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RESISTANCE SPOT WELDING OF MARTENSITIC STAINLESS STEEL (SS420) - PART I

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ABSTRACT

In the present investigation, 0.5 mm thin AISI 420 grade (0.29 % C) was selected for the study and effect of welding current (W2) and post heating (W3) on nugget dimension, tensile shear strength, cross tension strength and hardness was studied and lobe diagram was generated for said material. Result shows very narrow lobe width being 1.3 KA at 4 cycles and 0.7 KA at 7 cycles. It was observed that effect of W2 and W3 variables is similar on nugget diameter. Tensile-shear breaking load increases with increase in weld current while cross-tension breaking load & ductility ratio decreases with increase in weld current. Post-heat current leads to decrease in hardness with increase in nugget diameter.

Keywords: Resistance Spot Welding, Lobe diagram, SS420

1. INTRODUCTION

Spot welding is the chief welding process for automobiles and consumer goods. Spot welding is one of most mature applications in Robotics. Chao (2003) stated that the modern vehicle contains 2000 to 5000 spot welds. Today lot of research work is going on resistance spot welding. So quality of Resistance spot weld is one of the major concerns for both automobile and aerospace industry. Current design trends in automotive manufacture have shifted emphasis to lightweight materials in order to produce vehicles with higher fuel efficiency and lower the vehicle emission level.

In order to reduce body weight of the vehicle, hardened steel are potential alternates materials for automobile body. There is increasing emphasis to provide lighter cars. Therefore there is an effort to use high Strength steels such as HSLA, dual phase, in car body. Additionally the unique advantage of using stainless steel can be combined if martensitic stainless steel selected. However there use in restricted because of difficulty in producing consistently high quality resistance spot welds. There is a need to develop understanding of the behaviour of spot welds in terms of optimum parameters (lobe generation), metallurgy, failure mode and effect of post heat parameters on the quality of joints. Exploring the possibility of grade through RSW thus suitability for automobile industry and since RSW is chief method of fabrication and apply very widely, weldability of this material has to study, with this objective, martensitic stainless steel has selected for the study.

2. MATERIAL

Next Generation Vehicle (NGV) Project was organized by the three stainless steel producers ThyssenKrupp Nirosta GmbH, ArcelorMittal Stainless and Outokumpu Oyj demonstrated that stainless steel can be used to reduce weight and costs, and to improve safety and sustainability in structural automotive systems (Schuberth et al., 2008, pp G02-1). The steel used for investigation were three different grades of austenitic and one duplex grade. The characteristics of Martensitic Stainless Steel that necessitate careful attention to the details of operation include sensitivity of heat, low electrical and thermal conductivity, high melting temperature, high strength at elevated temperature and high co-efficient of thermal expansion .

The martensitic stainless steels most often welded AISI grades are 403,410,414, and 431. Martenstic stainless steel can be resistance spot welded either in annealed or in hardened & tempered condition. Regardless of condition, welding produces a hardened martensitic zone adjacent to weld. The hardness of this zone, although controlled to degree of welding procedure, depends mainly on carbon content. As the hardness of metal in the heat-affected zone increases, its susceptibility to cracking increases and its toughness decreases. Steels having a maximum carbon content of 0.15%, such as types 410 and 414, often produce satisfactory welds without post-weld heat treatment. Steels with higher carbon contents such as types 420 and 440A, generally require post-weld heat treatment was mentioned (Udin et al., 1954; ASM handbook, 1983)

An analysis shows that the welds are made quickly and such small volume of metal is heated, that the precipitation for stainless steel is generally negligible. For such condition, welding time should be reasonably short, and the cooling effect should be accelerated by quenching of electrode. Welding operations most likely to cause precipitation are in order, Fusion (Arc and gas), resistance flash and upset butt, seam and spot welding. Preferred alloy on which welding operations are performed should have maximum of 0.08%C, such as AISI 304, 308. For other stainless steel alloys precipitation will be less, mentioned in (RWMA, 1969).

Lobe Diagram **:**Lobe diagram is a graphical representation of ranges of welding variables over which the acceptable welds are formed on a specific material welded with the pre selected electrode force i.e. (Weld time Vs weld current) Welds made with currents or times exceeding the upper curve experience expulsion on welding and are considered unacceptable. Welds made with currents or times below the lower curve have insufficient nuggets size exhibit brittleness during tearing and are likewise considered unacceptable. Only welds made between these two limits are considered to be acceptable mentioned (Dickinson, 1980)

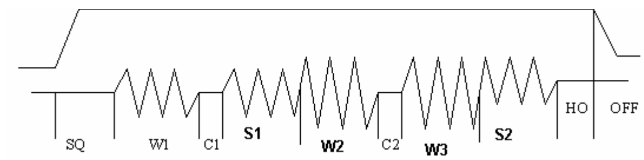
Tensile-Shear Test: This test consists of pulling in tension of two overlapping sheets to destruction, on a standard testing machine. During the tension-shear test, when the two sheets first pulled, weld nugget experiences a rotation, aligns the nugget with loading line. As the load increases, the deformation starts near nugget, and localized necking takes place at two points θ=0 and θ=180. Finally fracture takes initiates at one of the two points when ductility is reached. This crack grows around the circumference of the weld nugget. Although tensile-shear test provides a better visualization of weld strength, but it is not a pure tensile test, because the weld is not pulled along uniaxial direction so for measuring pure tensile strength, the tension test is done. There are two types of tension test (RWMA, 1969).

