Effect of Material Properties on Contact Resistance and Nugget Size during Spot Welding of Low Carbon Coated Steels

Mahadev SHOME and Sujit CHATTERJEE

Research & Development, Tata Steel, Jamshedpur 831007, India. E-mail: mshome@tatasteel.com, sujitchatterjee123@gmail.com

(Received on February 3, 2009; accepted on May 14, 2009)

Varying nugget sizes are obtained in different coated and bare automotive steel grades applying identical spot welding parameters. The strength of sheet surface asperities and surface topography together seem to influence contact conditions under applied pressure and welding temperature. The low fractal roughness and easily deformable asperities of soft steels decreases both static and dynamic contact resistance. Contrarily, high fractal roughness and stronger asperities of higher strength steels resist successive yielding of the asperities. This, in turn, produces more heat for melting and therefore larger nuggets. The heat efficiency of welding increases with yield strength as favorable contact resistance conditions are set in. Significantly, the iron–zinc intermetallic phases in the steel coating consume part of the latent heat of fusion and decrease the energy efficiency. Continuous modification of the surface with progressive melting of the intermetallic layers also contributes to this effect. For longer weld times in coated steels, the drop in contact resistance at the early stages of welding is compensated later, which improves overall heat efficiency.

KEY WORDS: spot welding; coated steel; contact resistance; surface roughness; nugget diameter; heat efficiency; medium frequency direct current.

1. Introduction

The factors influencing the formation and growth of the weld nugget in resistance spot welding of sheet metal have been adequately discussed. While weld current, weld time and electrode force are basic input parameters for heat generation, static and dynamic contact resistances influence melting and size of the nugget. While static electric contact resistance (ECR) largely depends on the characteristics of the two mating sheet surfaces prior to flow of the weld current, dynamic contact resistance (DCR) accounts for the combined effect of interfacial resistance and bulk material resistance during welding. The dynamic contact resistance depends on the surface asperities of the overlapping steels, extent of asperity collapse under heat and pressure, and bulk material resistivity as a function of temperature. In effect, the material dependent properties call for change in welding parameters for different grades of steel, which are distinguished by process windows (weld lobes).

Satisfactory models usually consider the underlying physics that goes behind establishing welding parameters and weld nugget formation. The essential factors include:

(i) Continuous changes that take place in the electrode/sheet and sheet-sheet contact areas during welding due to deformation of the electrodes as a consequence of electrode force and temperature. Variation in interface geometry alters the average current density across the contact interfaces, thereby influencing the rate of heat generation.

(ii) Contact resistance decreases as the applied load increases. It also depends on the electrode shape and the temperature distribution between the welding electrodes.

Numerous investigations have been carried out to establish the contact area developed between two interfaces under an applied load. It is well known that when two sheets are pressed by the welding electrodes, local contact is initially established through surface asperities. The sporadic contact points, decided by the fractal roughness and dimension, cause an increase in resistance to the current flow. The contact resistance created is influenced primarily by material properties like Poisson’s ratio, elastic modulus of the two surfaces, and yield strength (YS) of the asperities. It is agreed that the welding current required is based on the static contact resistance. However, the heat generation mechanism during the process depends on the dynamic contact resistance.

The shape of the dynamic resistance curve has been well documented in relation to weld formation for bare and coated steel. In general, the contact resistance waveform drops with collapse of asperities at the beginning, and then increases with material resistivity property, and finally tapers off with melting and reduced sheet thickness due to penetration of the electrode. In zinc coated steels, the DCR is an outcome of opposing effects of bulk resistance increase with increasing temperature and contact resistance decrease with asperity breakdown, melting of zinc, substrate softening and indentation. While these features are widely accepted, uncertainty remains regarding specific material properties that distinguish nugget size from one steel
composition to another. In particular, the resistance-time relationship plot is influenced by the interactive effects of the applied welding conditions.

In recent times the inverter based medium frequency direct current (MFDC) process is being increasingly used as it is considered to be a more efficient spot welding process than the conventional alternating current (AC) process. Most information available on this subject, however, is based on the AC welding system and do not cover the DC system. Although weld parameters and DCR have been dealt with adequately to understand the fundamental mechanism of nugget formation, a systematic study distinguishing their role in relation with various steel compositions and properties is lacking. There is also very limited information on the effective heat generated that affect weld nugget size in different steels, particularly under DC welding conditions. The current paper attempts to address the role of surface contact conditions on dynamic resistance and resulting nugget size during MFDC welding.

