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Investigation of corrosion properties of uncoated and hot dip galvanised dual phase steel (DP450) welded using spot welding

Mustafa ACARER[1], Hayrettin AHLATCI[2] and Fatih HAYAT[2]*

[1]Department of Materials, Technical Education Faculty, Karabuk University, Karabuk 78050, Turkey.
[*2]Metallurgy and Materials Engineering Department, Engineering Faculty, Karabuk University, Baliklarkayasi, 78050 Karabuk, Turkey.

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DP450 dual phase steel has attracted an increasing attention as a material with commercial value for certain applications in automotive industry, nowadays. The purpose of this study was to investigate microstructure, micro-hardness, tensile shear tests, and corrosion properties of DP450 dual phase steel sheet welded using spot welding under both uncoated and hot dip galvanised conditions. Experimental results concluded that there was an increase in joining strength with an increase in welding current and weld time; and welding parameters did not have any significant effect on corrosion properties. The uncoated specimens had more corrosion resistance in comparison to the hot dip galvanized specimens.

Key words: Dual phase steel (DP450), resistance spot welding, mechanical properties, corrosion.

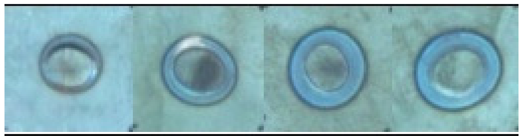
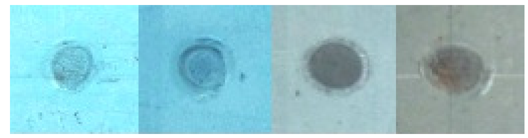
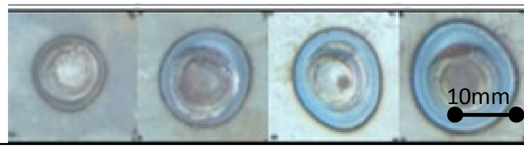
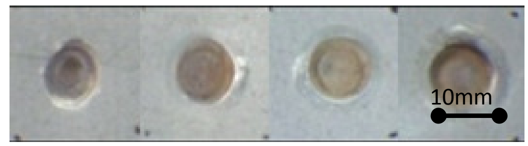
INTRODUCTION

Dual phase (DP) steels have a composite microstructure that is composed of martensite and ferrite. Characteristics of these steels are low yield strength, excellent elongation, good formability and high tensile strength (Aydin et al., 2010; Hayat, 2011; Hayat and Uzun, 2011; Luo and Shi, 2010; Sarkar et al., 2005; Nouri et al., 2010; Speach and Miller, 2010). Advanced high-strength steels (AHSS) are used in automotive industry in order to provide weight reduction, improve safety performance and offer cost saving. Dual phase (DP) steel is one of the most common AHSS steels (Speach and Miller, 1981; Hayat et al., 2007; Davies, 1981; Liang et al., 2008). Therefore, DP steel is considered an ideal material to manufacture automobile components, which requires good formability to reduce the weight of vehicle and thus to achieve fuel saving (Liang et al., 2008). Galvanising, an important procedure to provide corrosion protection, is carried out prior to forming any components, while finished components are paint baked (Speach and Miller, 2010). Galvanised DP steel sheets have been commonly used in construction with corrosion resistance and especially in automotive industry.

Protecting metals against corrosion is a major industrial problem that has been studied with numerous researches (Abiola et al., 2005; Eddy et al., 2009). The fact that road salt caused corrosion in automotive components has become one of widely recognised problems (Jones and Nair, 1985). The parts under the body of the car and the interior surface of body panels are easily damaged from corrosive attacks caused by sodium chloride solution deposited on roads to melt snow. In general, galvanic coupling to zinc, as either an anode or a coating, is an effective way to combat steel corrosion (Budinski and Wilde, 1987). Zinc coatings are extensively utilised by

*Corresponding author. E-mail: fhayat@karabuk.edu.tr. Tel: +90-370-433 2021/1331. Fax: +90-370-433 3290.

Table 1. DP450G-DP450U nugget images of the spot welded specimens.

