JMEPEG (2012) 21:748–755
DOI: 10.1007/s11665-012-0189-0

1059-9495/$19.00

Investigation of Mechanical Properties of Galvanized Automotive Sheets Joined by Resistance Spot Welding

Ugur Ozsarac

(*Submitted October 21, 2011; in revised form February 7, 2012*)

In this study, the electric resistance spot welding process was applied to zinc-coated steel sheets used in automotive industry. Spot welding parameters namely, electrode form, electrode material, and electrode force were stayed constant, and welding current and welding time have been changed to detect the optimum welding parameters for maximum joint strength. Using 4, 5, 6, 7, and 8 kA welding currents and 5, 10, 15, 20, and 25 cycles welding times 1.0-1.0 mm sheets were spot welded to prepare samples. These spot-welded joints were then exposed to uniaxial tensile test, and tensile-shear and tensile-peel forces prior to breaking were determined. In addition, microstructures were detected by SEM and micro-hardness was measured from different regions of resistance spot-welded samples and recommendations showing the optimum welding parameters were given to users.

Keywords automotive, joining, mechanical testing, tensile properties, welding

1. Introduction

Electrical resistance spot welding is a modern welding method commonly used in automotive manufacturing. It is one of the oldest electric welding processes in use by industry today. The weld is made by a combination of heat, pressure, and time. As the name implies, it is the resistance of the material to be welded to current flow that causes a localized heating in the part. The pressure is exerted by the tongs and tips. In resistance spot welding; electric current flow time, sheet thickness, the amount of current, cross-sectional area, and contact surfaces of the welding tips are important factors affecting the quality of weld joint (Ref 1, 2). Spot welding is one form of resistance welding, which is a method of welding two or more metal sheets together without using any filler material by applying pressure and heat to the area to be welded. The process is used for joining sheet materials and uses copper alloy electrodes to apply pressure and convey the electrical current through the workpieces (Ref 3). In all forms of resistance welding, the parts are locally heated. In automotive industry, weight reduction is strongly demanded for energy and natural resource savings. Resistance spot welding is a widely used and important welding process in automotive body construction because of its low cost, easy automation, minimum skill requirements, and robustness to part tolerance variations (Ref 3). Typically, there are about 2000-5000 spot welds in a modern vehicle (Ref 4). The quality and mechanical behavior of resistance spot welds significantly affect durability and crashworthiness of vehicle (Ref 5). In resistance spot welding, metallic sheets are joined by a nearly ellipsoidal region of melted and re-solidified metal called the nugget (Ref 6). Weld quality is highly dependent on nugget diameter. When the melting point of the metal is reached, the metal will begin to fuse and this nugget begins to form. The current is then switched off and the nugget is cooled down to solidify under pressure (Ref 4). In general, the spot weld failure occurs in two modes: interfacial and pullout. In the interfacial mode, failure occurs through nugget, while in the pullout mode failure occurs by complete (or partial) nugget withdrawal from one sheet (Ref 5). One of the problems facing in industry is the joining of dissimilar materials. In making a spot weld between dissimilar metals, a heat balance must be achieved that compensates for the differing properties such as electrical and thermal of the two metals resulting in the production of a weld nugget of the two metals, having approximately the same thickness on each side of the interface. Low carbon steel can be spot welded to most other ferrous metals and to many nonferrous materials producing a weld nugget that is an alloy of the two metals (Ref 7).

Many researchers investigated the joining of galvanized steels by electrical resistance spot welding and the other welding methods. Hamidinejad et al. (Ref 8) analyzed and modelled the process parameters of resistance spot welding on galvanized steel sheets used in car body manufacturing. Marashi et al. (Ref 5) studied the microstructure and failure behavior of dissimilar resistance spot welds between low carbon galvanized and austenitic stainless steels. Vural et al. (Ref 9) investigated the effect of welding nugget diameter on the fatigue strength of the resistance spot-welded joints of different steel sheets as galvanized steel sheets and austenitic stainless steel. Mei et al. (Ref 10) made a research on laser welding of high-strength galvanized automobile steel sheets.

This article is an invited submission to JMEP selected from presentations at the Symposia "Wetting, soldering and brazing" and "Diffusion bonding and characterization" belonging to the Topic "Joining" at the European Congress and Exhibition on Advanced Materials and Processes (EUROMAT 2011), held September 12-15, 2011, in Montpellier, France, and has been expanded from the original presentation.

Ugur Ozsarac, Department of Metallurgical and Materials Engineering, Technology Faculty, Sakarya University, Sakarya, Turkey. Contact e-mail: ozsarac@sakarya.edu.tr.

Goodarzi et al. (Ref 4) investigated the dependence of overload performance on weld attributes for resistance spot-welded galvanized low carbon steel. Kim et al. (Ref 11) welded galvanized sheets by CO_2 laser and micro-plasma arc hybrid welding method. Mozurkewich et al. (Ref 6) made tests of spot weldments by ultrasonic method. Tang et al. (Ref 12) studied the influence of welding machine on mechanical characteristics of the resistance spot welding process and weld quality. In addition to weld machine, the electrodes of the process play an important role on the quality of joints. For this reason, Zhang et al. (Ref 13), and Chatterjee and Waddell (Ref 14) investigated the characteristics of electrode wear in resistance spot welding of dual-phase steels, and Fukumoto et al. (Ref 15) studied the effects of electrode degradation on electrode life in resistance spot welding of aluminum alloys and finally, Holiday et al. (Ref 16) researched the relative contribution of electrode tip growth mechanisms in spot welding of zinc-coated steels. Not only steels but also nonferrous alloys can be joined by resistance spot welding; for example, Rashid (Ref 17) investigated the wear properties of electrode/worksheet interface joined by resistance spot welding of 5xxx series aluminum alloys used in auto body inner panel and frames. Except rare examples, spot welding method is applied to steels and the weldability of galvanized steel sheet is more demanding than that of ordinary steel sheets for the existence of spatter generating and electrode pollution during the spot welding. This limits the application of galvanized steel sheets and the large-scale automatic fabrication of automotive products.