2. Experiments

Spot welding tests were carried out on 1mm thick sheets of different cold rolled formable quality automotive steels, elemental composition of which are given in Table 1.

The investigation was carried out on two varieties of galvannealed interstitial free (IF and HIF) steels, a galvannealed low carbon (LC) steel, and a bare IF steel. All the three galvannealed steels used in the study were made according to JIS G3302 ZF100 specification with an average coating mass of 100 g/m$^2$ on both sides. The coating thickness is 9–11 μm in each side.

Two strips of the same steel with dimensions of 105 mm × 45 mm were considered for spot welding. The joint design and welding was carried out accordingly to BS 1140: 1993. A 150 kVA inverter based MFDC machine was used for spot welding. Truncated cone tips (inserts) of 16 mm diameter and 6 mm tip diameter made from RMAW Class II (Copper–Chromium) material were used as the electrode. Identical welding parameters were applied to each of the steel combinations for evaluating their dynamic contact resistance behavior. A toroidal coil and voltage clips, fixed to the electrodes, were used for acquiring the current and voltage waveforms during the welding experiments.

Peel tests were carried out and the nugget diameters were measured using a knife edged vernier caliper. The average of three nugget diameters has been reported. One weld joint for each of the parameters was precisely sectioned through the middle of the nugget, ground, polished, etched using 2% nital and then observed under an optical microscope.

Atom force microscopy (AFM) studies were carried out to evaluate the surface characteristics of the sheets considered for the study. For this purpose specimens of 10 mm × 10 mm were cut from freshly produced sheets. Microhardness measurements were carried out under 0.49 N load to estimate the strength of the surface asperities. Surface resistance measurements of the sheets were carried out using the spot welder by passing a low current of 2 kA under electrode pressure of 2.3 kN.

3. Results

3.1. Sheet Characteristics

The mechanical properties, surface and electrical properties of the as-received steels are given in Table 2 and Table 3. It is evident that LC(C) has the highest YS as compared to the other steels. The surface roughness varies from steel to steel, and is found to be higher for higher strength steels. It is low in coated steel as compared to the equivalent bare steel. The micro-hardness obtained is in tune with the mate-

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemistry (Atomic %)</th>
<th>C%</th>
<th>Mn%</th>
<th>Si%</th>
<th>P%</th>
<th>S%</th>
<th>Ti%</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF (C)</td>
<td>Galvanized</td>
<td>0.003</td>
<td>0.08</td>
<td>0.011</td>
<td>0.007</td>
<td>0.04 (Ti) + 0.035(Nb)</td>
<td></td>
</tr>
<tr>
<td>HIF (C)</td>
<td>Galvanized</td>
<td>0.004</td>
<td>0.53</td>
<td>0.029</td>
<td>0.104</td>
<td>0.04 (Ti) + 0.039 (Nb)</td>
<td></td>
</tr>
<tr>
<td>LC (C)</td>
<td>Galvannealed</td>
<td>0.04</td>
<td>0.28</td>
<td>0.012</td>
<td>0.012</td>
<td>0.006 --</td>
<td></td>
</tr>
<tr>
<td>IF (B)</td>
<td>Bare</td>
<td>0.003</td>
<td>0.07</td>
<td>0.006</td>
<td>0.008</td>
<td>0.007</td>
<td>0.087 (Ti)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YS, MPa</td>
</tr>
<tr>
<td>IF (C)</td>
<td>160</td>
</tr>
<tr>
<td>HIF (C)</td>
<td>224</td>
</tr>
<tr>
<td>LC (C)</td>
<td>317</td>
</tr>
<tr>
<td>IF (B)</td>
<td>131</td>
</tr>
</tbody>
</table>
rial strength, showing higher values in steels with more carbon and manganese contents.

Similarly, the surface resistance and bulk resistance increases with increase in steel strength. The AFM pictures in Figs. 1 and 2 indicate that the number density is more and depth of asperity is less in EIF coated steel as compared to the corresponding uncoated steel. EIF(C) has low fractal roughness \(R_a\) and height scaling parameter \(R_z\), while LC(C) has higher \(R_a\) and \(R_z\) values.