Welding current (kA)	DP450U*				DP450G*			
	Weld time (Cycles)				Welding time (Cycles)			
	10	20	30	40	10	20	30	40
3								
9								

*Specimens labelled as - U: Uncoated and G: Galvanised.

automobile manufacturers to improve the corrosion resistance of car bodies due to their sufficient negative potential to cathodically protect steel. The reasons behind why galvanised steels, produced especially using the hot dip process, are preferred for such applications are their high coating thickness, superior corrosion resistance and excellent sacrificial protection capability (Rajiv and Richard, 2009).

Automotive manufacturers have used coated sheets in automobile manufacturing in recent years (Bian et al., 2006). Galvanising, which is an important procedure to provide corrosion protection, is carried out prior to forming any components, while finished components are paint baked (Speich and Miller, 1981). Resistance spot welding, one of the oldest electric welding processes, is the most frequently used joining technique for sheet materials in automotive industry in particular. The body-in-white is assembled by the industry using spot welding today (AWS Handbook, 1991; Kocabekir et al., 2008).

There are several studies available in the literature that investigated dual phase steel and their spot resistance welding (Hayat et al., 2007; Ma et al., Xinsheng et al., 2010; Hayat, 2011) as well as the corrosion properties of dual phase steels (Speich and Miller, 1981). However, as a result of literature review, there has been no study focusing on corrosion properties of dual phase steel welded using spot welding. Therefore, the purpose of this study is to investigate the corrosion behaviour of uncoated and hot dip galvanised DP450 dual phase steel welded using spot welding.

MATERIALS AND METHODS

Uncoated and hot dip galvanised DP450 dual phase steel were used to conduct this study. The uncoated and hot dip galvanised materials had ferrite-martensite microstructure with 1 mm thickness. Chemical composition (in wt%) of DP450 dual phase steel was 0.054 C, 1.32 Mn, 0.129 Si, 0.515 Cr, 0.020 Ni, 0.005 S and 0.0058 N. The coatings of galvanised specimens in 30×30 mm areas to be subjected to spot welding were submerged into HCl (hydrochloric) acid under laboratory conditions in order to be removed.

Welding procedure was carried out using water cooled by a conical Cu-Cr alloy electrode with contact surface of 8.0 mm in diameter. In order to achieve the joining, 10, 20, 30 and 40 cycles (1 cycle: 0.02 s) weld time and effective welding current (3 to 9 kA) were applied while other welding parameters such as electrode pressure (6×10^5Pa) and holding time of electrode (25 cycles) were kept constant.

Metallographic examination, microhardness measurement (load: 200 g) and tensile test were conducted on both uncoated and hot dip galvanised welded specimens. Tensile tests were carried out at room temperature at a crosshead speed of 2 mm min^{-1} for flat test pieces in accordance with the ISO Standard (ISO, 2009). For the corrosion test, the specimens were tested by immersion in the 3.5% NaCl + 1% HCl solution in accordance with ASTM Standard (ASTM, 2004). Specimens were subjected to corrosion test in the prepared solution at 3 different time intervals (1 day, 6 days and 9 days), and their weights were measured. Dual phase steels have two different phases and corrosion usually may occur in the phase boundary in these steels. Due to the fact that 3.5% NaCl + 1% HCl solution is aggressive environment on the phase and/or grain boundary, in this study, corrosion tests were carried out in the solution.

Galvanostatic polarisation technique was used to study the corrosion properties of DP450 specimens in 3.5% NaCl + 1% HCl solution. The polished surface was used as a working electrode when it was immersed in the solution taken in an electrochemical cell comprising the Pt auxiliary electrode and saturated calomel electrode as reference. The current during steps was changed to investigate both cathodic and anodic polarisation behaviours of the specimens with the arrangement of the electrochemical cell. The corrosion current density (I_{corr}) and corrosion potential (E_{corr}) were figured out from the polarisation curve.

RESULTS

Table 1 shows the images of the nugget diameters for uncoated and hot dip galvanised DP450 dual phase steel. It was observed that there was a difference in the increase of the nugget diameter as a result of the welded joint during the experiments.

