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Effect of process parameters on the mechanical performance of resistance spot welded joints of AISI 409M ferritic stainless steel

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In this study, the effect of process parameters on mechanical performance of the resistance spot welded joints of AISI 409M ferritic stainless steel sheets is investigated. Mechanical performance of the spot weld is evaluated in terms of output quality characteristics, such as load carrying capacity and energy absorption capacity. Important process variables, such as current, time, electrode force and holding time were varied separately and corresponding output parameters, which decide the mechanical performance of the spot welded joint have been analysed. Weld nugget geometrical parameters such as nugget size and surface indentation have also been analysed with respect to various process variables. It has been found that peak load and energy absorption capacity are in direct relationship with welding current as well as welding time, in expulsion free welds. Surface indentation increases with increase in current and welding time. It has also been observed that increasing electrode force results in slight reduction of both tensile shear strength and energy absorption capacity. The effect of holding time on mechanical performance of the resistance spot welded joint is found to be almost insignificant. Regression-based relations are developed to correlate the mechanical performance of the spot welds with nugget size.

Keywords: Resistance spot welding, AISI 409M, Peak load, Failure energy, Failure mode

Resistance spot welding (RSW) is a dominant welding process, used in sheet metal fabrication industries[1]. In RSW, two or more metal sheets are joined together by fusion, at discrete spots at the interface of work-pieces. Heat generated at the interface of the sheets, due to the resistance of the material to the flow of current through it[2]. The volume of the metal from the work-pieces that have undergone heating, melting, fusion and re-solidification is called the weld nugget[3]. In this process, two copper electrodes are used to hold the work sheets together and to pass a high current through it[4]. RSW is getting significant importance in automobile and rail car industries, as it is a fast process and can be automated easily[5]. A modern vehicle typically contains 2000 to 5000 spot welds[6]. Quality, performance and the failure characteristics of resistance spot welds are important aspects determining the durability and safety design of the vehicles, as they govern the transfer the load through the structure of the vehicle, during a crash[7].

Ferritic stainless steels account to nearly half of the AISI 400 series stainless steels. They are considered as cheaper substitutes to austenitic stainless steels[8,9]. Nowadays, ferritic stainless steels are widely used for structural applications of buses and railway coaches[10].

There are three indices to describe the quality of a spot weld, such as fusion zone size, mechanical performance and failure mode. Among these, fusion zone size is the most important factor describing the quality of spot weld. Load carrying capacity (peak load) and failure energy, measured at the time of tensile shear test, are the two important quantitative measurements, describe the mechanical performance[11-13]. Failure mode of spot welds is used as a qualitative measure to describe weld reliability[14]. Tensile shear test is usually used to evaluate the mechanical behavior of the spot weld[15].

Crashworthiness of a vehicle is defined as the capability of its structure, to provide adequate protection to its passengers, against injuries during a collision[16]. In order to ensure spot weld joints of high crashworthiness, it is necessary to have a deep understanding about the correlation between input and output parameters. There is an increasing demand of AISI 409M ferritic stainless steel in rail car industry, for structural applications. Hence, in this work, the effects of various input variables (current, weld time,

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electrode force and hold time) on the output quality characteristics (peak load, failure energy, nugget size, failure mode and surface indentation) of resistance spot welded joints of AISI 409M stainless steel are investigated.

Materials and Methods

In this study, 2 mm thick sheets of ferritic stainless steel AISI 409M were used. Test samples for tensile shear test were made ready, confirming to ISO 14273 standards. The size of the test specimen used in this study is of 60 mm width and 138 mm length. Chemical composition of the test material was tested with spectrometer and is shown in Table 1.

Values of tensile strength and hardness of the material used in this study were 455 MPa and 162 Hv, respectively. The whole welding process was conducted on a PLC controlled, 75 KVA, water cooled, pneumatically operated, pedestal type resistance spot welding machine (make-Jayahind Schiaky, model- P252). Truncated electrodes of 45°, with a tip diameter of 8 mm, RWMA class 3, were used for welding. Weld schedules have been made as given below, with five levels of equal interval for each of the parameter, based on preliminary trials. Welding was carried out at each level of all parameters, one at a time, keeping middle values for the rest of the parameters, thereby making a total of 20 weld schedules. Three trials were made in each schedule. The chosen levels for each parameter are given below.