Cross-Tension Test: This test is designed to stress the weld in a direction normal to the surface of the material. Special holding fixture must be designed for this test to perform. Various methods for holding the fixture such as pin connections, wedge grips or threaded fixtures are used. In the cross-tension test, two sheets are pulled in the opposite direction on the standard testing machine. Sometimes special spacer block is provided to applying the load exactly on the weld. The standard geometry of the specimen for this test according to BS: 1140:1978, used (Gupta et al., 1988).

Peel Test: The peel test is a quality test of the spot weld. If it is hand peel test, it provides qualitative information of the strength. Also it indicates the area where there is a lack of fusion. Two sheets are pulled apart along the uniaxial direction until fracture takes place. However in Tensile-peel test, the specimen is bent along the certain distance and one sheet is fixed in the machine and other sheet is pulled in opposite direction and fracture occurred is observed

3. EXPERIMENTAL PROCEDURE

Equipment: Resistance spot welding equipment is attached with Miyachi Controller. This controller can precisely regulate the welding sequence including preheating and tempering cycle for the spot weld, thus providing scope for setting welding cycle in vast range. Such multiple impulse controller is more useful for high carbon steels and stainless steels to control hardness and strength of nugget.



SQ- squeeze cycle,
W1- Preheating Current
C1- Cooling 1, S1 –Slope 1
W2 –Welding Current,
C2- Cooling 2
W3 – Post heating,
S2 –Slope 2
HO- Hold time,
OFF –Off time

Fig.1 shows special welding cycle of miyachi controller.

Electrode: Cu- Be truncated cone shaped electrode used for experimental work.
Electrode tip diameter was 5.92 mm.
RWMA classification; Group A- class 3 (AWS handbook, 2000)

Chemical Composition: Composition of Martensitic stainless steel (SS420) as given in Table 1.
Thickness of sheet: 0.5 mm;
Condition: Cold rolled

Table 1: Chemical composition of SS 420

Element	C	Mn	Si	P	S	Cr
Percent	0.29	0.48	0.77	0.002	0.0005	13.33

Lobe Generation: Weld time of 4, 5, 6 and 7 cycles are selected and expulsion and no weld limits are found out. The maximum and minimum currents for above four cycle are shown in the table 2. Lobe diagram for MSS 420 is shown in figure 2.

Table 2: Expulsion and no weld limits for Martensitic stainless steel SS420 for various weld time

Weld time in cycles	Maximum weld current in KA	Minimum weld current in KA	Lobe Width (kA)
7	1.9	1.2	0.7
6	2.2	1.3	0.9
5	3.1	2.0	1.1
4	4.4	3.1	1.3

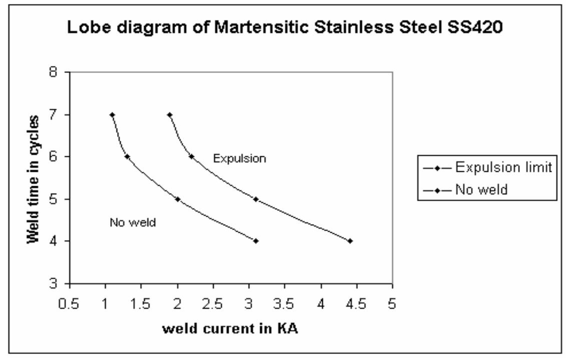


Figure 2: Lobe diagram of MSS steel SS 420

Measurement of Nugget Dimensions: Toolmaker microscope was used for measurement of nugget dimensions. The nugget dimensions of Martensitic stainless steel SS420 in cold rolled condition for various W2 and W3 variables is shown in table 3. List count of tool maker microscope was 0.01mm.While studying effect of W2, W3 welding current and time was kept zero (0).While studying effect of W3, W2 welding current and time was kept zero (0)

Table 3 Effect of W2 and W3 on nugget dimensions for Martensitic stainless steel SS 420

	W2		Nugget dimensions (mm)				Remark
Sr. No.	Current Amp	Time cycles	d: diameter	h: height	h/d	Volume mm^3	
1	1.4	7	1.33	0.495	0.372	0.737	Porous weld
2	1.5	7	1.38	0.505	0.366	0.8256	Ditto
3	1.7	7	1.40	0.60	0.423	0.8620	Ditto
4	1.9	7	1.65	0.625	0.379	1.411	Expulsion
5	2.2	7	1.95	0.645	0.331	2.329	Ditto
6	1.6	6	1.32	0.55	0.417	0.7225	No expulsion
7	1.8	6	1.41	0.555	0.394	0.8806	Ditto
8	2.0	6	1.70	0.595	0.35	1.5435	Porosity, cracks
9	2.2	6	1.75	0.560	0.32	1.684	Expulsion
10	2.3	5	1.35	0.555	0.411	0.7729	No expulsion
11	2.5	5	1.44	0.58	0.403	0.9380	Ditto
12	2.7	5	1.55	0.51	0.330	1.170	Ditto
13	2.9	5	1.63	0.64	0.393	1.3605	Ditto
14	3.1	5	1.82	0.675	0.371	1.8939	Expulsion
15	3.3	4	1.30	0.58	0.446	0.6902	Ditto
16	3.5	4	1.38	0.68	0.492	0.8256	Ditto
17	3.7	4	1.50	0.595	0.396	1.0602	Ditto
18	3.9	4	1.52	0.575	0.379	1.103	Ditto
19	4.1	4	1.57	0.625	0.372	1.215	Ditto
20	4.3	4	1.68	0.59	0.351	1.490	Ditto
21	4.4	4	1.74	0.60	0.349	1.655	Expulsion