Welding nugget diameters of both galvanised and uncoated DP450 steel sheets increased with the increase in welding current and weld time. Nugget diameter values

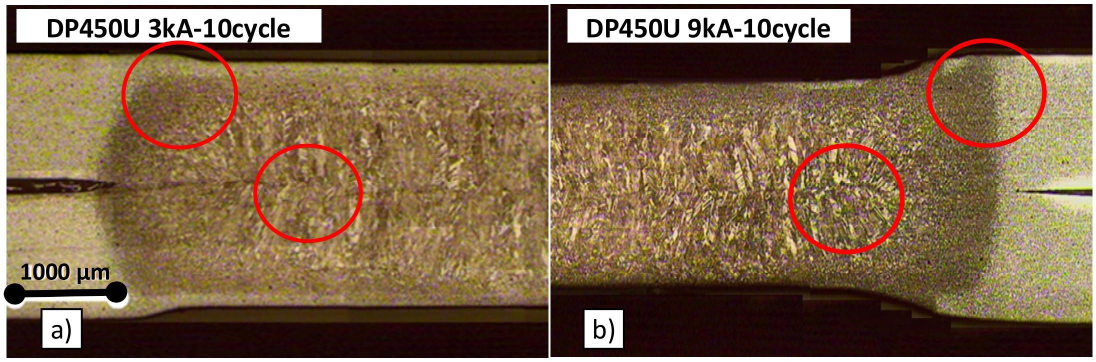


Figure 1. DP450U (a) 3kA-10c and (b) 9kA-10c macrostructure of spot welding.

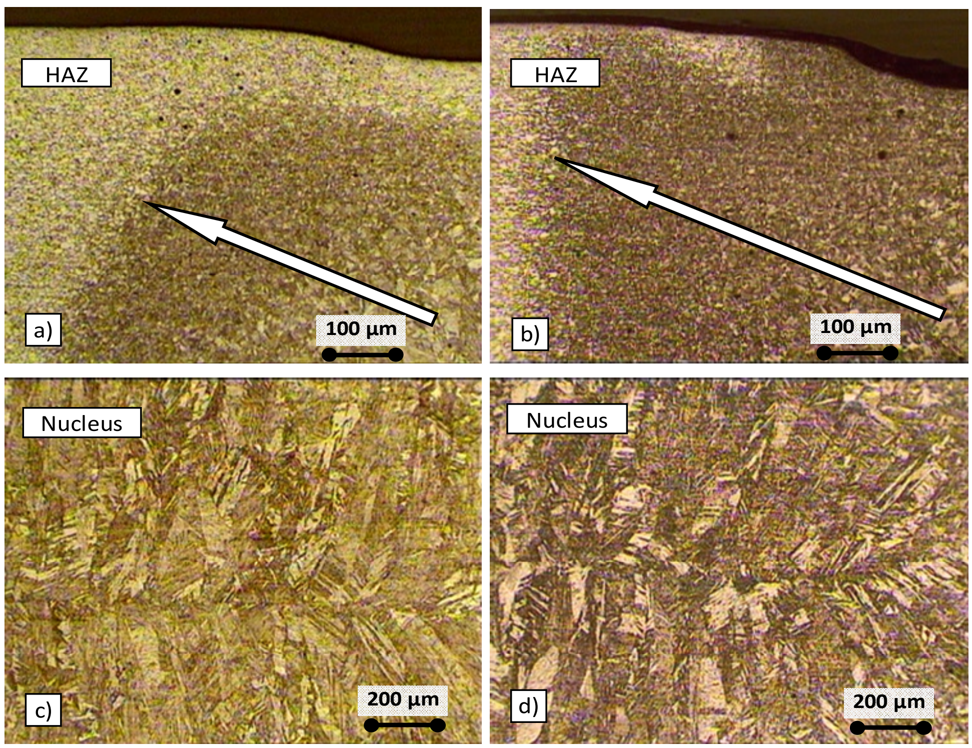


Figure 2. DP450U 3kA-10c (a: HAZ, c: nucleus) and 9kA-10c (b: HAZ, d: nucleus) microstructure of spot welding.

of the galvanised specimens are lower in comparison to the uncoated specimens. Figure 1 illustrates the macrostructure images taken at fixed welding times at different welding currents.