Welding current 8.0, 9.5, 11.0, 12.5, 14.0 kA
Weld time 8, 9.5, 11, 12.5, 14 cycles
(1 cycle = 20 milliseconds)

Electrode force 2.5, 3.0, 3.5, 4.0, 4.5 kN
Holding time 10, 20, 30, 40, 50 cycles

Other parameters such as squeeze time and off time were kept constant, as 40 cycles, 20 cycles respectively.

Mechanical tests

Tensile shear test was conducted on a universal tensile testing machine (Make-TE-Jinan, Model No. -WDW 100). Tensile shear strength, corresponding to the peak point in the load-displacement curve of tensile shear test (peak load), was recorded for each test sample. The energy absorbed during failure was determined by measuring the area below the load-displacement curve, up to the peak load, of tensile shear test (Fig. 1). Mode of failure such as, interfacial mode or pull out mode, in each sample was noted during the tensile shear test. To determine the size of the nugget, peel test was carried out on specimens. Surface indentation was measured with a digital depth gauge of 0.01mm accuracy.

Results and Discussion

Output values were measured corresponding to each weld schedule. Their correlation with various input parameters is discussed below.

Effect of welding current on mechanical performance

Peak load, the maximum load at the point of initiation of failure for each sample, at varying current, was recorded. Experimental results indicate that peak load of the weld joint varies directly with respect to welding current. The nature of correlation between welding current and peak load is shown in Fig. 2a. It was noticed that peak load maintains a direct relationship with welding current, even though, at higher values of current (>12.5 kA), with the onset of expulsion of molten metal, this relationship becomes inconsistent. Expulsion results in heat and metal loss from the weld, causing reduction in the load bearing capacity of the joint.

Increase in current increases the heat input, which in turn causes more melting of metal, at the faying surfaces. It results in enlargement of the nugget, both in terms of nugget diameter and fusion penetration depth, with subsequent increase in peak load, as there is more area with increased nugget size, to withstand the external load. Variation of nugget diameter with

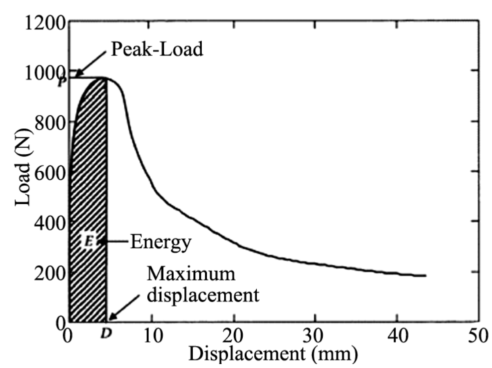

Fig. 1 — A typical load-displacement graph[24,25]

Table 1 — Chemical composition of test materials (wt%)

Grade	C	Si	Mn	P	S	Cr	Cu	Ni	Ti	Al	Fe
AISI 409M	0.030	0.415	0.875	0.027	0.013	12.32	0.014	0.072	0.02	0.014	Balance

respect to variation in current is shown in Fig. 2c. Nugget diameter determines the overall bonding area of the joint and is directly proportional to the heat input which in turn depends upon welding parameters.

As in the case of peak load, failure energy or the energy absorbing capacity of the weld was also found to be in direct relation with welding current. The correlation between failure energy and current is given in Fig. 2b. However, again at higher current values, expulsion causes drop in failure energy due to loss of molten metal and the heat energy associated with it. Failure energy is an important parameter associated with vehicle crashworthiness.