	W2		W3		Nugget dimensions (mm)				Remark
Sr. No.	Current Amp.	Time cycles	Current Amp	Time Cycles	d: diameter	h: height	h/d	Volume mm^3	
				Effect of W_3 on nugget dimensions					
22	3.2	4	1.2	3	1.35	0.50	0.370	0.7729	Good weld
23	3.2	4	1.5	3	1.50	0.53	0.353	1.0602	Good weld
24	3.2	4	1.8	3	1.80	0.60	0.333	1.8321	Expulsion
25	3.2	4	2.1	3	2.05	0.68	0.331	2.706	Ditto
26	2.9	5	1.2	3	1.65	0.71	0.430	1.4412	Expulsion
27	2.9	5	1.5	3	1.67	0.70	0.419	1.4631	Expulsion
28	2.9	5	1.8	3	1.75	0.60	0.343	1.6836	Ditto
29	2.9	5	2.1	3	2.02	0.56	0.277	2.589	Expulsion
30	1.8	6	1.2	3	1.35	0.62	0.459	0.7729	Pointed nugget
31	1.8	6	1.5	3	1.65	0.65	0.393	1.4112	Good weld
32	1.8	6	1.8	3	1.69	0.60	0.355	1.5164	Expulsion
33	1.8	6	2.1	3	1.75	0.60	0.343	1.6839	Ditto
34	1.5	7	1.2	3	1.65	0.60	0.364	1.4112	Ditto
35	1.5	7	1.5	3	1.95	0.54	0.277	2.329	Ditto
36	1.5	7	2.1	3	2.05	0.56	0.273	2.7065	Ditto

Ditto: Same as above

Table 4: Effect of W2 on Tensile-shear strength for Martensitic stainless steel *SS420*

Weld current KA	Weld time cycles	Breaking load for T-S test in Kg	Mode of failure
3.4	4	50.75	Interfacial
3.7	4	81.25	Ditto
4.4	4	103	Ditto
2.4	5	53.25	Ditto
2.7	5	124	Ditto
3.1	5	155	Ditto
1.7	6	36.25	Ditto
1.9	6	102	Ditto
2.2	6	121	Ditto
1.5	7	73.75	Ditto
1.7	7	95.5	Ditto
1.9	7	124	Ditto

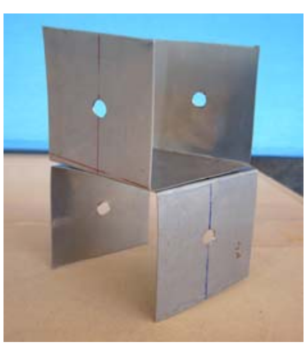


Figure 3 (a) Cross-tension sample

Figure 3 (b) Sample loaded in tensometer

Tensile-Shear Test: The tensile-shear test was performed using a tensometer (Model INSTRON 1185). Samples were prepared according to ANSI/AWS standard (IS, 1968). The breaking load of tensile-shear test is shown in table 4.Base metal strip was tested under straight tension and breaking load was: 86.5 kg. Post heating current (W3) and time was kept zero (0)

Cross-Tension Test: Cross-tension test was performed using as tensometer. The top and front view of cross-tension test sample is shown in figure 3 (a), dimension of specimen published by Zhou M. (1999, pp , 305-s to 313-s) (Zhou et al, 1999). The tensometer is shown in figure 3 (b). The breaking load of cross-tension test and ductility ratio for various W2 variables is shown in table 5. Post heating current (W3) and time was kept zero (0)

The ductility ratio, given in Table 5, is defined as the ratio of the breaking load of the C-T test and the breaking load for the T-S test. A ratio of 1 indicates maximum ductility of the spot weld and 0 reflects extreme brittleness. The values shown in Table 5 are very low and indicate that the spot welds are predominantly brittle in nature.