Figure 2 illustrates microscopic images from HAZ and nucleus at the same magnification of 200 µm, and the Figures 2c and 2d illustrate acicular martensite and ferrite in the structures.

According to the microstructure images taken from both welded specimen groups, HAZ expanded and structures in the weld nucleus coarsened with increasing welding current and weld time (Figure 2a, b, c and d). In addition, cavities occurred at some points in the joining areas of the galvanised specimens.

Figure 3 shows the microhardness test results of the galvanised and the uncoated steel sheets welded using spot welding.

In the Figure 3, it can be seen that microhardness values of the galvanised and uncoated specimens were similar under all welding conditions. Microhardness in the base metal was 190 HV, while it increased to 420 HV in the HAZ and weld nucleus.

Figure 4 presents tensile shear values of the galvanised and the uncoated DP450 specimens. As

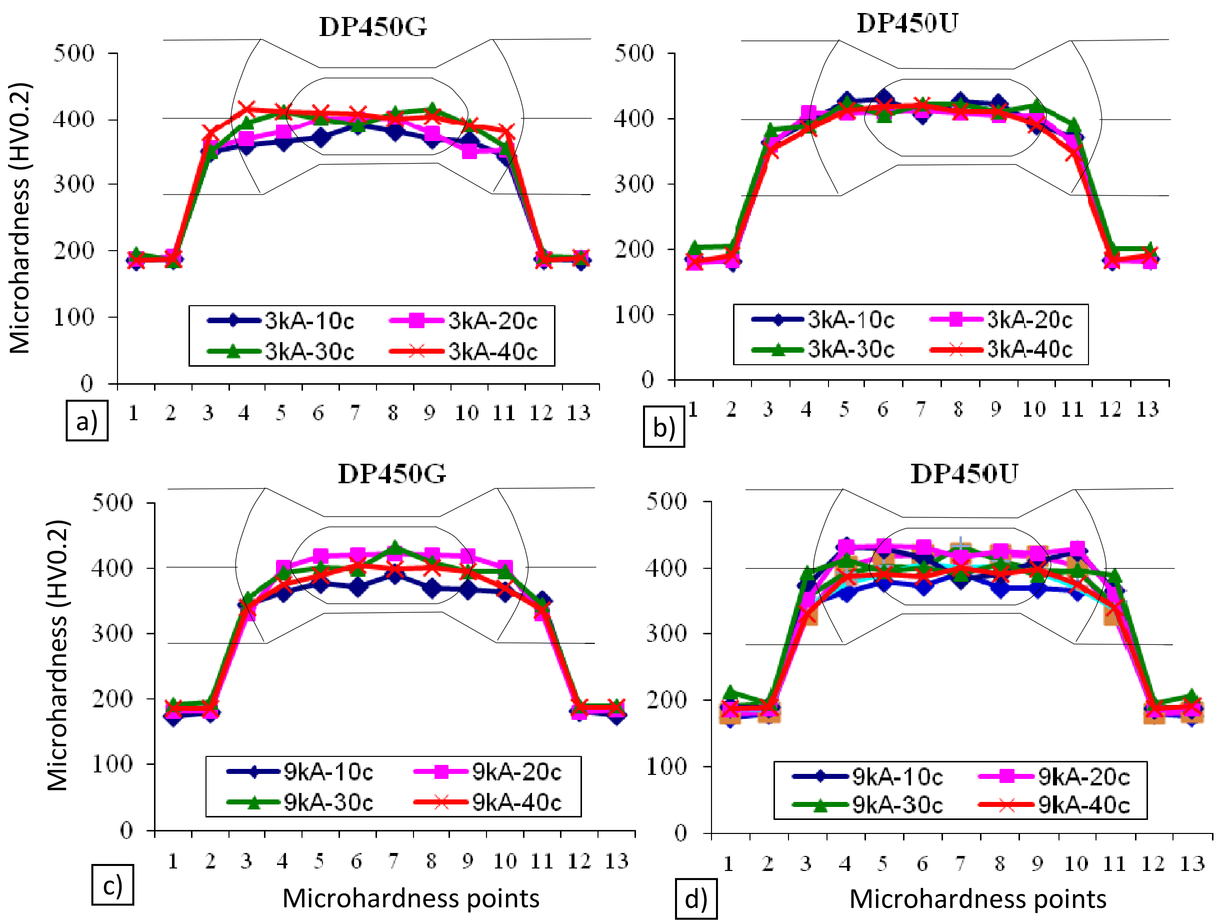


Figure 3. Micro-hardness values of DP450 steels welded by resistance spot welding at 10, 20, 30 and 40 cyles; (a) DP450G with 3 kA (b) DP450U 3 kA (c) DP450G 9 kA and (d) DP450U with 9 kA.

illustrated in the Figure 4, although tensile shear load capacity increased based on the increasing weld time, it showed a tendency to decrease at 40 cycles, the highest weld time. Furthermore, the galvanised specimens had weaker joints at lower welding current and weld values in comparison to the uncoated specimens.