This research study was carried out to show the effect of spot welding parameters on tensile properties of zinc coated (i.e., galvanized) steel sheet joints, because these are applied in automotive applications by resistance spot welding method. There are many publications mentioned above dealing with spot welding technique especially with the electrodes used and their specifications, failures, etc.; but there are fewer studies exhibiting the effect of the main welding parameters like welding current and weld time (cycles) on mechanical properties of joints. In a recent study, Aslanlar (Ref 2) has presented the effect of nucleus size (weld nugget size) on mechanical properties of spot-welded galvanized micro-alloyed steel sheets with 0.8 mm thickness. In this study, the spot welding method was applied to galvanized steel sheets with a thickness of 1.0 mm. The failure in spot weld nugget was seen at the end of two tests named tensile-shear and tensile-peel during loading conditions, and both types of tensile tests were applied to specimens to characterize the failure mode in this study.

2. Experimental Work

2.1 Materials

In this study, zinc-coated (i.e., galvanized) steel sheets were selected and joined by the electrical resistance spot welding method. The electrode form and material and electrode force were assumed constant, and welding current and welding time were selected as parameters. The specimens were prepared according to the standards and the sizes of them are shown in Fig. 1 and the chemical composition of galvanized steel is given in Table 1.

The galvanized steels should be exposed to skin-pass application, because skin-passing is a critical step to achieve superior surface quality, especially for painted and coated steel products. It also produces an extra smooth bare product and is especially beneficial for painted products. The increased requirements demanded of cold-rolled steels in terms of mechanical properties and surface quality have meant that skin pass rolling, as the last step in the process chain, has become more important because the control of flatness and surface quality are required by automotive industry. Steels used in this study were skin-passed in dry condition and exposed to low volume lubrication. In this study, our galvanized steels were zinc-coated by electro-galvanizing method and the corresponding Zn coating thickness was 2.8 µm. The coated surface shall have good phosphating, painting finish, and corrosion resistance. The measured surface roughness value prior to spot welding operations was R_a = 1.21 µm. This was a reasonable value, because the target of steel producers is 1.0-1.8 µm for Roughness-A value.

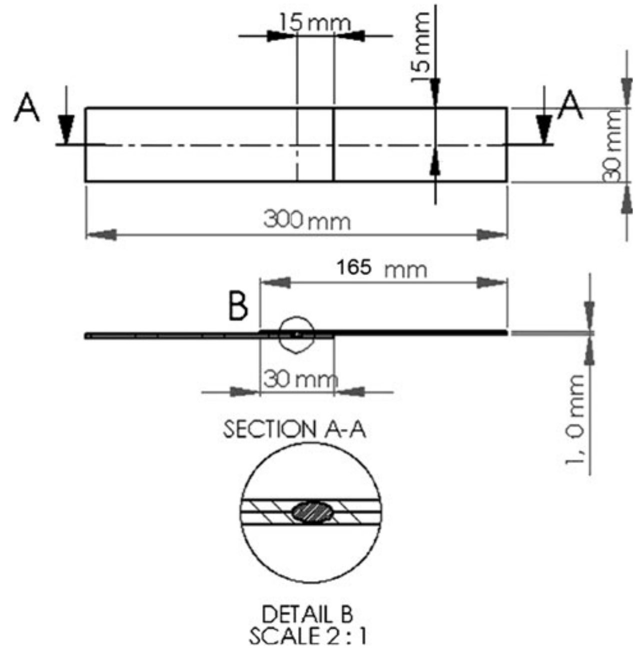

Fig. 1 Specimen sizes in electrical resistance spot welding

Table 1 Spectrometric analysis of galvanized steel sheets

Chemical composition	C	Mn	P	S	Si	Al	Ti
wt.%	0.039	0.039	0.009	0.008	0.012	0.039	0.001

2.2 Welding Operations

The electric resistance spot welding operations were performed with a time and current controlled double armed, pneumatic and having 120 kVA capacity spot welding machines. The electrode compression force was continuously measured and controlled during the operations. In addition, the welding current was measured and recorded. The other parameters were adjusted automatically. The spherical toe electrodes having 16 mm diameter were used. The specimens were prepared and cleaned. After that, these parts were overlapped with 30 mm spacing and spot welded. The welding times were selected as 5, 10, 15, 20, and 25 periods (i.e., cycles) and the welding current was determined as 4, 5, 6, 7, and 8 kA. The welding current was increased from 4 to 8 kA by 1 kA increments. The electrode pressure was stayed constant at 6 kN. All specimens were cleaned with alcohol and acetone sequentially prior to welding. The spot welding path is shown in Fig. 2 schematically. Spot-welded joints were then subjected to the tensile-shear and tensile-peel tests as presented in Fig. 3 and 4, respectively, in Instron 5582 type tensile test machine.

