Resistance spot welding of mild steel sheets

—*A literature review* (Concluding part)

By Dr. R. S. Chandel

Mechanical Characteristics of Spot Welds

There are many techniques for assessing the properties of spot welds, for example, destructive vs. non-destructive tests ; qualitative vs. quantitative tests ; tests for quality control vs. information for design ; static vs. dynamic tests ; and shear vs. tension tests etc. [22]

Static Tensile-Shear Tests

The most widely used mechanical test for spot welds is the tensile-shear test, which gives some measure of operative strength. The test specimen is prepared by overlapping two pieces of the material and joining them by a spot weld then the weld is nominally stressed in shear, and because the finished specimen is subjected to a tensile load as in conventional tensile testing, the test is called tensile-shear test, Figure 12.

The main advantages of the tensile-shear test are as follows :

(i) The result is expressed in units which closely approach the needs of the designer ;

(ii) The simplicity of the specimen preparation ; and

(iii) The availability of tensile testing equipment.

The main objections to this test are :—(i) the unavoidable eccentricity of loading due to the geometrical features of the test, causing distortion of the specimen and (ii) the fact that a pure shear or a pure tensile stress is never achieved.

The mechanism of failure of a single-lap spot weld is a complex mechanical phenomenon explained in the following manner [10,23] : the misalignment of the overlapping strips allows a couple to form which causes bending near to the weld ;

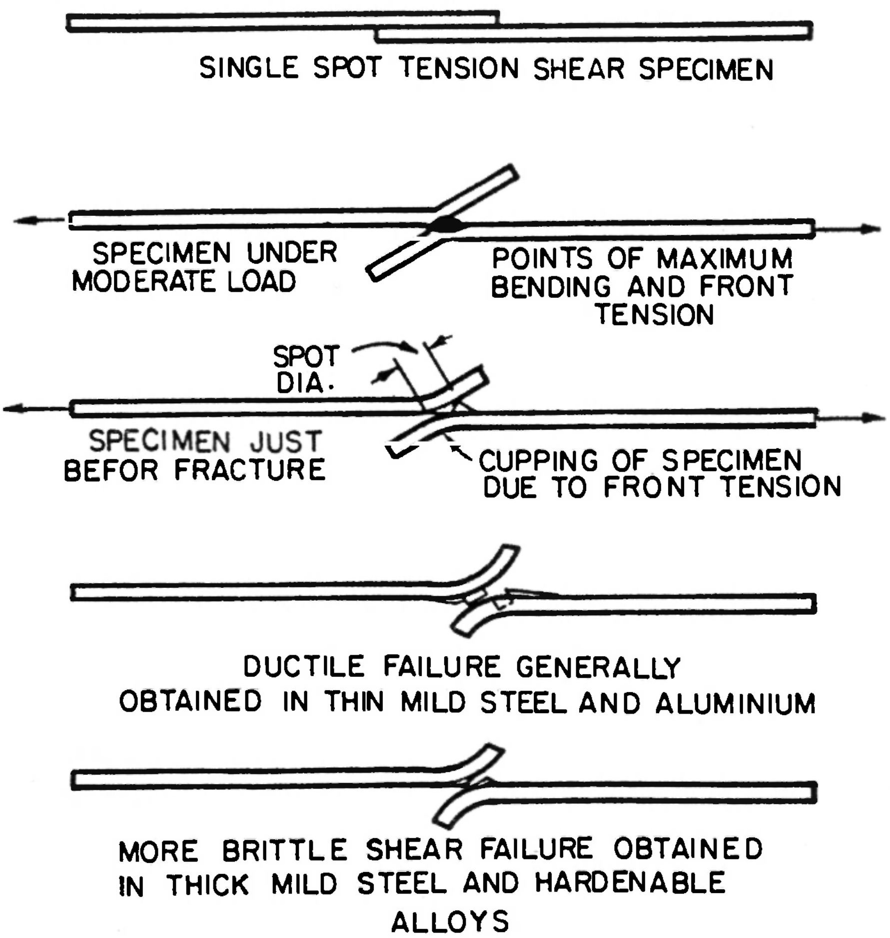

Figure 12 - Behaviour of a single spot tensile-shear specimen during testing (Ref. 5).