Figure 5 shows the weight loss measured for the galvanised and uncoated specimens at the end of the immersion corrosion test in 3.5% NaCl+1% HCl solution. As illustrated in Figure 5, weight loss of both the DP450G and DP450U specimens remained almost constant at welding current of both 3 and 9 kA. In addition, weight loss of the galvanised specimens was higher in comparison to the uncoated specimens.

I_{cor} value corresponding to a different weld time and welding current obtained from the polarisation curve by extrapolation can be seen in Figure 6. As illustrated in Figure 6, the galvanised welded specimens had higher current values when the welded joints of the DP450G and DP450U steels were compared. In addition, according to E_{cor} values in Figure 7 the corrosion resistance was weaker.

When the welded joints of the DP450G and DP450U steels were compared, galvanised welded specimens had higher I_{cor} and more negative E_{cor} values, which indicates a weaker corrosion resistance.

DISCUSSION

As illustrated in Table 1, the nugget diameters of the uncoated specimens are larger compared to the galvanized ones. This condition was caused by the difference in the heat and the electrical conductivity of zinc; which was the coating material and the steel in general. According to the Joule rule, the heat input occurring between electrodes at the electric resistance welding is expressed using below-stated Equation 1.

$$Q \text{ (calorie)} = 0.239\, I^2\, R\, t \qquad (1)$$

where; Q is the heat generated in calorie; I is current intensity; R is resistance of the material and T is weld time.

As illustrated in Equation 1, the generated heat appears as a function of the current intensity (I), resistance of the materials (R) and time (t). In addition,