### 3.2. Dynamic Contact Resistance

Spot weld nugget of HIF(C) is shown in Fig. 3 with the

<table>
<thead>
<tr>
<th>Steel</th>
<th>Hardness, H, (\mu)</th>
<th>Surface Roughness, (R_a) (nm)</th>
<th>Surface Resistance, (R_s) ((\mu)A)</th>
<th>Resistivity, (\Omega\cdot m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIF(C)</td>
<td>35</td>
<td>2.5</td>
<td>3</td>
<td>313</td>
</tr>
<tr>
<td>HIF(C)</td>
<td>47</td>
<td>3</td>
<td>15.6</td>
<td>360</td>
</tr>
<tr>
<td>LC(C)</td>
<td>52</td>
<td>10.4</td>
<td>33.9</td>
<td>418</td>
</tr>
<tr>
<td>EIF(B)</td>
<td>31</td>
<td>16</td>
<td>71.4</td>
<td>846</td>
</tr>
</tbody>
</table>
nugget diameter $\phi$ inscribed. Table 4 shows that the nugget diameters are larger in LC(C) steel than those in EIF(C) and HIF(C) steels. Bigger nuggets are produced in coated steels with higher YS. Again, the nugget formed in bare EIF steel is bigger than that in coated EIF steel.

The profiles in Figs. 4–7 depict the DCR behavior of different steels for weld time of 120 ms. Amongst the coated steels, the ECR values of HIF ($367 \mu\Omega$) and LC ($607 \mu\Omega$) steels are higher than EIF ($294 \mu\Omega$) steel. Significantly the bare sheet has the highest ECR value of $828 \mu\Omega$. During the initial 40 ms of upslope time, the contact resistance falls rapidly to a minimum. Distinct serrations are observed in the DCR plot of coated steels in Fig. 4–6 during upslope time. Following minima, the DCR increases and attains $\beta$-peak, which is the highest dynamic resistance value following reversal. Subsequently, the resistance falls by a small

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Current, kA</th>
<th>Time, ms</th>
<th>Nugget diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIF(C)</td>
<td>8</td>
<td>120</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>5.2</td>
</tr>
<tr>
<td>HIF(C)</td>
<td>8</td>
<td>120</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>6.0</td>
</tr>
<tr>
<td>LC(C)</td>
<td>8</td>
<td>120</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>6.4</td>
</tr>
<tr>
<td>EIF(B)</td>
<td>8</td>
<td>120</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Note. Other parameters include: Squeeze time=470ms, Upslope time=40ms, Hold time=200ms, Electrode force = 2.3kN.
margin and becomes steady till the end of the process. The area under the DCR plot indicates the total heat input during welding, details of which are given in Table 5. A comparative DCR of LC(C) steel and EIF(B) steel is shown in Fig. 8, wherein the heat evolution is distinctly high in the latter.

Table 5 indicates that the heat utilized for nugget formation is a small percentage (9.8–19.5%) of the total heat input during spot welding. In case of coated steels, the heat efficiency increases marginally with increasing strength of steel. Here heat efficiency (η) may be defined as the percentage of heat (H) used for nugget formation out of total energy input (E), i.e. $\eta = 100 \times H/E$. Longer weld time show greater efficiency in coated steels. The heat efficiency during welding of bare EIF steel is significantly higher than that of the corresponding coated steel.

### 3.3. Heat Calculation from Nugget Volume

CAD software was used to reconstruct three dimensional images of the nugget from cross-sectional optical microscopy images of the nugget, and volume of each nugget calculated. A representative CAD image of the nugget in Fig. 3 is shown in Fig. 9.

The heat (H) required to produce the corresponding nugget volume was calculated as $H = m(C_p\Delta t + L)$ using standard heat balance formula involving mass $m$, specific heat capacity $C_p$, latent heat of fusion $L$, and temperature rise ($\Delta t$) to melting point. The $C_p$ of the steels was considered as 0.45 J/g°C, $L$ as 247 J/g, and melting point of 1535°C. Details of the calculations are given in Table 5. The heat input values obtained from DCR curves and nugget volume show good correlation with the nugget sizes; more the heat energy, larger is the nugget size.

The heat consumed during melting of the Fe–Zn intermetallic was calculated using a derived latent heat of fusion value of 126 J/g. Considering that elemental proportion of Fe and Zn is in the ratio of 1:9 in galvannealed coating, individual latent heat of fusion values of these elements was used in the same ratio to arrive at the latent heat value. Based on this the heat energy consumed was found to be of the order of 0.7 J considering melting of 200 g/m² of total coating material (for two sheets) over an area corresponding to the electrode tip diameter of 6 mm.

### 4. Discussion

The DCR characteristic varies from one steel to another and causes difference in weld size. The DCR determines energy input and controls nugget formation during spot...
welding. It depends on several material features like coating type and thickness, surface roughness, strength of the surface asperities, bulk material resistance and external factors like temperature and pressure. A schematic diagram explaining the same is given in Fig. 10.