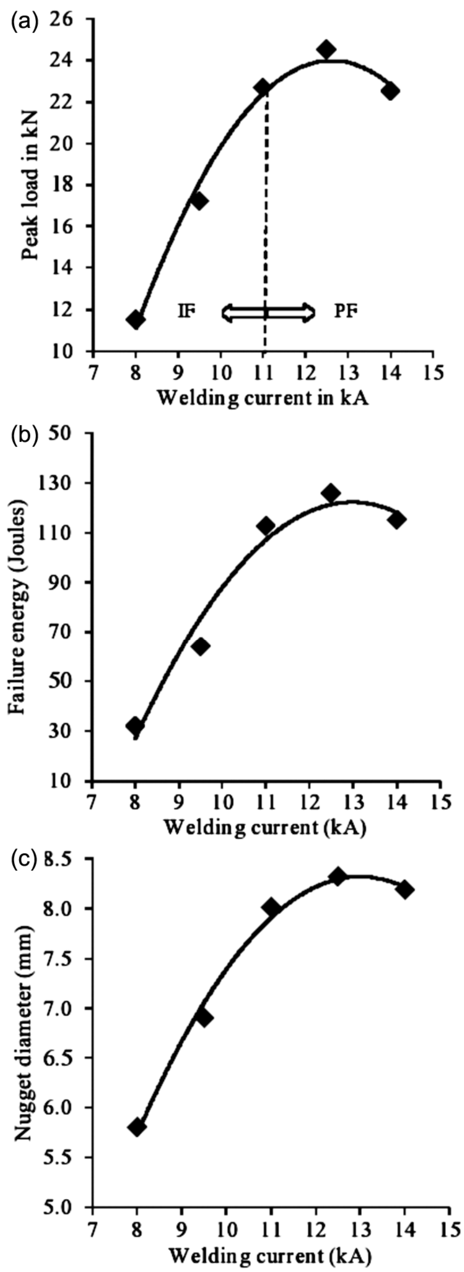

Fig. 2 — Effect of current on (a) peak load, (b) failure energy and (c) nugget diameter

It is well documented that in resistance spot welding, usually failure occurs in two modes such as, interfacial mode and pull out mode. In interfacial mode, failure occurs by propagation of crack along the nugget in a plane parallel to the surface of the sheet, whereas, in pull out mode, nugget withdraws itself completely from one of the sheets, in the form of a button[18,19]. It is also well documented that increase in welding current and subsequent increase in nugget diameter results in change of failure mode from interfacial to pullout[25]. However, the transition of failure mode from interfacial to pullout mode is not only governed by the nugget size alone, but also by the hardness characteristics of the weld and loading condition[20]. Pullout failure is usually associated with a considerable amount of plastic deformation in the surrounding area, whereas, in case of interfacial failure, almost no plastic deformation occurs. With increasing current, nugget size increases and a point is reached where the shear force along the nugget is larger than the tensile force along the circumference of the nugget and the transition from interfacial mode to pull out mode takes place. In the present investigation, it has been observed that transition of failure mode takes place at 11 kA of welding current (Fig. 2a), with other parameters kept at mid values of the chosen weld schedules. It has also been noticed that the nugget diameter corresponding to the transition from interfacial to pullout failure mode is 7.9 mm for the investigated material of 2 mm thickness.

Experimental results indicate that surface indentation is influenced by welding current in a positive way. The relation between welding current and indentation is given in Fig. 3. Increase in current

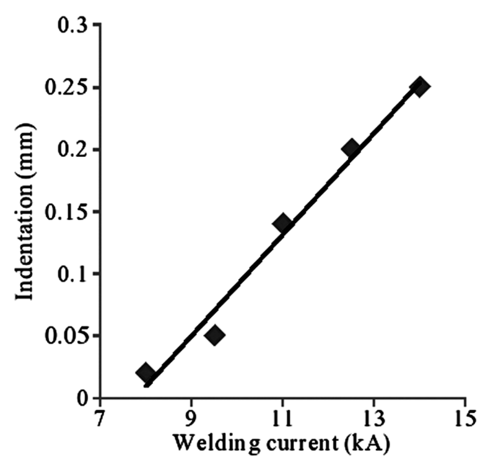

Fig. 3 — Effect of current on surface indentation

increases the heat input, thereby promotes plastic deformation at the surface of the sheet, where electrode force is acting. This leads to deeper indentation on the surface of the nugget. Severe expulsion and the metal loss thereby, associated with high current, also promotes surface indentation.