2.3 Tensile Tests

Mechanical properties and performance of resistance spot-welded joints are generally considered under static or quasi-static loading condition. The tensile-shear and tensile-peel tests are the most widely used tests for evaluating the spot weld mechanical performance in static conditions. More cracks and failures tend to occur around these welds, in the heat-affected zone (HAZ), because those joints are exposed to dynamic and static loads in the automobile structures (Ref 4, 7). Specimens were prepared according to the mentioned weld current and weld cycle parameters by means of spot welding method, and the tensile test results were given below. Every tensile test was repeated three times and the mean of them is given as bar plots in Fig. 6.

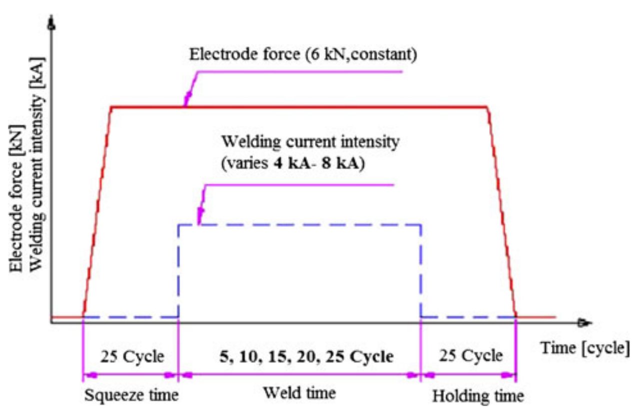

Fig. 2 Basic welding cycle for spot welding

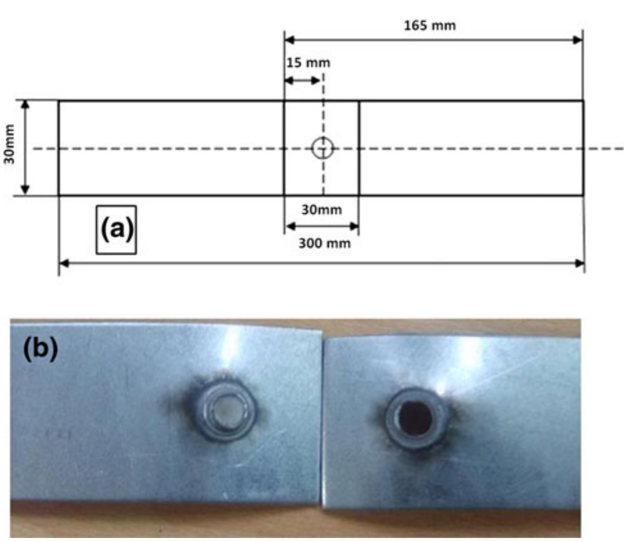

Fig. 3 (a) Sizes of tensile-shear test sample and (b) specimens after tensile-shear test

3. Results and Discussion

3.1 The Tensile-Shear and Tensile-Peel Test Results

The galvanized steel sheets were joined by means of resistance spot welding in a combination as 1.0-1.0 mm and were exposed to tensile-shear and tensile-peel tests. The tensile speed was remained constant during the tests. The values given as tensile-shear and tensile-peel strength are the maximum values read from the scale of the machine. The welding time and the welding current affect the tensile-shear and tensile-peel strengths of weld joints, so they were chosen as parameters. The sizes of weld nugget (nugget diameter: dn and nugget height: hn) occurred in joint zone of sheets are very important

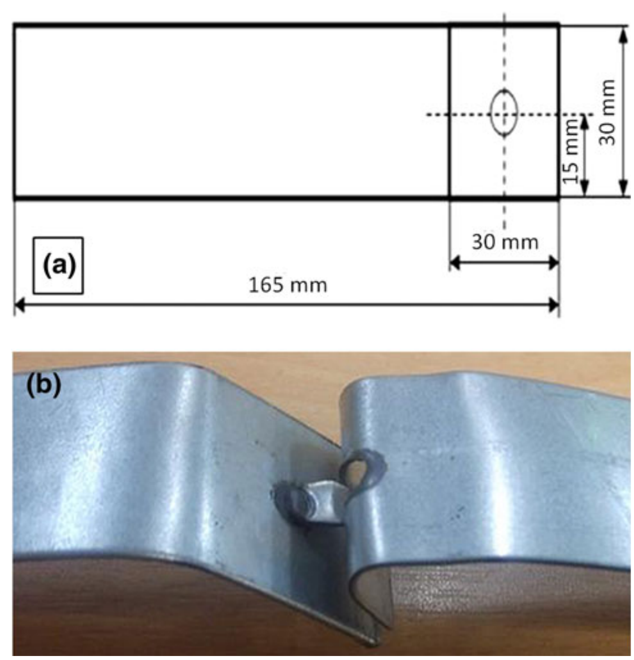

Fig. 4 (a) Sizes of tensile-peel test sample and (b) specimens after tensile-peel test