Hardness Test: Vickers' Macro-hardness test is used for measurement of hardness of particular spot. The Vickers' Macro-hardness for various W2 and W3 variables are shown in table 6

Load applied: 20 kg

Base metal hardness: 198.36 HV

Table 5: Effect of W2 variables on Cross-tension strength of MSS420

Weld current in KA	Weld time in cycles	Breaking load for C-T/ T S	Ductility ratio	Mode of failure
4.4	4	5 / 103	0.0485	Interfacial
3.1	5	10.5 /155	0.0677	Ditto
2.2	6	15.5 / 121	0.1280	Ditto
1.9	7	17 / 124	0.1371	Ditto

Table 6: Effect of W2 and W3 on Vickers' hardness

Weld time in cycles	Weld current in KA (W2)	Post-heat time in cycles	Post-heat current in KA (W3)	Vicker Macro-hardness in HV
4	3.7	0	0	623
5	2.6	0	0	613
6	1.8	0	0	528
7	1.5	0	0	426
4	3.7	3	1.2	575
4	3.7	3	1.5	457
4	3.7	3	1.8	412
4	3.7	3	2.1	278
5	2.6	3	1.2	557
5	2.6	3	1.5	540
5	2.6	3	1.8	358
5	2.6	3	2.1	299
6	1.8	3	1.2	505
6	1.8	3	1.5	310
6	1.8	3	1.8	232
6	1.8	3	2.1	197.8
7	1.5	3	1.2	412
7	1.5	3	1.5	386
7	1.5	3	1.8	291
7	1.5	3	2.1	233

4. RESULTS

Effect of Variable W 2

i)

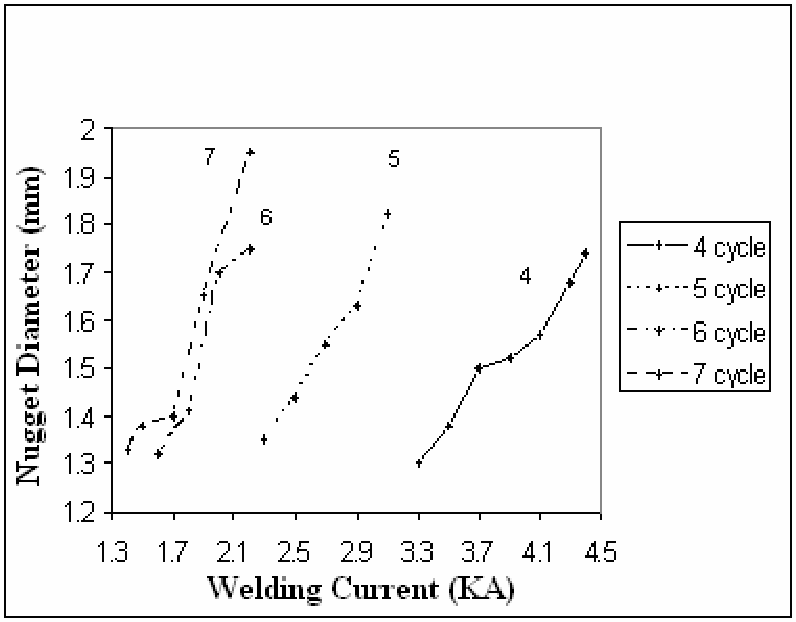


Fig 4 : Nugget diameter Vs Weld current

ii)

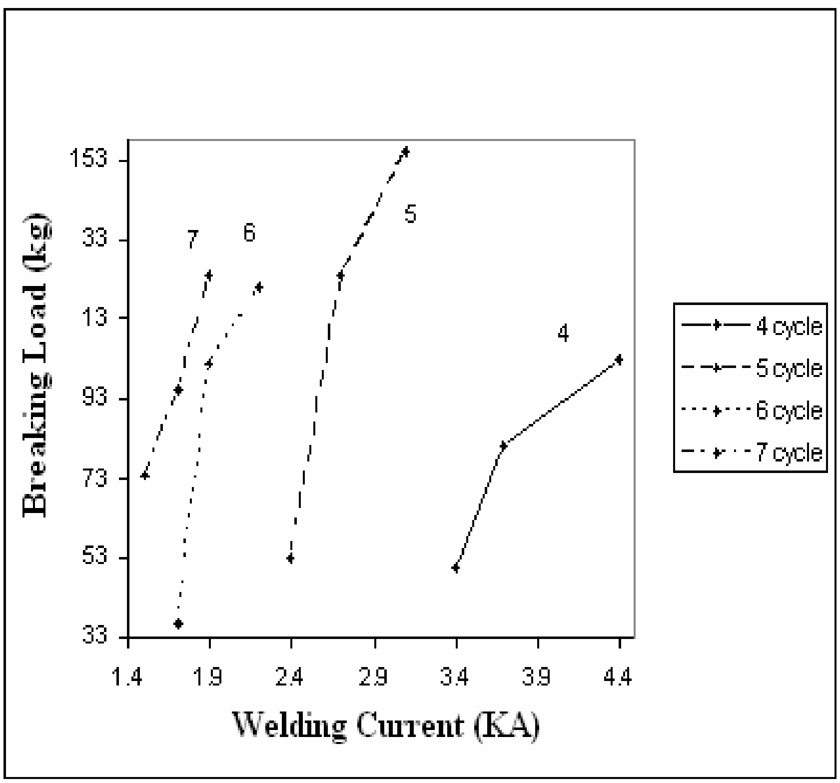


Fig 5: Breaking load Vs Weld current for TS

iii)

