 1, Number 2, p. 18). Zenodo. https://doi.org/10.5281/zenodo.10033153*