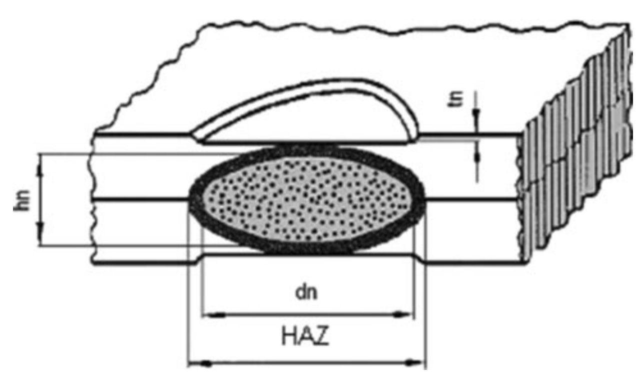

Fig. 5 Weld nugget geometry (Ref 2) (dn nugget diameter, hn nugget height, and tn the depth of electrode indentation)

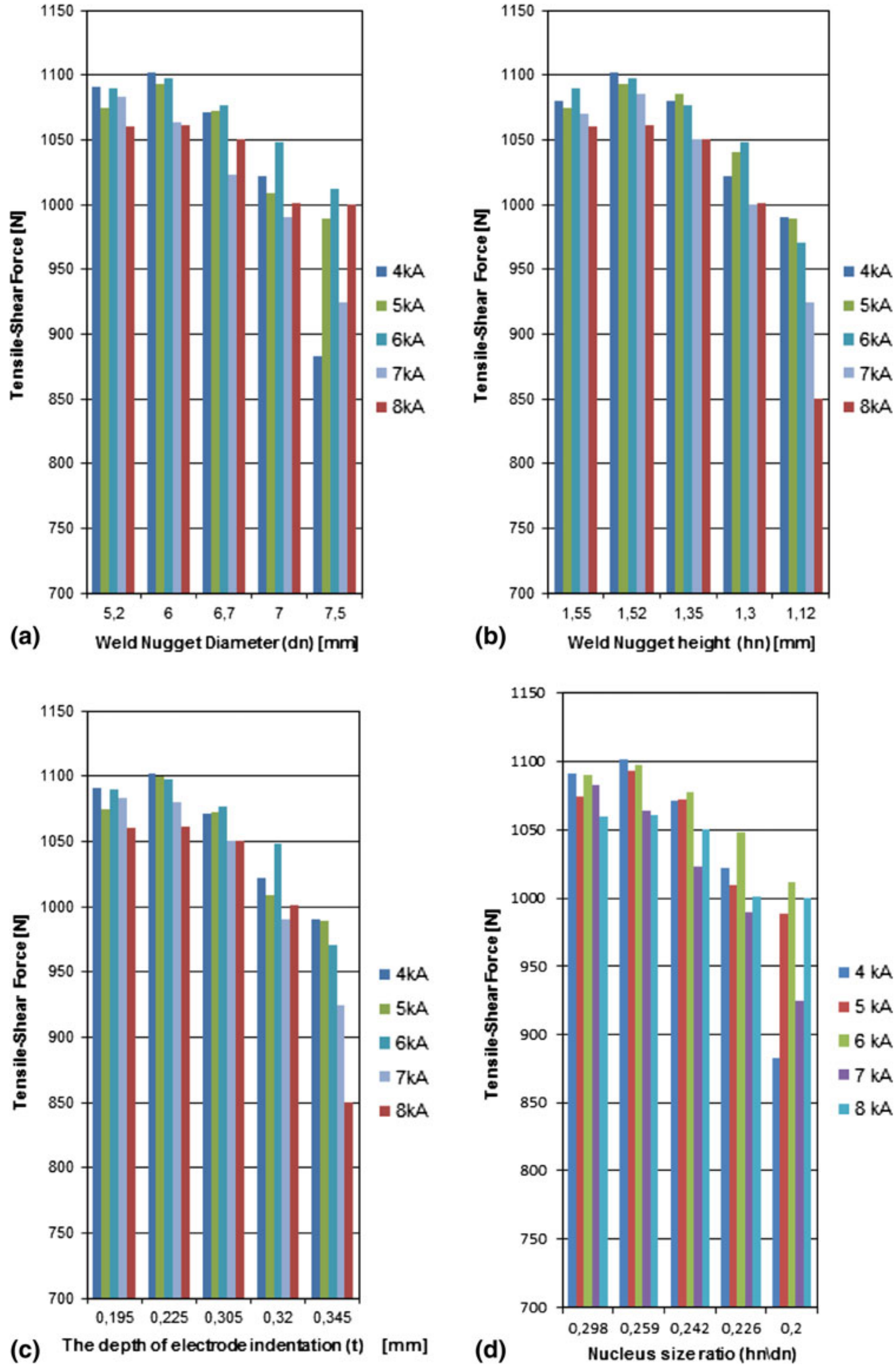

Fig. 6 The effect of weld current (kA) parameters on tensile properties: (a) tensile-shear force versus weld nugget diameter; (b) tensile-shear force versus weld nugget height; (c) tensile-shear force versus the depth of electrode indentation; (d) tensile-shear force versus nucleus size ratio; (e) tensile-peel force versus weld nugget diameter; (f) tensile-peel force versus weld nugget height; (g) tensile-peel force versus the depth of electrode indentation; and (h) tensile-peel force versus nucleus size ratio

parameters affecting the strength of weld joint seriously. However, only nucleus diameter, dn, or nucleus height, hn, is not enough to explain the effect of welding nucleus on tensile-shear and tensile-peel strengths of joints (Fig. 5). Therefore, nucleus size ratio, hn/dn, can be used for this purpose (Ref 2).