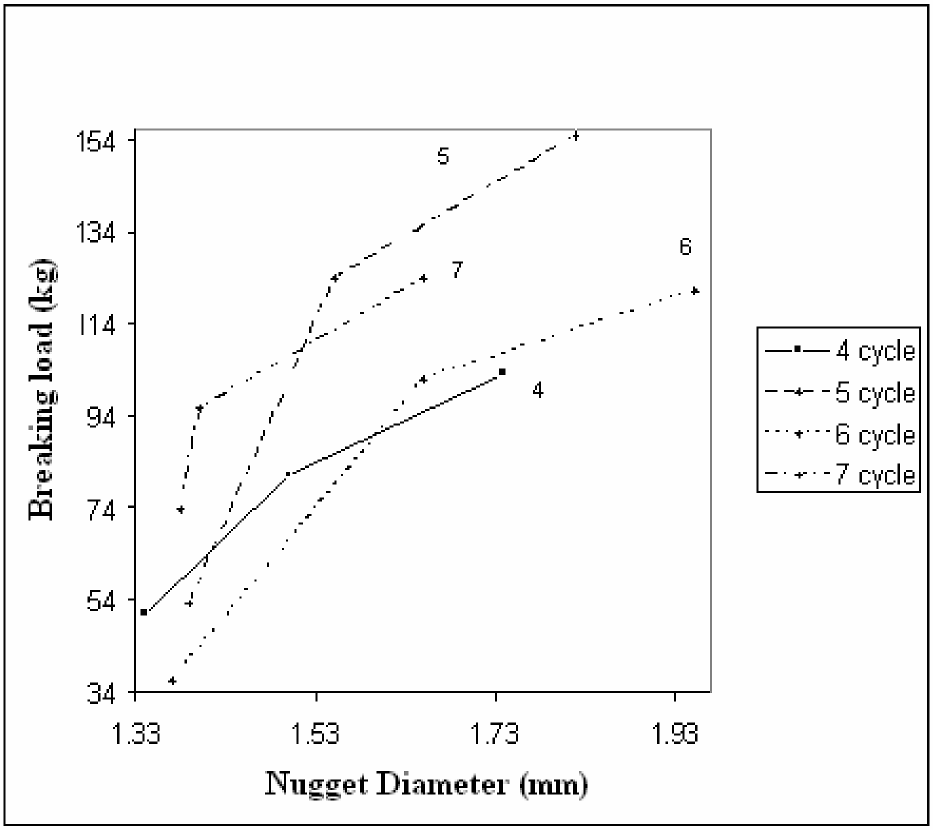


Fig 6: Breaking load Vs Nugget diameter for TS

vi)

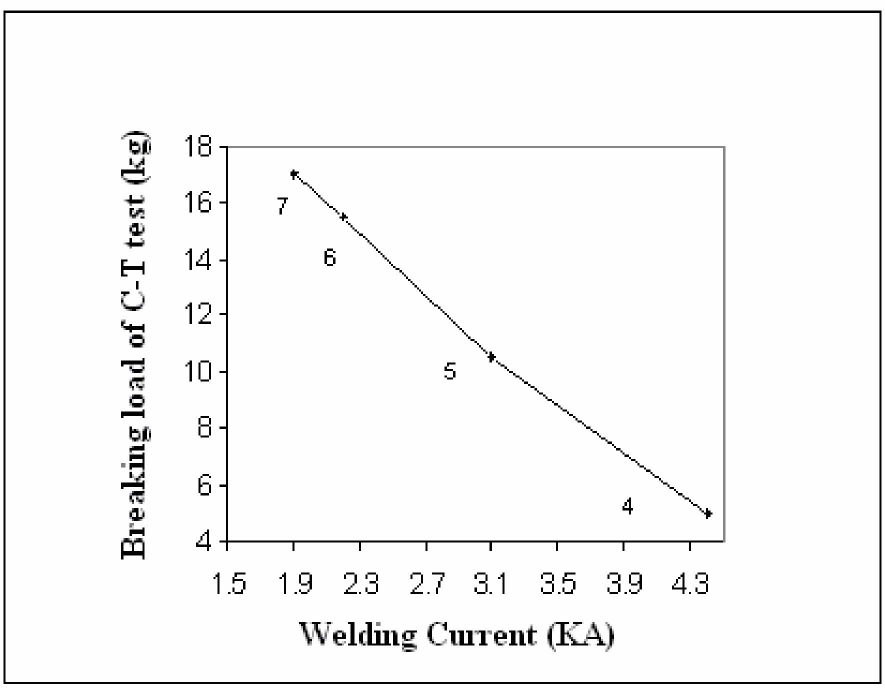


Fig 7: Breaking load Vs Weld current for CT

v)