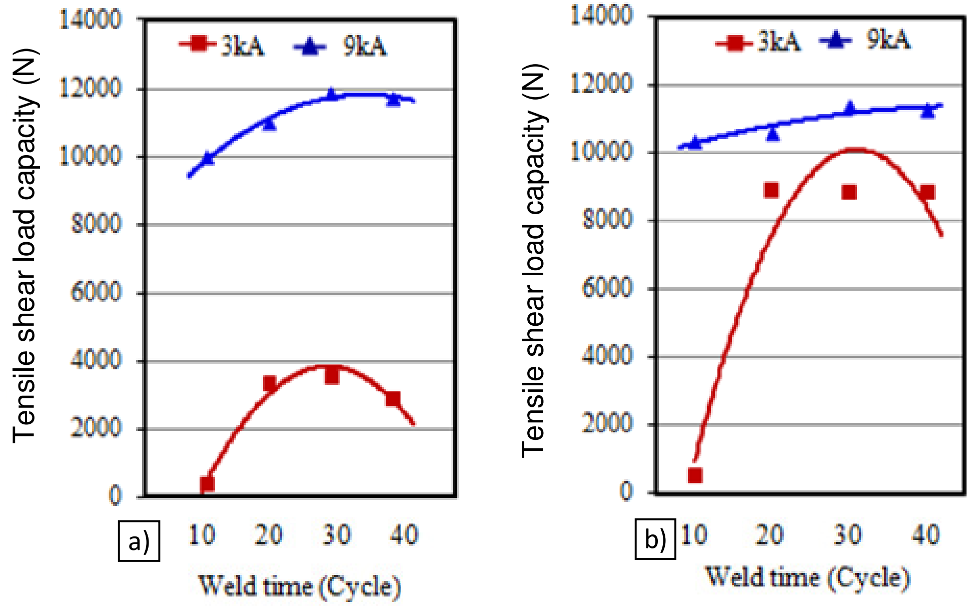


Figure 4. Tensile shear load capacities of the welded specimens. a) galvanised specimen, b) uncoated specimen.

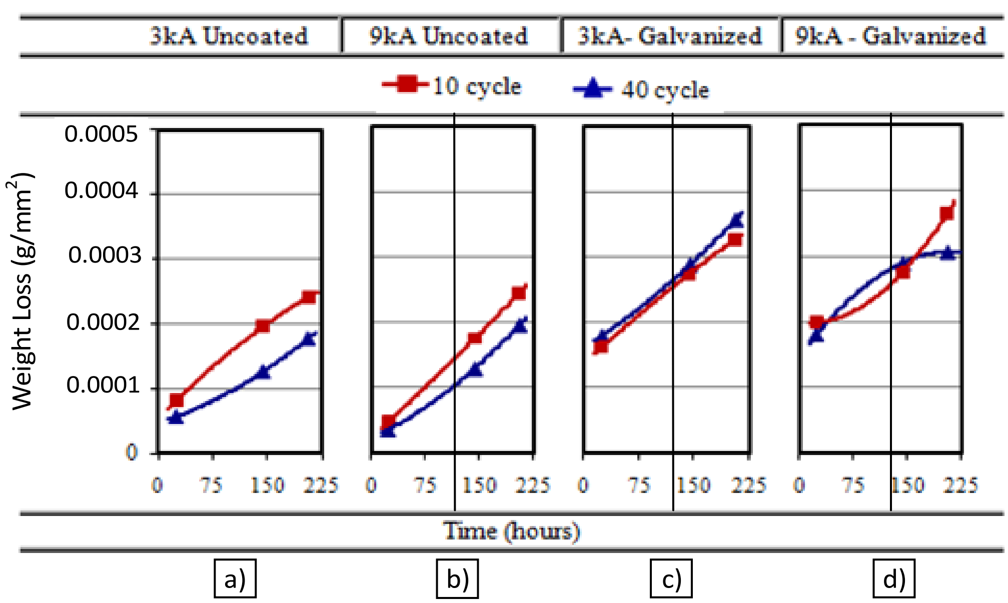


Figure 5. Change of weight loss in the welded specimens of the galvanised and uncoated steels.

the electric resistance welding ability is expressed with an empirical formula given in Equation 2.

$$S=10^4/\alpha\lambda T_m \quad (2)$$

where, α is electrical conductivity of the welded material ($m/\Omega mm^2$), λ is heat conductivity of the welded material (cal/cms°C), and T_m is melting temperature of the welded material (°C).

The Equations 1 and 2 shows that weldability at the resistance spot welding depends on the material type. In order to welding at the electrode contact zone, the R resistance must be high enough. Since the resistance that the material shows, when an electric current flows through it, is inversely proportional to the material's capability of electrical conductivity, it is understood that the higher the material's electrical conductivity, the worse its spot welding ability is (Vural and Akkus, 2004). The