4.1. Surface Characteristics—Coating

As the coating thickness is almost same in the three steels, it is assumed to have similar coating features, i.e. the microstructure and distribution of Fe–Zn intermetallic phases, considering the coating to have complied with JIS G3302 standard. Here it may be mentioned that in soft steels the substrate chemistry does not influence the coating features; the galvannealing process is optimized to ensure standard morphology and phase distribution.9) Regarding the effect of subtle variation in coating thickness and characteristics during welding of galvannealed steels, one may refer to the observations made by Gedeon and Eager.7) Their findings suggest that small variations in coating thickness do not have a significant effect on the position or width of the weld current lobe. Similarly, coating characteristics with identical coating thickness does not significantly affect the current range as the zinc coating becomes soft and deforms very early in the welding sequence. Barring initial static contact resistance, the coating has minimal role as far as heat generation for nugget formation is concerned.

4.2. Surface Characteristics—Roughness

In the as-received condition, LC(C) with higher Ra and Rz values (Figs. 1 and 2) has more surface roughness than EIF(C) and HIF(C) steels. Unlike soft steels, the surface roughness of the cold rolled full hard material is more in higher strength steels. During galvannealing, a reconstruction process of the original cold rolled surface takes place wherein the surface features are effectively transferred to the coating surface that contains the $\zeta$ phase.10) The proportion of $\zeta$ phase in the Fe–Zn layer influences the surface roughness to a great extent. Consequently, the surface roughness of coated steels shows an increasing trend with increasing YS. Apart from the steel grade, the processing conditions and surface profile of the skin pass roll influences the surface.11) Steels with higher $R_s$ values have a higher percentage of peaks; thereby the peak to valley ratio is high and hence the surface resistivity is enhanced. As given in Table 3 this is prevalent in higher strength steels.

4.3. Effect of Roughness and YS on ECR

The varying ECR values (Figs. 4–7) in different steels depict the relative behavior of the surface asperities during squeezing operation. As the electrodes apply pressure the asperities of the two surfaces initially meet, then deforms and establishes local contacts. The fractal geometry ($R_a$) and the number density of the asperities determine the actual area of contact. The extent by which the asperities would deform depends largely on the YS of the material, apart from the elastic modulus and Poisson’s ratio.1,2) Considering the low YS of EIF(C) steel, the asperities easily deform under squeeze pressure. Again, low surface roughness and asperity height are favoured for producing more local contacts. This justifies the relatively low ECR in EIF(C) steel as compared to the higher strength steels. The high surface resistivity substantiates for the high $R_z$ in LC(C) steel. The LC(C) steel with higher YS and higher asperity peaks ($R_z$=33.9 nm) resist deformation and have less contact sites. Therefore the ECR in this case is greater. The HIF(C) steel with material properties in between EIF(C) steel and LC(C) steel behaves in an intermediate manner, corroborating the stated reasons. As compared to EIF(C) steel, the corresponding bare steel shows a higher ECR because of higher surface resistance (Table 3). The higher peak heights and lower number density of the asperities enhance surface resistance.

4.4. Changing Effect of Material Features on DCR and Heat Energy

The material features seem to change as a function of temperature under applied pressure, which in turn influences the DCR. During upslope time, the current is ramped up to the peak current of 8 kA in 40 ms. The heat produced during this period softens the asperities. Under applied pressure, the asperities of low YS steel deform readily. The increase in localized contacts results in the drop of DCR. As mentioned by Eager et al.,7) surface roughness has minimum effect on heating; rather asperity collapse has a major effect. With heating in progress, the bulk resistance increases with increase in temperature. The DCR depends on
the counteracting effects of decreasing surface contact (interfacial) resistance and increasing bulk resistance. As long as the interfacial resistance dominates, the DCR continues to decrease. Amongst all steels, EIF(C) steel experiences the lowest DCR value at the end of upslope time (Fig. 4), primarily because of the soft asperities. The minimum DCR in LC(C) steel is higher that that of EIF(C) steel as the asperities in LC(C) steel resist deformation to a greater extent under the combined effect of pressure and temperature (Fig. 6). The increasing bulk resistance arrests further fall of DCR. The EIF(B) steel with low strength asperities collapse significantly with a sizable drop of DCR from a maximum of 828 $\mu$W to a minimum of 146.6 $\mu$W. However, as the asperity size of EIF(B) steel is bigger, the decrease of DCR is less than in EIF(C) steel (Fig. 7).