Having completed tensile-shear and tensile-peel tests, the fractured specimens were cut in cross-sectional direction and the weld nugget diameter (dn) and weld nugget heights (hn) were measured by means of a stereoscope. The obtained results are graphed in Fig. 6(a) to (h).

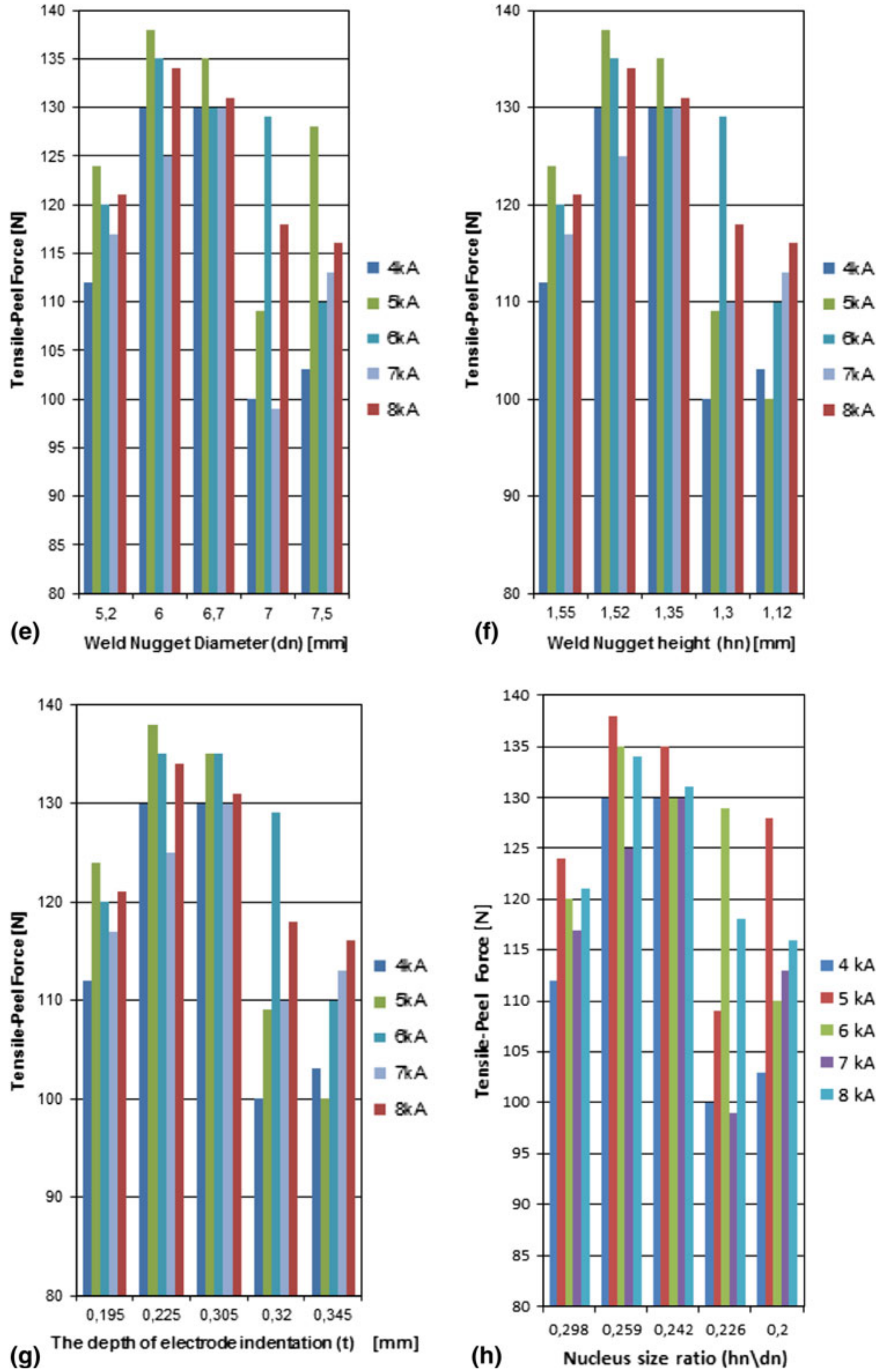

Fig. 6 continued

Based on these graphs, the highest tensile-shear strength values were obtained in between 5.5 and 7 mm weld nugget diameter (1150-1050 N) and also 1.20-1.75 mm weld nugget height (1050-1100 N) in 4 kA weld current for 1.0-1.0 mm thickness joints. The weld nugget diameter continues to increase, but the tensile-shear strength starts to decrease after 7 mm nugget diameter. Because the heat input increases with time in weld zone resulting a large weld pool. As a result of this situation, the depth of indentation of electrode increases and splashing occurs in weld zone, the weld nugget becomes flat and its diameter increases while its height decreases. All these occurrences cause a sharp decrease in tensile-shear strength of spot welded joints. It is obvious from Fig. 6(c) that the highest tensile-shear strength values can be obtained in low depth of electrode indentations as 0.20-0.30 mm.