Effect of welding time on mechanical performance

As stated in the case of welding current, both peak load and failure energy were found to be in direct relationship with welding time.

Increase in welding time is associated with higher heat input and hence more fusion takes place at the faying surfaces. More fusion results in larger nugget size, in terms of both diameter and penetration. A larger nugget can withstand increased load and absorb higher amount of energy, than that of a smaller size. Variation of peak load, failure energy and nugget diameter with variation in welding current are shown in Fig. 4. However it can be observed that the increase in peak load, failure energy and nugget diameter with respect to increase in welding time is not as drastic as that with increase in welding current. The influence of welding time in heat generation and subsequent nugget formation is less compared to that of welding current, as the heat generated is proportional to the square of current, according to Joule’s law.

Indentation values were analysed in relation with the welding time values. Increased amount of indentation was noticed with increase in welding time (Fig. 5).

Other parameters being constant, increase in welding time results in increased heat input and promotes plastic deformation of the sheet areas in contact with the electrodes and results in deeper indentation. Because of the poor surface finish attached with indentation, usually it is not desirable in manufacturing processes. Also, surface indentation will alter the stress level at the periphery of the nugget and deep surface indentations lead to premature failure[11].

Effect of electrode force on mechanical performance

Effect of electrode force on various mechanical properties has been analysed. It has been found that parameters such as, peak load, failure energy and nugget size reduce slightly with respect to increase in electrode force (Fig. 6). Static electrical resistance (i.e. contact resistance) at the faying surfaces is mainly governed by the electrode force[21].

When the electrode force increases, the contact area at the faying surfaces increases and as a result,

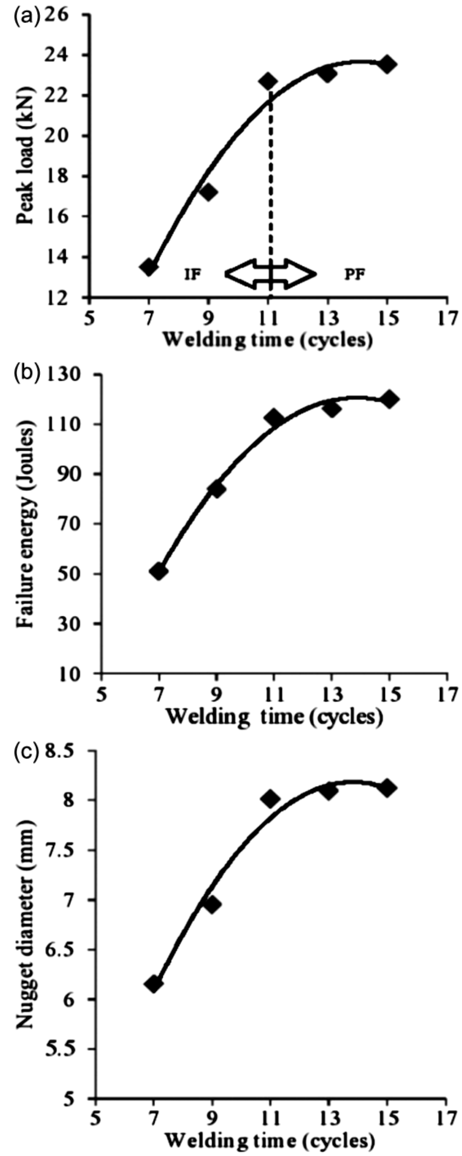

Fig. 4 — Effect of welding time on (a) peak load, (b) failure energy and (c) nugget diameter