The first part was published in the January, 1985 issue of this journal.

this bending progressively increases with tensile load on the specimen and the plane of the weld becomes inclined at an increasing angle to the line of pull, introducing a tearing action concentrated on two points on the circumference at opposite diameters of the weld. Thus as the load increases, the character of the test changes from what originally started as a pure shear test to a complex system of shearing and tearing when failure occurs. [24]

Tylecote [25] studied the stress distribution around the edges of a model spot weld in xylonite by a photoelastic method and found the stress concentration factor as high as ×7.7 for shear stresses and ×4.6 for principal stresses before bending started. This means that a single-spot weld of high potential breaking strength is liable to premature failure by tearing, owing to the bending of the component plates. Assuming that a sound weld has been made, the maximum possible strength is given when the weld is sheared through the middle during tensile testing and without rotation of the components. Due to the bending of the specimen during testing and the stress concentration in the front of weld, the weld is thrown more and more into tension as the load increases and the nugget comes out from one plate, which is termed as a 'plug' failure. Any resistance to bending prevents this type of failure. Obviously for a given material and thickness, the wider the specimen is made, the higher becomes the resistance to bending and hence the specimen is more likely to fail by 'shear'.

Nikolaev[26] studied the dimensional effects of the spot-welded specimen on the tensile-shear strength of single-spot joints and found that a decrease in the width of plate from 5d to 3d (d being the diameter of the spot) did not affect the strength value to any appreciable extent ; however, a decrease of width to 2d had a pronounced effect and lowered the strength about 25%. Dearden and O'Neil [10] reported that the width of strip had an appreciable influence on the form of failure, particularly in thin sheets. Brown[27] also noted the influence of width and his results are shown in Figure 13. According to Dearden and O'Neil [10] the thickness of strip influences the strength of the spot weld in the same way as width, because the resistance to bending is proportional to the width and square of the thickness of the test specimen.

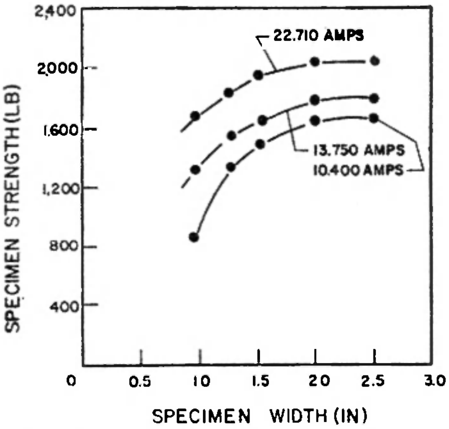

Fig. 13. Effect of the width of specimen on the strength of spot weld.

Chandel and Garber [58] studied the effect of prior-microstructure on the tensile-shear strength of spot welds made in ·06%C and ·38%Mn steel. Their results showed that the spot welds made in martensitic, bainitic, and cold worked sheets were stronger than those mode in subcritically annealed sheets. Microhardness surreys and metallographic examination showed that the difference was due to different conditions in the respective heat affected zones, where failure took place.

Static Tensile Tests of Spot Welds

The tensile-shear values obtained in the tension-shear test described in previous section, do not in themselves provide a good discrimination between a ductile weld and a brittle weld.

Although, the brittleness of a weld can be judged after an intelligent examination of a broken tension-shear specimen, the information is very qualitative. This indicates the desirability of having a more discriminating test to assess the spot weld quality.

A tension test of cross (+) or U-type is probably one of the more popular discriminatory tests used for this purpose. Its results are combined together with those of the tensile-shear tests to give a "ductility ratio=tensile strength/tensile-shear strength", which is supposed to reflect the quality of the weld or the spot weldability of a particular material.[5] Beever[28] suggests that the tension-shear test of a spot weld is less sensitive to brittleness than tension test because the stress concentration in this case is of shear type without triaxial tension with which the brittleness or the suppression of the plastic flow is usually associated. In contrast, the tension test introduces almost the worst combination of loads, giving triaxial tension at the notch roots, and brittle behaviour with low strengths is a frequent result.

In an attempt to assess the effect of post weld heat treatment of spot welds, Hipperson and Watson[5] found that the improvement in ductility affected by the heat treatment was clearly indicated by the results of the U-tensile test, which showed an improvement of almost 100% in one case, whereas the corresponding improvement in tensile-shear strength was only 10%. This behaviour was confirmed by Hess and Herrschaft[29], who found that spot welds made in SAE 1020 (C=0.21%, Mn=0.46%) steel gave a tensile-shear strength of 1500 lbs (0.04 in), and U-tensile strength of 350 lbs (ductility ratio=0.23). After heat treatment the U-tensile strength was raised to 1100 lbs while the tensile-shear strength was raised only to 1650 lbs (ductility ratio=0.6). Beevers and French [30] also report similar results ; the improvement in the ductility of the spot welds made in hardenable steels can be brought out clearly by this tension test.