The tensile-peel strength values of spot-welded joints with respect to weld nugget geometry are given in Fig. 6(e) to (h). In the light of these graphs, the highest tensile-peel strength values were obtained between 5.5 mm and 6.7 mm weld nugget diameter (140-125 N) and also 1.35-1.52 mm weld nugget height (135-130 N) in 4 kA weld current for 1.0-1.0 mm thickness joints. Having reached 6.7 mm nugget diameter tensile-peel strength shows a sharp decrease, although the nugget diameter continues to increase. In addition, welding current intensity increases with time and an excessive melting occurs in weld zone, the depth of electrode indentation increases and splashing occurs between two galvanized steel sheets and copper electrodes. As a result of this splashing, the nucleus size ratio (hn/dn) decreases due to decreasing weld nugget height (hn) causing a decline in tensile-peel strength as seen in Fig. 6(h). These happenings bring about decrease not only in tensile-peel strength, but also in tensile-shear strength of resistance spot-welded joints as shown in Fig. 6(d). However, it is conspicuous from Fig. 6(g) that the highest tensile-peel strength values can be obtained in low depth of electrode indentations as 0.225-0.300 mm. By combining all data taken from tensile-shear and tensile-peel test results, the optimum resistance spot welding parameters were detected and an ideal spot welding region called "weld lobe" was drawn. In Fig. 7, this weld lobe was seen plotted using weld current (kA) versus weld time (cycle) results of galvanized steel sheets used in automotive applications. This enclosed dark region shows the safe resistance spot welding condition with high strength and durability. A welder should determine the weld time versus weld current values inside of this weld lobe before starting electrical resistance spot welding operation to obtain good welding quality.

In the light of these findings, it was seen that the weld nugget diameter increases with increasing weld current (kA) up to a limit value and then starts to decrease due to deformations occurred in welding area. Our results are relevant with literature, for example, Goodarzi et al. (Ref 4) joined galvanized low carbon steels by means of resistance spot welding method by applying higher currents between 10 and 12.5 kA and declared same tendency having measured fusion zone size. Aslanlar (Ref 2) and Vural et al. (Ref 9) reported the similar findings not only for nugget size dimension but also for electrode indentation and tensile loads. After the tensile-shear and tensile-peel tests, some cracks and failures were occurred around these welds especially in the HAZ. Spot welds that fail in nugget *pullout* mode provide higher peak loads and energy absorption levels than those spot welds which fail in *interfacial* failure mode. To ensure the reliability of the spot welds during vehicle lifetime, process parameters should be adjusted so that pullout failure mode can be guaranteed. In this study, failure occurred in pullout mode by partial nugget withdrawal from one sheet after tensile-peel test and in interfacial mode through nugget after tensile-shear test.

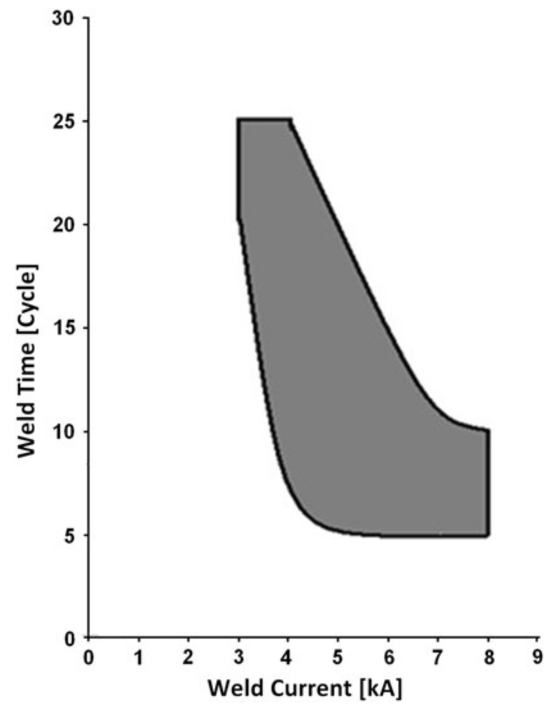

Fig. 7 The weld time versus weld current diagram (weld lobe)

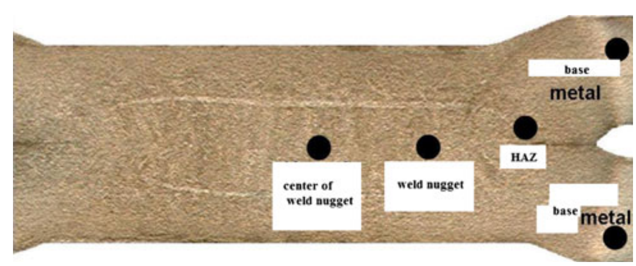

Fig. 8 Macro-structure and different regions in spot-welded sheets

3.2 Micro-hardness Results

The micro-hardness values of specimens were measured from four different points in 1.0-1.0 mm thickness galvanized steel sheets in Vickers scale with 100 g load (i.e., $Hv_{0.01}$), as shown in Fig. 8. Every hardness measurement was repeated three times and the mean of them was given. The highest tensile-shear and tensile-peel forces were reached and the highest strength values were calculated in specimens welded in 4 kA weld current. In base metal, the average microhardness value is 123 $Hv_{(0.01)}$. Its value increases in HAZ of spot joint as 150 $Hv_{(0.01)}$ mean value, and reaches the top value in weld nugget as 295 $Hv_{(0.01)}$. Finally, we described an extra zone called "center of nugget" (Fig. 8) and measured the microhardness value of this zone as 332 $Hv_{(0.01)}$. Our measurements are relevant with literature, Goodarzi et al. (Ref 4) measured that weld nugget hardness is about 2.4 times the value for base metal, due to martensite formation in this zone. This rate was about 2.1 times in Marashi's study, but he joined galvanized steel with austenitic stainless steel (Ref 5). The hardness measured in center of weld nugget for this study was 2.7 times greater than that of base metal's hardness.