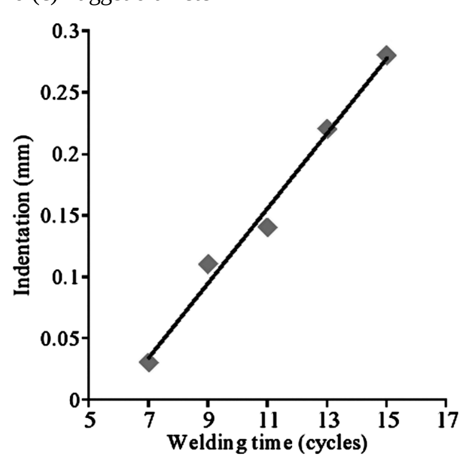

Fig. 5 — Effect of welding time on indentation

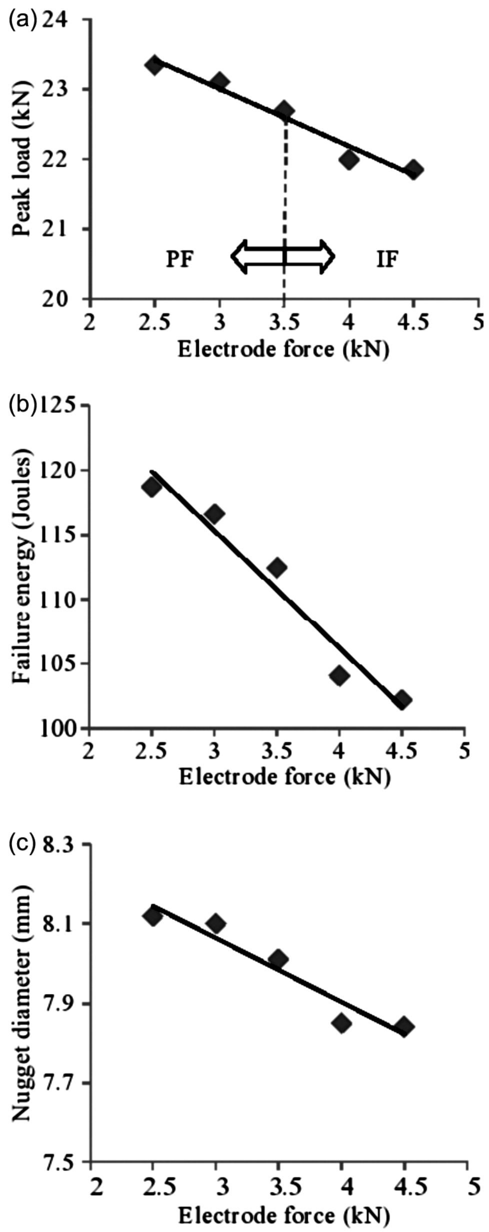

Fig. 6 —Effect of electrode force on (a) peak load, (b) failure energy and (c) nugget diameter

the static electrical resistance there reduces. Since the heat generated at the joint interface is directly proportional to electrical resistance, reduction in resistance causes decrease in heat generation and therefore, retards the nugget growth. Hence with increased electrode force, there is a negative impact on nugget size and it causes the peak load and failure energy values to drop.

However, surface indentation value was found to be increasing with increase in electrode force as shown in Fig. 7. Increased electrode force results in

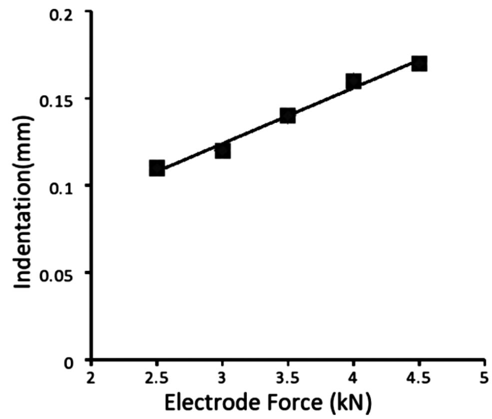

Fig. 7 — Effect of electrode force on indentation

increased amount of plastic deformation on the surface and this gives way to increased surface indentation.