Effect of the chemical composition of the sheet material on the ductility ratio has been studied by Bibber and Heusschkel. [31] It was shown that although the tensile-shear strength increased with the carbon content, there was a considerable decrease in tensile values (the ductility was lowered). Pollard [32] compared the spot weldability of VAN -80 steels (VAN -80 is a vanadium-nitrogen hot rolled steel with yield strength of 80.000 P.s.i) with that of SAE 1008 (C=0.078, Mn=.36%) steel and found that the ductility ratio of spot welds made in VAN-80 was 0.4 to 0.6 compared to values to 0.8 to 1.0 for SAE 1008 steel. French and Well [33] showed that within the welding range, the ductility ratio of spot welds made in three steels (0.04C, 0.09C, 0.2C) was not changed by varying the current.

The U-tensile strength of a given size of weld in a given material thickness is just as dependent upon specimen width and supported length as is the strength given by the tension-shear test i.e., the tensile strength increases with increasing width of the specimen. [5] Pollard [32] found that with increasing sheet thickness, the tensile strength and ductility are increased.

Chandel and Garber[59] showed that prior microstructure had considerable influence on the U-tensile strengths and ductility ratios of spot welds.

Impact properties of Spot Welds

Whereas the tensile-shear and U-tensile tests give a measure of the spot weld ductility at slow strain rates, it might be expected that an impact type test would more closely reflect the brittleness or toughness of spot weld under dynamic loading conditions. Impact strengths of spot welds can be measured on tensile-shear or tensile specimens, but the exact design of the specimen might have to differ from material to material depending upon the thickness of the sheet. [5]

Dearden and O'Neill [10] tested in impact the strength of spot welds made in ¼ in. thick mild steel (0.17C). The material was in the "as-received" metallurgical condition. The form of impact-shear test they used is shown in Figure 14. The bent plate component of the specimen was secured to the anvil of an Izod impact machine, to enable the upper horizontal plate of the specimen to be dynamically sheared by the impact of the striker. In some cases when a single blow was insufficient to fracture the weld, the energies of several blows were added together. The results show that a steady increase in impact values was observed upto a certain static tensile-shear strength, above which a very rapid increase occurred. It was pointed out that the increase in the impact values coincided with a rapid growth of the ingot portion of the weld, the size of which had a vital effect on the resistance to impact. It was concluded that the shock resistance of spot weld was almost entirely dependent upon the development of an "ingot" or fusion zone of adequate size within the weld. These results agree with those obtained by Unger et. al, [6] who made impact tests on single-spot weld specimen ¾ in. wide and 2 in. long. The plate was 0.05 in. thick low-carbon mild steel. The specimens were tested in shear and the results indicate that for a given diameter, welds made with the shortest time gave the greatest impact strength. Many of the specimens fractured in the plate.

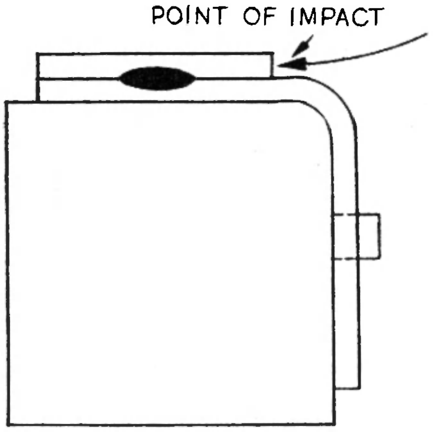

Fig. 14. Impact shear test specimen (Ref. 10)

Single and multiple-spot welds made in 0.31 and 0.39 in. thick mild steel (0.16C) by means of a pulsing technique were subjected to impact tests by Gelman.[34] Impact values ranging from 4.4 to 6.7 mkg/cm² were recorded for the single-spot welds and 2.8 to 17.3 mkg/cm² for multiple-spot welds were found sometimes as high as 18.1 mkg/cm². There was considerable scatter of the values but this was attributed to the defects purposely left in the welds in order to study their effects. An increase in the electrode pressure resulted in higher impact strengths.