3.3 Micro-structure and Macro-structure Appearances

The optical microscope and JEOL JSM 6510 SEM were used to examine the microstructural variations. The typical macro-structure of spot-welded galvanized steel sheets is shown in Fig. 8. The joint region consists of four distinct structural zones: 1—center of weld nugget, 2—weld nugget which is melted during welding process and is re-solidified showing casting structure. Therefore, weld nugget consists of

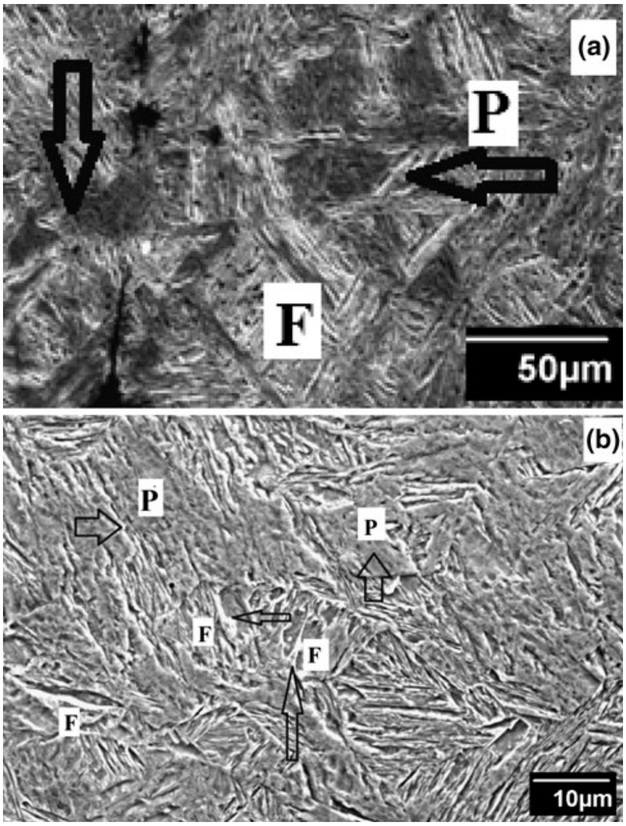

Fig. 9 SEM microstructure of (a) base metal and (b) HAZ of galvanized steel. P: perlitic (dark regions) and F: ferritic grains (light areas). The microstructure is fully martensitic in the center of spot welds (nugget). Here, in (b) martensitic needles start to form in ferritic-perlitic microstructure of HAZ

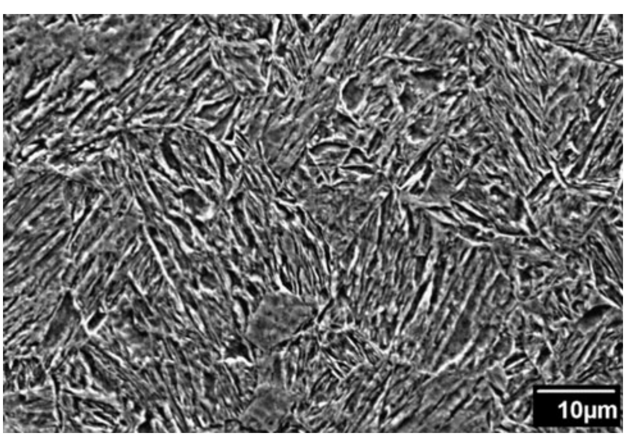

Fig. 10 SEM micrograph of weld nugget zone. Martensitic needles were homogenously distributed in microstructure of weld nugget

columnar grains, 3—HAZ which is not melted but undergoes microstructural changes different to other welding methods, and finally, 4—base metal.

The much higher hardness or strength in the weld nugget is apparently attributed to the formation of martensite. There are typically two phases present in the microstructure of zinc-coated steels; ferrite and perlite, because zinc-coated (galvanized) steel is ferritic-perlitic steel as seen in base metal and HAZ regions of SEM micrograph (Fig. 9).

As seen in SEM micrographs, acicular martensite formation in needle-like morphology was observed in welding zone (weld nugget) of specimens. Martensite becomes larger and its volume fraction is higher in the HAZ than in the base metal. The fusion zone is nearly full of martensite, as seen in Fig. 10. The similar structures were detected by Goodarzi et al. (Ref 4), Marashi et al. (Ref 5), Mei et al. (Ref 10), and Vural et al. (Ref 9).

By the way, the zinc is an important element in galvanized steel, because these steel sheets were immersed into zinc bath to obtain a Zn-rich coating layer onto the surface. Therefore, EDS analysis was done to control the presence of Zn element. However, zinc element was not detected in weld zone (i.e., weld nugget) providing EDS analyses on SEM. It was thought that Zn element, inside the coating layer of galvanized steel, was burnt and evaporated practically during spot welding process.