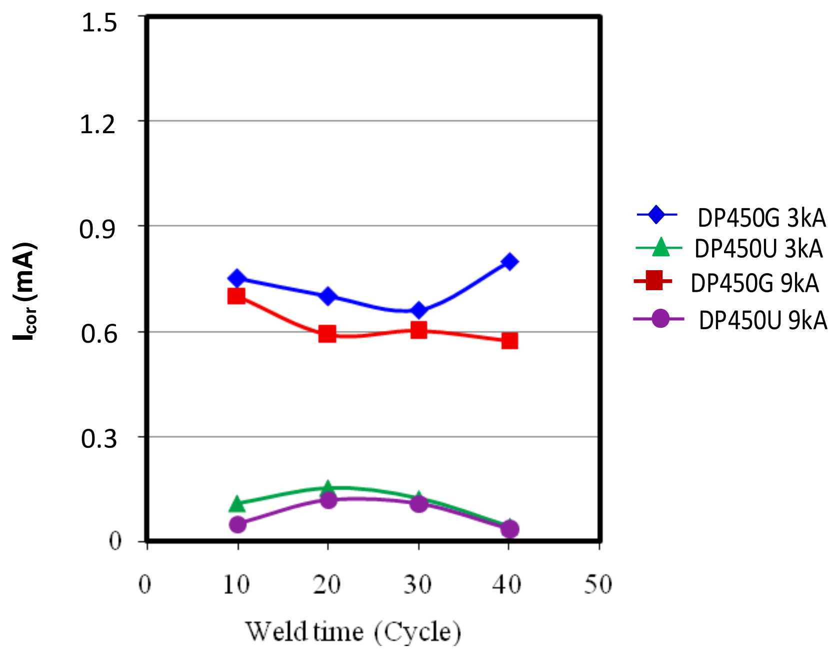


Figure 6. I_{cor} values of the welded specimens of the galvanised and uncoated steels.

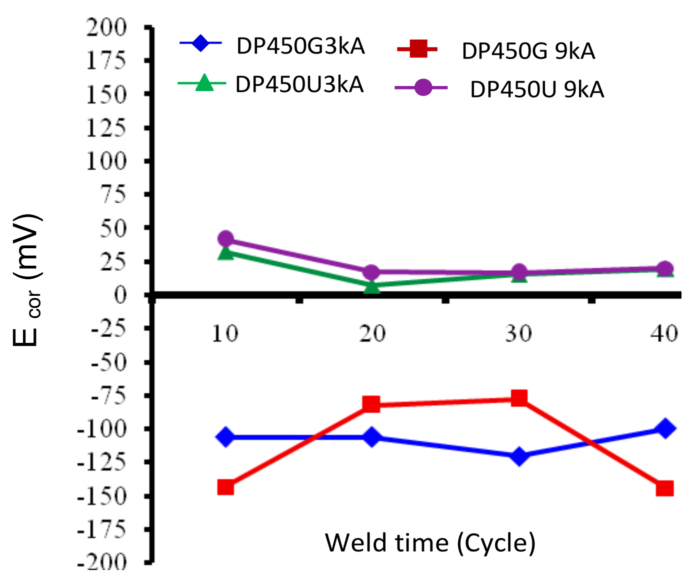


Figure 7. E_{cor} values of the welded specimens of the galvanised and uncoated steels.

zinc has approximately 2 times the thermal conductivity and 3 times the electrical conductivity in comparison to the steel (Aydın and Gulenc, 2003). The electric conductivity of the galvanised steel is higher at the electric resistance welding, and accordingly its heat accumulation shall be lower. Consequently, the nugget diameter of the galvanised steel will be lower in comparison to uncoated steel (Aydin and Gulenc, 2003; Vural and Akkus, 2004; Anık et al., 1999). In addition, the zinc layer on the galvanised steel surface melts at a 420°C. The heat formed at the electrical resistance of the steel sheet is high enough to cause the melting of this layer. With the melted zinc layer sticking to the copper electrodes, the resistance increases at these points. For this reason, welding nuclei in inadequate size are obtained at these points (Vural and Akkus, 2004; Anık et al., 1999). Aydin and Gulenc (2003) reported that the coating type and the coating thickness had an effect on electrical and thermal conductivity and therefore on the thermal condensation; accordingly they affect the welding capability. Vural and Akkus (2004) had reported that, at a perfect resistance welding, the current that flows through the electrodes should be as constant as possible and as well as high welding current, the low melting temperature of the zinc layer affects this condition significantly. The zinc coating layer made as an electrolytic melts approximately at 420°C. The zinc layer of the steel sheet melts during the electric resistance welding and sticks upon the copper electrodes. The electrical resistance increases at these points. This metal bonding shows an irregular distribution on the electrode surface in general and forms especially in the middle of the electrodes or in their hallow regions. In conclusion, since this situation causes changes in the contact resistance, the current will begin to flow irregularly and spot welding sources with that have inadequately sized welding nuclei can be obtained (Vural and Akkus, 2004; Anik et al., 1999).