Effect of holding time on mechanical performance

Holding time is the time period in cycles, during which the pressure is continued to be maintained after weld is made. Holding time affects the solidification of the molten metal in RSW. It has been reported that the cooling rates associated with RSW are extremely high, in the order of 1000–10,000 °C/s[19]. This is mainly due to the quenching effect provided by the water cooled copper electrodes. It was noticed that, with increasing value of holding time, parameters, such as peak load, failure energy and nugget size remained, more or less, unaffected, as shown in Fig. 8. Since holding time does not contribute to heat generation, there is no much significant effect for it, on the nugget size. As nugget size remains unaffected due to change in holding time, no much significant effect was seen on the mechanical performance parameters such as peak load and failure energy. There was no effect of holding time variation on failure mode, as all the samples failed in pull out mode. In the same way, on surface indentation also, no effect was seen due to variation in holding time as the observed indentation values corresponding to various holding time were nearly the same (Fig. 9). From these results, it is clear that holding time has no significant effect on the mechanical performance parameters, as its variation does not influence the geometrical aspects of the weld.

In this experiment, with other parameters being constant, transition of failure mode from pullout to interfacial was noticed, with increase in electrode force. This can be attributed to reduction in heat input

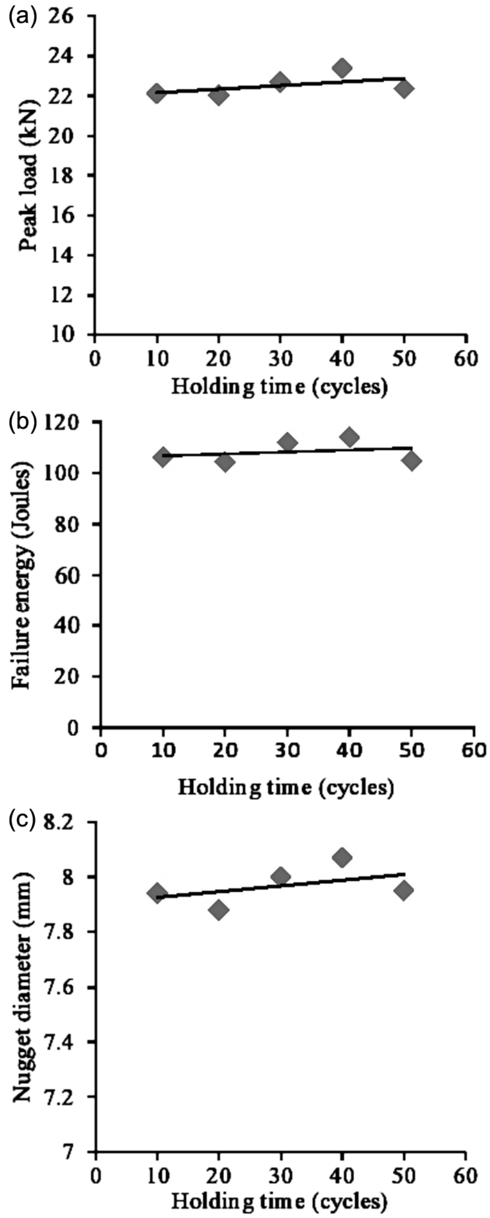

Fig. 8 — Effect of holding time on peak (a) peak load, (b) failure energy and (c) nugget diameter