4. Conclusions

The effect of spot welding parameters on tensile properties of zinc-coated steel sheet joints was investigated and the following conclusions were drawn:

(1) The galvanized steel sheets were joined by means of resistance spot welding method and the prepared joints were exposed to tensile tests. The highest tensile-shear and tensile-peel strengths were obtained in 5.5-8 mm weld nugget diameters, 1.20-1.70 mm weld nugget height, and 0.15-0.26 nucleus size ratio in 4 kA weld current. In these values, the depth of electrode penetration (0.20-0.35 mm) is equal to 10 and 17.5% of sheet thickness. These recommended values are lower than 20% critical limit value which was required to obtain a good surface quality in weld joint. Therefore, high-quality spot-welded joints can be achieved with galvanized steel sheets with a thickness of 1.0 mm. However, weld time (cycle) versus weld current (kA) should be selected from loop given in Fig. 7 called weld lobe.

(2) A significant hardness increment from base metal (123 $Hv_{0.01}$) to weld nugget (332 $Hv_{0.01}$) due to high cooling rate was seen. The electric resistance spot welding operations were started without any pre-heating to specimens, so if it is applied to sheets, a lower hardness value and more ductile weld nugget can be obtained.

(3) The failure occurred in interfacial mode through nugget after tensile-shear test and in pullout mode by partial nugget withdrawal from one sheet after tensile-peel test.

Acknowledgment

The author wishes to thank Sakarya University Scientific Research Foundation (Project number: 2010-05-04-004) for their support.

References

1. Safety and health fact sheet no. 21, American Welding Society, 1999
2. S. Aslanlar, The Effect of Nucleus Size on Mechanical Properties in Electrical Resistance Spot Welding of Sheets Used in Automotive Industry, *Mater. Des.*, 2006, **27**, p 125–131

3. R. Qiu, H. Shi, H. Yu, K. Zhang, Y. Tu, and S. Satonaka, Effects of Electrode Force on the Characteristic of Magnesium Alloy Joint Welded by Resistance Spot Welding with Cover Plates, *Mater. Manuf. Process.*, 2010, **25**(11), p 1304–1308
4. M. Goodarzi, S.P.H. Marashi, and M. Pouranvari, Dependence of Overload Performance on Weld Attributes for Resistance Spot Welded Galvanized Low Carbon Steel, *J. Mater. Process. Technol.*, 2009, **209**, p 4379–4384
5. P. Marashi, M. Pouranvari, S. Amirabdollahian, A. Abedi, and M. Goodarzi, Microstructure and Failure Behavior of Dissimilar Resistance Spot Welds Between Low Carbon Galvanized and Austenitic Stainless Steels, *Mater. Sci. Eng., A*, 2008, **480**, p 175–180
6. G. Mozurkewich, B. Ghaffari, and T.J. Potter, Spatially Resolved Ultrasonic Attenuation in Resistance Spot Welds: Implications for Nondestructive Testing, *Ultrasonics*, 2008, **48**, p 343–350
7. S.M. Darwish, M.S. Soliman, and A.M. AI-Fahead, Characteristics and Variables of Spot Welding and Weldbonding Biomaterials, *Mater. Manuf. Process.*, 1997, **12**(2), p 175–186
8. S.M. Hamidinejad, F. Kolahan, and A.H. Kokabi, The Modeling and Process Analysis of Resistance Spot Welding on Galvanized Steel Sheets Used in Car Body Manufacturing, *Mater. Des.*, 2011. doi: 10.1016/j.matdes.2011.06.064
9. M. Vural, A. Akkus, and B. Eryurek, Effect of Welding Nugget Diameter on the Fatigue Strength of the Resistance Spot Welded Joints of Different Steel Sheets, *J. Mater. Process. Technol.*, 2006, **176**, p 127–132
10. L. Mei, G. Chen, X. Jin, Y. Zhang, and Q. Wu, Research on Laser Welding of High-Strength Galvanized Automobile Steel Sheets, *Opt. Laser Eng.*, 2009, **47**, p 1117–1124
11. C.H. Kim, Y.N. Ahn, and J.H. Kim, CO_2 Laser-Micro Plasma Arc Hybrid Welding for Galvanized Steel Sheets, *Trans. Nonferrous Met. Soc.*, 2011, **21**, p 47–53
12. H. Tang, W. Hou, and S.J. Hu, Influence of Welding Machine Mechanical Characteristics on the Resistance Spot Welding Process and Weld Quality, *Weld. Int.*, 2003, **5**, p 116–124
13. X.Q. Zhang, G.L. Chen, and Y.S. Zhang, Characteristics of Electrode Wear in Resistance Spot Welding Dual-Phase Steels, *Mater. Des.*, 2008, **29**(1), p 279–283
14. K.L. Chatterjee and W. Waddell, Electrode Wear During Spot Welding of Coated Steels, *Weld. Mater. Fabr.*, 1996, **3**, p 110–114
15. S. Fukumoto, I. Lum, E. Biro, and D.R. Boomer, Effects of Electrode Degradation on Electrode Life in Resistance Spot Welding of Aluminum Alloy, *Weld. Int.*, 2003, **5**, p 11307–11312
16. R. Holiday, J. Parker, and N.T. Williams, Relative Contribution of Electrode Tip Growth Mechanisms in Spot Welding Zinc Coated Steels, *Weld World*, 1996, **37**(4), p 186–193
17. M. Rashid, Some Tribological Influences on the Electrode-Worksheet Interface During Resistance Spot Welding of Aluminum Alloys, *J. Mater. Eng. Perform.*, 2011, **20**, p 456–462