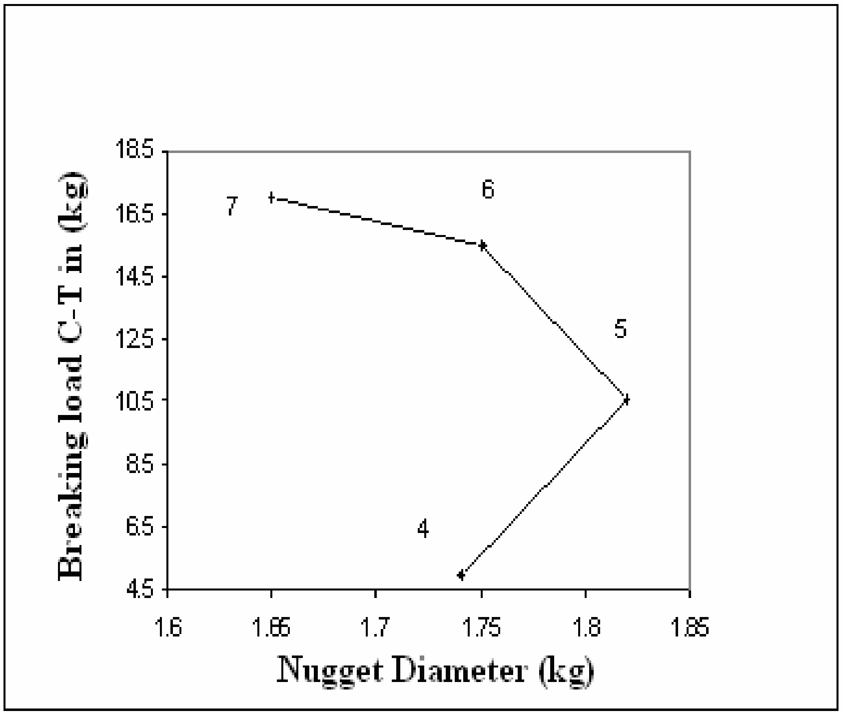


Fig 8 : Breaking load Vs Nugget diameter for CT

vi)

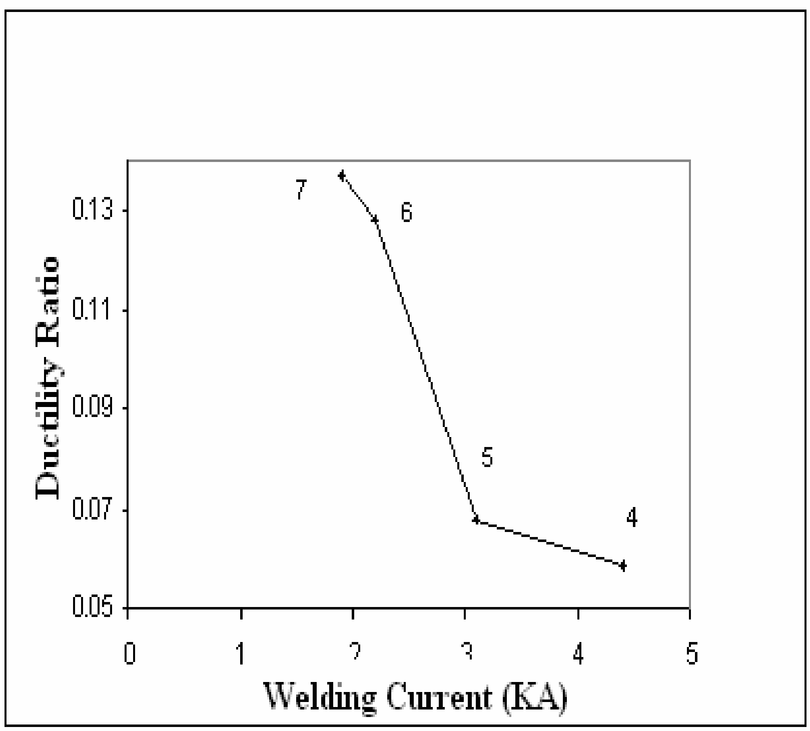


Fig 9 Ductility ratio Vs Weld current

vii)

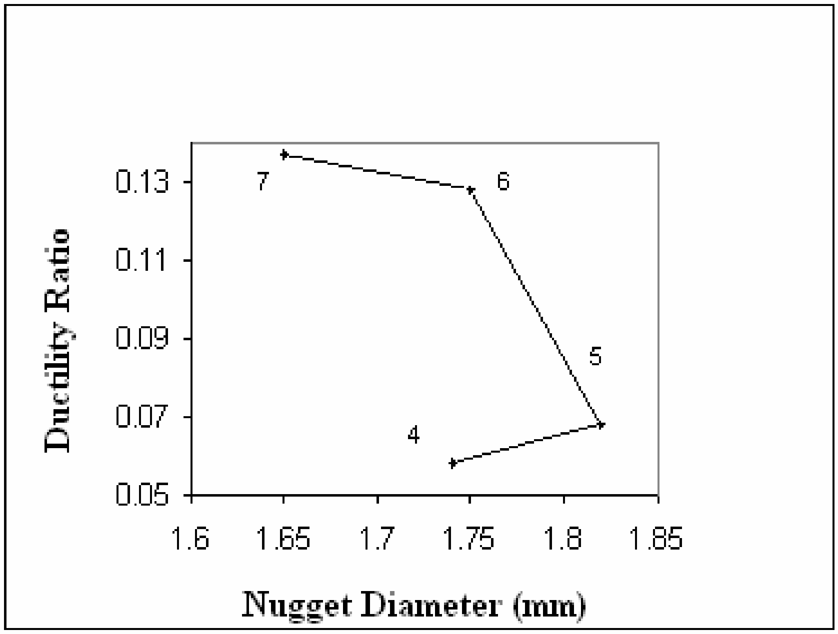


Fig 10 Ductility ratio Vs Nugget diameter

viii)

Fig 11: Vickers' hardness Vs Weld current

W3 Variables

(i)