The dual-phase steel DP 450 typically has a body-centred cubic (bcc) ferrite and a body-centred tetragonal (bct) martensitic structure. The microstructure in Figure 1 and the hardness profiles in Figure 2, present that a martensitic that has higher volume and is wider than the base metal, formed in the heat affected zone. The reason behind this may be the thickness of the materials used in this study and that the cooling speed necessary (40 to 120°C/s) for the formation of the martensite during welding was higher than the cooling speed stated in the previous studies (Ma et al., 2008; Gould et al., 2006; Tumuluru, 2006; Khou, 2002) in terms of welding parameters. Therefore, it is thought that the lath-type martensites formed at these regions. In addition, the high carbon and manganese contents in the dual-phase steel DP 450 causes high hardenability. Both the high cooling rate during welding and high hardenability cause formation of the martensite on the welding metal and in heat affected zone. Depending on the change in the microstructure, it has caused the hardness of the HAZ and the melted region to be higher than the base metal.

Tensile shear load capacity increased depending on the increasing weld time and it shows a tendency to decrease at 40 cycles which is the highest weld time. This observed effect of weld time on strength can essentially occur by increasing the weld nugget diameter to a critical degree. Due to the low amount of heat given to welding current region at the low current intensity (6 kA), the nucleus diameter is also small. Since the joining surface area was small, a separation-type rupture occurred, which caused the tensile-shear strength to be below the tensile strength of the metal. Depending on duration of the welding current applied, as the current intensity increases, the nugget diameter increases and accordingly the tensile-shear value increases with an increase in the joining surface area. In association with the nugget diameter, the galvanised specimens had weaker joints at low welding current and weld values in comparison to the uncoated specimens (Vural and Akkus, 2004).

Cathodic protection provided protection from corrosion in the coating of iron-steel products with zinc: that is, zinc coating, which behaves as steel cathode and is more anodic than steel, is the corroded side. It reduces the corrosion rate by forming a protective layer on the surface of zinc with the effect of corrosive medium. As mentioned above, faster corrosion observed after welding procedure compared to uncoated steel is associated with its contribution with galvanic match to the corrosion loss of steel which is exposed to medium with the peeling of zinc coating from the surface. The zinc-coating provides a three-way protection for the steel wire materials and significantly increases their life span. Firstly, an oxide layer covering the entire surface formed on the zinc-galvanised surface and this layer protects the material against any corrosion by acting as a barrier between the steel wire and the external environment. Secondly, due to the fact that zinc is a more active material compared to steel, zinc sacrifices itself and enables the protection of the steel wire material when the galvanised materials contact with the external environment. In the event that the metal comes out on the zinc-galvanised materials, the zinc wastes itself and prevents the steel from suffering corrosion. Qualifying the materials as active and passive is in accordance with their positions at the galvanic series. In the galvanic series, the materials that have lower energy are qualified as active and the materials that have higher energy are qualified as passive. Since the zinc has lower energy than iron, it is a more active metal (Porter, 1991).

Conclusion

It was observed that the micro-hardness in the weld nugget and HAZ increased with the increase in cycle values in resistance spot welding.

In general, joining strength showed an increase with the increase in welding current and weld time.

The results obtained from corrosion tests of welded joints in galvanised and uncoated DP sheets, concluded that the galvanised welded specimens showed more negative Ecor and higher Icor values, which indicates that their corrosion resistance was weaker.

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