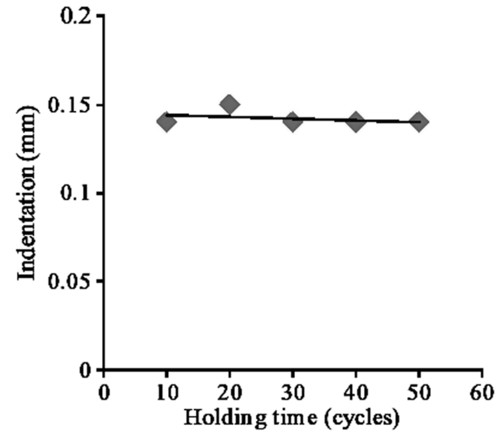

Fig. 9 — Effect of holding time on indentation

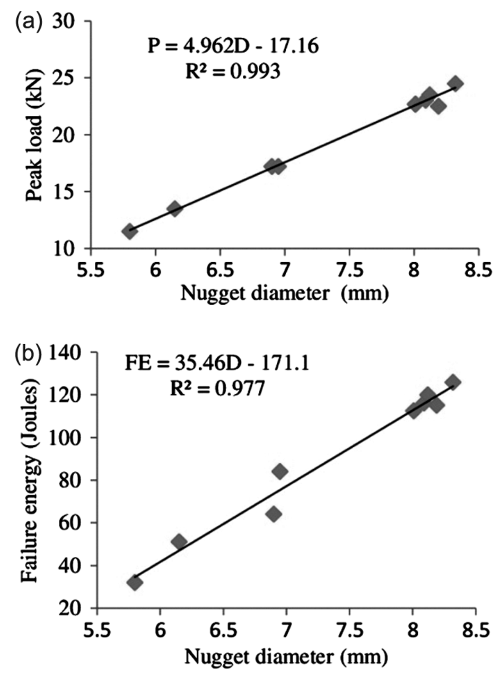

Fig. 10 — Effect of nugget size on (a) peak load and (b) failure energy

and thereby the nugget size, associated with increase in electrode force.

Effect of nugget size on mechanical response

To examine the effect of nugget size on the peak load, a scatter plot was constructed and a trend line was added to it with the corresponding equation and R-squared value, to get the nature of correlation between these two parameters (Fig. 10a). From the graph, it can be seen that there is a direct relationship exists between nugget size and peak load. To describe the correlation between the two parameters for the investigated material, the following relationship was developed using mathematical regression, with the help of Minitab software. To develop the same, the values of both nugget diameter and peak load obtained from all the twenty weld schedules have been used.

$$\text{Peak load (kN)} = 4.962D - 17.16 \quad \ldots (1)$$

where D denotes nugget diameter in mm.

The R-squared value obtained for the above equation was 0.993, which is a very high value, indicating that the data is well fitted in the regression model.

In the same way, to examine the effect of nugget size on failure energy, another scatter plot was constructed with trend line, corresponding equation and R-squared value, as shown in Fig. 10b. The data for the same was taken from the results of all the 20 weld schedules. The graph shows that a direct relationship exists between nugget size and failure energy. The relation between nugget diameter and failure energy, for the investigated material, can be expressed mathematically, with the help of the following equation, which was developed using mathematical regression.

$$\text{Failure energy} = 35.46D - 171.1 \quad \ldots (2)$$

The R-squared value obtained for the above equation was 0.977, which also is a very high value, indicating that the data is well fitted in the regression model.

The positive correlation between peak load and nugget diameter can be explained as below. With increasing nugget diameter, the area to resist the external load increases and as a result, the joint fails at a relatively higher load. In the same way, failure energy also increases with increase in nugget diameter. Failure energy is a function of failure load as well as the amount of plastic deformation the metal undergoes prior to breakage. Here failure energy increases, as the failure load increases due to increase in the nugget size.

Macrostructure of the weld

Macrograph image of the weld is shown in Fig. 11. There are three distinct zones such as, (a) fusion zone (FZ), where metal was melted during welding and solidified on cooling, (b) heat affected zone (HAZ), where metal was not melted but phase transformations occurred, and (c) base metal(BM), where no phase transformation occurred (Fig. 12).

Microstructure of the weld

Microscopic examination of the spot welded joint showed largely of columnar ferrite grains. However, some amount of martensite was present along the ferrite grain boundaries. Base metal consists of a fully ferritic microstructure.

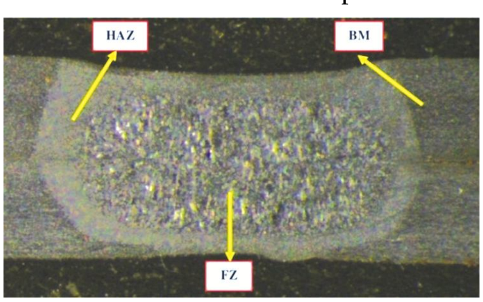

Fig. 11 — Macrograph of the weld

HAZ region of the weld also consists of ferritic microstructure, however, with some amount of grain growth at the high temperature region and some amount of martensite formation along the ferrite grain boundaries in the low temperature region. The phase transformations in the HAZ and FZ of AISI 409M steel welds during RSW have been reported in the past[22,23] .