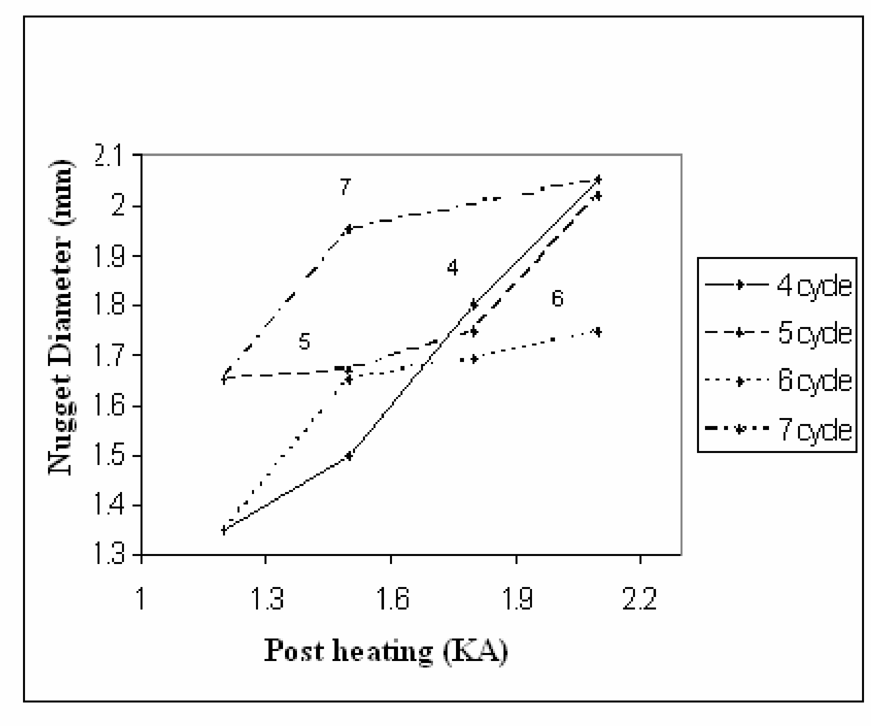


Fig 12 Nugget diameter Vs Post-heat current

(ii)

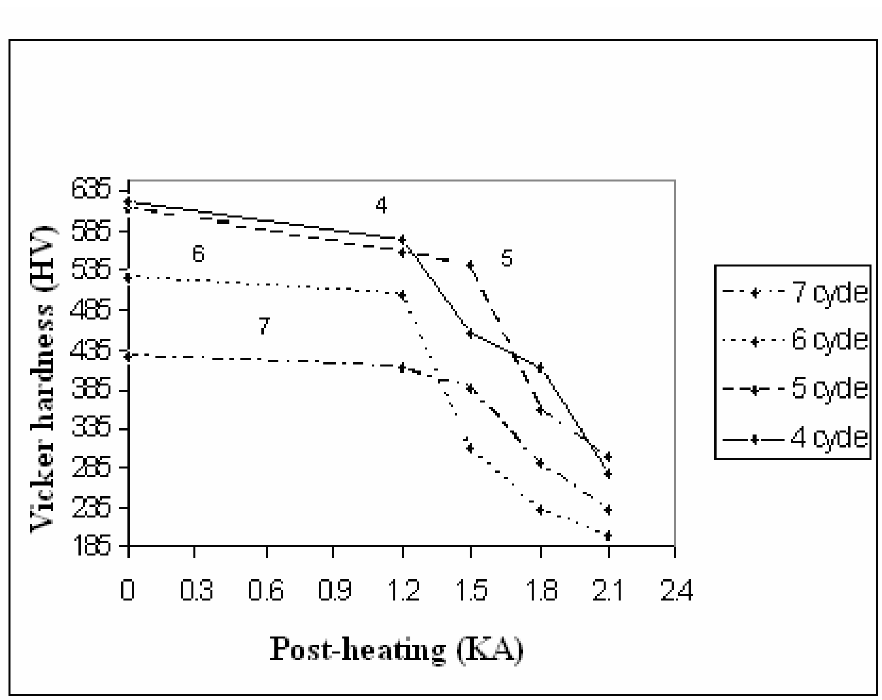


Fig 13 Vickers' hardness Vs Post-heat current

OBSERVATIONS

(a) W2 variables

(1) Change in Nugget Diameter with Weld Current

- Figure 4 shows that nugget diameter increases with increase in weld current (W2) for each weld cycle. Tensile shear breaking load value also depends on nugget diameter, higher the value more will be strength of weld nugget.
- Maximum nugget diameter observed at 7 cycles and 2.2 KA is 1.95 mm.
- Effect of W2 and W3 on nugget diameter is nearly similar. The limiting value of nugget diameter is 2.10 mm irrespective of weld current and weld time.

(2) Change in Breaking Load with Weld Current and Nugget diameter for tensile-shear test

- Figure 5 and 6 shows that breaking load increases with increase in weld current (W2) and nugget diameter for each weld cycle.
- Maximum breaking load of 155 kg is observed at 5 cycles and 3.1 KA with nugget diameter of 1.82 mm (Table 3).
- Better tensile-shear breaking load in 5 cycle for MSS.
- The tensile-shear test provides a better visualization of the weld strength, but it is not a pure tensile test, because the weld is not stressed uniaxially. The global mode of the failure is by shear.