Bibber and Heuschkel [31] obtained the impact data for single-spot welds in different grades of USS-Air Ten steel (0.12C max) specimens. The results show that the steel grade did not influence the impact values greatly. All welds failed by pulling out buttons from the sheet. Varying degree of tearing occurred in one or both sheets and it was concluded that the energy absorbed in foot-pounds was almost proportional to the amount of tearing that occurred; those specimens which tore considerably gave higher impact values than those with less tearing.

Recently Pollard[32] measured the impact strengths of spot welds made in VAN-80 and SAE 1008 steel sheets in different thicknesses. It was found that impact-shear strengths were similar for VAN-80 and SAE 1008 spot welds, when tested in the temperature range of+75 to-100°F.

With the exception of the welds made in 0.10 in. thick grade SAE 1008 steel, there was no abrupt decrease in impact strength within the above mentioned temperature range. All welds failed by buttons being pulled out from one sheet, except with those welds made in SAE 1008, 0.10 in. thick sheets when tested at −90°F. In this case the failure started in the heat-affected-zone and a brittle fracture propagated outwards through the base metal in a direction transverse to the impact direction.

Fatigue Testing of Spot Welds

Spot welding was first used on items which were subjected to very little static stresses, but as the confidence in the consistency of the spot welding process grew and the quality of the weld was improved, their use was diversified to joints subjected to repeated loading—such as automobile frames, railroad car sides and aircraft.

Test

Considerable work has been done on the fatigue testing of spot welds, and fatigue tests of tension-shear type specimens have been described.[35,36,37] It is the general conclusion of all the workers that the fatigue strength of spot welds is inherently low, 10-15% of the static tensile-shear strength. Johnson[38] attributed this to a result of mechanical phenomenon and not because of metallurgical changes due to welding heat.

The Welding Research Council[39] recommends the use of a shear/less shear stress cycle (pull-pull loading) for the fatigue testing of single-spot welded joints rather than a zero stress/shear stress test situation, probably this is because of the difficulty in precisely setting the zero stress and consequently if a compressive loading occurs, there is a danger of undesirable specimen buckling.

Mode of Failure

Hess, et. al, [40] examined the behaviour of the spot welds in aluminium alloy Alclad 243-T under repeated stresses and found that fatigue failure at higher ranges of stresses generally occurred by a shear fracture across the weld or by the tearing of the weld in the form of a button out of the sheet. At lower stresses (and long life) the failure occurred by propagation across the sheet specimen of a crack that originated in the heat affected zone of the weld. It was also found that any factor that affected the static strength of the spot weld considerably influenced its fatigue strength.

Unger, et. al,[41] studied the fatigue behaviour of spot welds in a low-alloy steel called Cor-Ten. It was suggested that the low fatigue strength obtained with this material was due to the presence of a notch at the junction of two sheets. Holt and Hortman [42] observed that the fatigue strength of lap joint with single spot weld was inferior to lap joint with a single rivet having the same static strength. Welter [43] used an artificial spot and testing under a repeated load, found that an artificial weld behaved in the same way as a real one. This led him to conclude that the heat affected zone around the spot was not the main cause of fracture by fissure of sheet. It was further concluded that the low fatigue resistance of spot welded joints was very likely due to combination of the tensile and bending stresses rising to fairly high level exactly in the zone adjacent to the spot and on itstension side, Figure 15.

Welter and Chaquet[44] applied hydrodynamically compressive stresses on the spot welds and tested them under fatigue stresses. The fatigue strengths were improved by 200 to 300% which thus appeared to demonstrate that the presence of residual stresses in the spot weld was a major cause for the normally low fatigue strengths of these welds.

Location of Fatigue Fracture

In further work by Welter, et. al.,[43] it was reported that in the fatigue tests of spot welds in mild steel, the fracture occurred on the tension side and in the immediate neighbourhood of the spot. These cracks were more or less in the form of sinusoidal curve surrounding the spot in its upper part and could be seen with the naked eye. Unger, et. al., [22] investigated the location of the fatigue fracture in a spot weld and reported that the fracture initiated in the vicinity of the spot. This is explained on the basis that the maximum stress in the spot weld is at the notch, but the strength of material is higher at that location, therefore, the fracture takes place at the point where the fatigue strength of material is exceeded at the end of the heat affected zone. A further reason the crack does not begin at the junction point is the increased thickness of the material at this location due to the welding.