Hardness profile of the weld

Microhardness at various locations such as base metal, heat affected zone and fusion zone has been measured and the hardness profile of the spot welded joint is given in Fig. 13. It can be seen that the microhardness at fusion zone (FZ) is higher than that at the base metal. This can be attributed, largely to the presence of martensite along the grain boundaries of

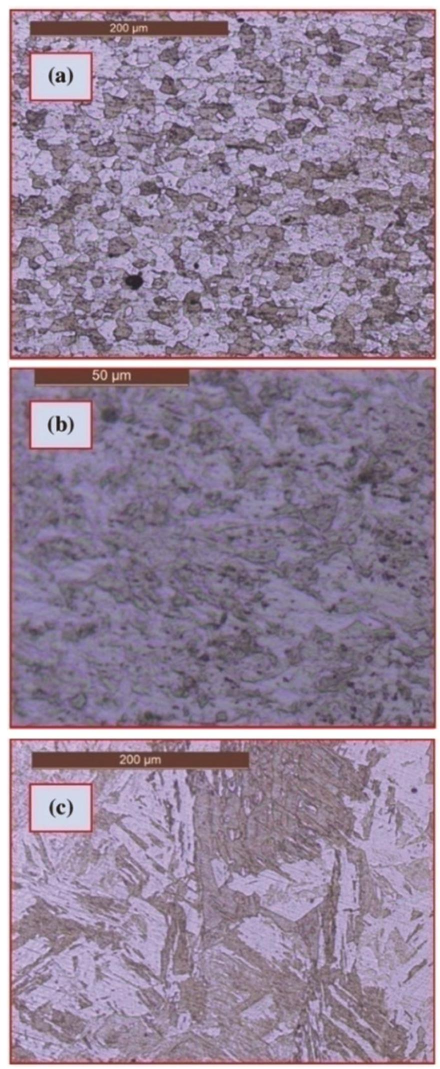

Fig. 12 — Microstructure of (a) base metal, (b) HAZ and (c) FZ

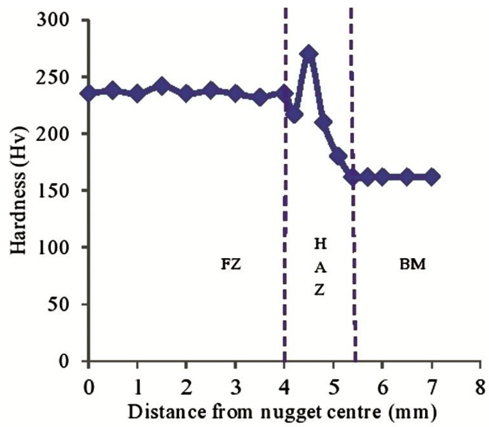

Fig. 13 — Hardness profile of the weld joint

columnar ferrite, in the fusion zone. In the high temperature heat affected zone there was a drop in hardness, with respect to fusion zone, due to grain coarsening effect. However, the highest value of hardness was noticed in the low temperature heat affected zone, due to the presence of martensite, transformed from austenite, attributed to the high cooling rates, inherent with RSW process[22].

Conclusions

In this study, the effect of various input parameters on the output quality characteristics of resistance spot welded joints of AISI 409M ferritic stainless steel has been discussed. The following are the conclusions of this investigation.

(i) With increasing weld time, values of peak load, failure energy, nugget size, and indentation were found to be increasing, up to expulsion point.

(ii) With increasing electrode force, values of peak load, failure energy, and nugget size were found to be reducing.

(iii) Effect of holding time on peak load, failure energy, and nugget size was found to be almost insignificant for the investigated material.

(iv) A regression-based mathematical relation was developed to correlate the mechanical performance of the spot welds with nugget size.

(v) It has been noticed that the minimum nugget diameter to ensure pullout mode of failure, for the investigated material of 2mm thickness, is 7.9mm.

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