(3) Change in Breaking Load with Weld Current and Nugget diameter for cross-tension test

- Figure 7 and 8 shows that breaking load decreases with increase in weld current and nugget diameter.
- Maximum breaking load of 17 kg is observed at 7 cycles and 1.9 KA with nugget diameter of 1.65 mm and minimum breaking load of 5 kg is observed at 4 cycles and 4.4 KA with nugget diameter of 1.74 mm.
- Tensile-shear breaking load increases with increase in weld current while cross-tension breaking load decreases with increasing weld current.
- In the cross-tension test, the two sheets are pulled in opposite directions on a standard testing machine. The fracture mode at the global level is tensile

(4) Change in Ductility Ratio with Weld Current and Nugget Diameter

Figure 9 and 10 shows that ductility ratio decreases with increase in weld current and nugget diameter.

- Maximum ductility ratio of 0.1371 is observed at 7 cycles and 1.9 KA with nugget diameter of 1.65 mm.
- Minimum ductility ratio of 0.0485 is observed at 4 cycles and 4.4 KA with nugget diameter of 1.74 mm.
- Nugget is more ductile at 7 cycle and less ductile/brittle at 4 cycle.

(5) Change in Hardness with Weld Current. Figure 11 show that hardness increases with increase in weld current.

- Maximum hardness of 623 HV is observed at 4 cycle and 3.7 KA.
- Minimum hardness of 426 HV is observed at 7 cycle and1.5 KA.

(b) W3 variables

(1) Change in Nugget Diameter with Post-heat current

- Figure 12 shows that nugget diameter increases with increase in post-heat current (W3) for each weld cycle with constant weld current and constant post-heat time.
- Maximum nugget diameter observed at post-heat current of 2.1 KA with 4 and 7 cycle is 2.05 mm.

(2) Change in Hardness with Post-heat Current

- Figure 13 shows that hardness decreases with increase in post-heat current with constant weld current and constant post-heat time.
- Maximum hardness of 623 HV is observed at 4 cycles with post-heat current of 0.0 KA
- Minimum hardness of 198 HV is observed at 6 cycles with post-heat current of 2.1 KA.

5. DISCUSSION

The welding lobe diagram (Figure 1) and the data shown in Table 2 indicate that the current range required for satisfactory spot welding is relatively narrow and that the lobe width increases slightly with decreasing cycle time (0.7 to 1.3 kA for 7 to 4 cycles). During production, there are wide variations in surface condition of sheet and hence variation in contact resistance leading to variation in spot size. Additionally electrode tip size increases during extended use of electrode. All such cases may lead to variation in contact resistance and spot size. If welding lobe is narrow, condition of no weld or expulsion may be encountered more often. However in case of wider lobe, the possibilities of such situation are less likely to be encountered and sound weld may be obtained in spite of variation in contact resistance, surface condition of sheet and due to mushrooming of electrode.

Cooling rates associated with spot welding are extremely rapid (on the order of 10^3 to10^5 ◦C/sec). A hardened microstructure with a large amount of martensite will also favour brittle cleavage fracture. Rapid cooling rates have also been associated with tendency for solidification cracking. Chemical composition of Martensitic stainless steel also play major role. Chromium, in SS 420 is 13.33 %. Being strong promoter of hardenability, chromium causes the

formation of martensitic structure even with relatively slow rates of cooling; this harder martensite will provide a path for a crack to propagate through nugget. A hardened microstructure with a large amount of martensite will also favour brittle cleavage fracture. In order to restore the ductility in weld nugget, post heating is necessary.
Tensile shear strength depends on Nugget Diameter, and Nugget Diameter depends on Welding Current and Cycle. With increasing current nugget diameter increases (Fig 4), which increases the tensile shear strength. Figure 5 illustrates that, tensile shear breaking load increases steeply with welding current and the results for 7, 6 and 5 cycles are close to each other. However, the shortest cycle time of 4 cycles requires much higher welding currents.

The ductility ratio, given in Table 5 (plotted in fig 9) is defined as the ratio of the breaking load of the C-T test and the breaking load for the T-S test. A ratio of 1 indicates maximum ductility of the spot weld and 0 reflects extreme brittleness. The values shown in Table 5 are very low and indicate that the spot welds are predominantly brittle in nature.

Table 6 and Fig 13 shows that with increasing post heating current, there is decrease in hardness for all four cycles. It also reflects in Fig 13. On the basis of these it is obvious that post heating is necessary to control the hardness and ductility ratio (AWS handbook, 2000).

Mode of failure of 0.5mm thin Martenstic stainless steel (AISI 420-0.29 % C) was also studied under different testing conditions discussed in part II, which will be publish in subsequent issue of the same journal. Part of investigation presented at International welding congress held at Chennai, India (Badheka et al., 2008).

6. CONCLUSIONS

(1) Lobe width for SS420 steel is 1.3 KA at 4 cycles and 0.7 KA at 7 cycles, narrow lobe width.

(2) 5 cycle is the most appropriate cycle for SS 420 and properties are better at this cycle.

(3) Low values of ductility ratio indicate that the spot welds are predominantly brittle in nature

(4) Post heating is necessary for SS 420 to control the hardness and ductility ratio of weld nugget

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