In coated steels, part of the heat generated during upslope is consumed by melting of the Fe–Zn layer. The serrations observed in the DCR profiles during upslope time is an indication of this phenomenon, wherein the Fe–Zn intermetallics start melting in the temperature range of 530 to 782°C. The energy (of 0.7 J) utilized in melting the Fe–Zn intermetallic in both sheets apparently seems to be small, but is significant considering that only a small percentage of the heat generated contributes to nugget formation; most of it lost to the surrounding. With less heat available, increase of bulk resistance is arrested. In contrast, the excess heat available in EIF(B) steel increases its bulk resistance. Therefore, the contribution of bulk resistance in DCR of EIF(B) steel is greater than that in EIF(C) steel.

Following upslope time the reversal of DCR takes place and increases with increasing temperature of the weld joint. The rising temperature reduces interfacial resistance by softening and eventual breakdown of asperities on one hand, and increasing bulk resistance on the other hand. The latter has a bigger effect, and therefore the rate of increase of resistance is high. As a significant portion of the heat generated is used up in melting of the Fe–Zn, temperature rise is limited in coated steels. The bulk resistance, therefore, does not increase by a great extent. Hence the $\beta$-peak is lower in EIF(C) steel as compared to EIF(B) steel. Again, as the strong asperities in LC(C) tend to resist deformation, the $\beta$-peak experienced is higher than that of EIF(C) steel. The DCR continues to increases as long as some portion of the interface within the current path is in solid state. As melting begins and becomes dominant, the interface resistance reduces. The DCR is therefore observed to taper off and gets saturated with bulk resistance only contributing to this effect.

4.5. Heat Efficiency During Welding of Different Steels

Interfacial and bulk resistance together causes enhanced DCR in higher strength steels. Therefore excess heat is available (Table 5) for nugget formation in these steels. Accordingly, the heat input in LC(C) steel is relatively more than other coated steels. Again, the surface features of EIF(B) steel result in more heat generation than coated steels. For long weld times of 200 ms the effect seems to reduce (Fig. 8) as most of the heat is utilized for nugget formation early in the process. Large volume of molten metal in the interface region prevents resistance heating at the later stages of welding. Contrarily in coated steels, with less melting happening early, the interface contributes to sustained heating even at the later stages that enables continuous nugget growth. The lower melting point associated with higher carbon equivalent steels favours formation of greater melt volume. Therefore, despite lower heat evolution, larger nugget size is observed in LC(C) steel as compared to EIF(B) steel.

The energy utilized depends entirely on the DCR of the steels, wherein the material properties play a definitive role. Significantly more than 80% of the energy sourced is lost in the surroundings, only a part is used for nugget formation. The contact properties to a lesser extent and bulk properties to a greater extent determine the efficiency of the process. As compared to the low strength EIF(C) steel, the HIF(C) and LC(C) steels generate more heat and shows better heat utilization. The poor heat efficiencies associated with leaner chemistry steels indicate that more heat is required to produce equivalent size nuggets. Therefore, higher current and weld time parameters are necessary to compensate for the low contact resistance values prevailing during welding. Longer weld time values show improved efficiency in coated steels, because a part of the initial heat is spent in melting of the zinc coated layer; the contribution towards nugget growth being more at a later stage. Heat used in melting of the coating layer contributes to lower efficiencies in coated steels.

5. Conclusions

The principle findings of the study are summarized as follows.

1. The mechanical properties and surface features of coated and bare steel sheets determine the contact conditions and influence static and dynamic contact resistance during spot welding. Higher yield strength with stronger asperities and enhanced modulus of elasticity resist early collapse during squeezing and welding.

2. Under identical welding conditions, larger nuggets form in higher strength steels. Higher static and dynamic contact resistance generate more heat and cause enhanced melting.

3. Varying surface conditions of coated and bare steel show different responses towards nugget formation. The iron–zinc intermetallic phases on the surface of galvannealed steel soften with increasing temperature, modify the interface condition and limit the dynamic contact resistance. In contrast, bare steel maintains higher contact and bulk resistance and utilize the same for melting and nugget formation.

4. Heat efficiency is more in higher strength steels; the stronger asperities and rougher surface features contribute to more melting. From a heat-input perspective, longer weld times are energy efficient and help form large nuggets. Energy utilization during welding of bare sheets is more than that of coated sheet.

Acknowledgement

The authors are grateful to the management of Tata Steel for permitting to publish this paper. They wish to record their thankfulness to Mr. L. R. Murmu, Research Assistant, R&D, Tata Steel for assisting in carrying out the welding
experiments.

REFERENCES