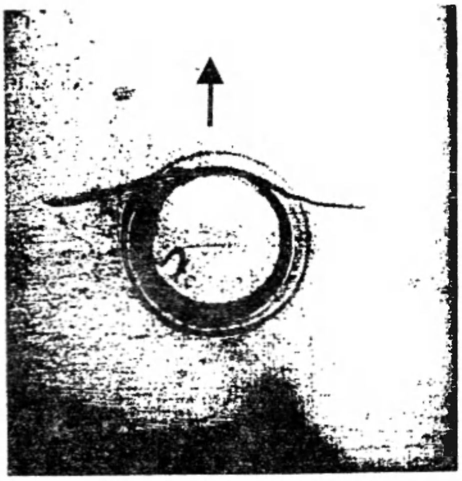

Fig. 15. Appearence of the fatigue crack in the plane of the sheet. Arrow shows the direction of tensile loading (Ref. 58)

Effect of Residual Stresses upon the Fatigue properties of Welds

Residual stresses may play an important role in fatigue failures by radically changing the mean stress.[45] Thus, if residual stresses are compressive, they will improve the fatigue life by lowering the mean stress towards compressive side and vice versa.

There is considerable experimental evidence both for and against the importance of residual stresses as contributing factor to the fatigue behaviour of materials. It is known that the process of welding introduces high residual tensile stresses into the structures.[46] Therefore, it would be reasonable to repeat that any adverse influence which residual tensile stresses might have on fatigue are most likely to appear in weldments. [47] In variance with the expectation, tests conducted with specimens in both the 'as-welded' and 'stress relieved' conditions by Wilson[48] did not show any significant difference in the results. Thum and Erker,[49] Norton and Rosenthal[50] and Maloof[51] reached similar conclusions from a limited number of tests performed on mild steel flat specimens both with and without notches.

In contrast to the above Buhler and Buchholtz [52] found that by relieving residual stresses the fatigue strength of a weld made in steel plate was raised by 22%. Test results of Schmidt [53] showed an improvement of 30% in the endurance limit of fillet welds due to stress relieving. Welter, et. al.[57,56,55,54] in work on the improvement of the fatigue strengths of spot welds concluded that by suitably adjusting the residual stresses, the endurance limits of spot welds could be elevated considerably.

Chandel and Garber [59] reported that stress relief of spot welds by plastic compression significantly increased their fatigue strengths and endurance limits in martensitic, bainitic, cold rolled and subcritically annealed materials, and the greatest improvement in the fatigue properties of welds was in the martensitic sheets.

References

1. Milner, D. R., and Apps, R. L., Introduction to Welding and Brazing, Pergamon Press, 1968.
2. Beevers, A., M.Sc. Thesis, University of Newcastle Upon Tyne, 1968.
3. Stanley, W. A., Resistance Welding : Designing, Tooling and Applications, McGraw Hill, 1950.
4. Chandel, R. S., Ph.D. Thesis, University of Birmingham,1975.
5. Hipperson, A. J. and Watson, T., Resistance Welding in Mass Production, Iliffe & Sons Ltd., 1950.
6. Unger, A. M., The Welding Journal, 19(10), 687, 1940.
7. Welding Handbook, American Welding Society, Sixth Edition, Section Two.
8. Wulf, J., Uddin, H. and Funk, E. R., Welding for Engineers, John Wyle & Sons. Inc. 1954.
9. Nolen, R. K. et. al., The Welding Journal, Research Supplement, 33(4), 129-s, 1954.
10. Dearden, J. and O'Neill, H., Transaction of Institute of Welding, 6(1), 8, 1943.
11. Hess, F. W. and Wyant, R. A., The Welding Journal, Research Supplement, 18(10), 329-s, 1939.
12. Tylecote, R. F., Transaction of Institute of Welding, 4(3), 154, 1941,
13. Jeff, H.S., Sheet Metal Industry, 231, April 1935.
14. Neuman, J. A. and McCreery, R. D., Welding Engineers, 25 (12), 20, 1935.
15. Albutt, K. J., Ph.D. Thesis, University of Birmingham, 1967.
16. Albutt, K. J. and Garber, S., J.I.S.I., 205, 738, 1967.
17. Wulf, J. et. al., The Welding Journal, Research Supplement, 35(1), 18-s, 1956.
18. Heuschkel, H. J., ibid, 26(10) 560-s, 1947.
19. "Spot Welding of Low-carbon Mild Steel", British Welding Research Association, Publication No. T21A.
20. Hagler, R. J., Master's Thesis, Rensselaer Polytechnic Institute, Troy, N. Y., 1963.
21. Bellamy, G., Ph.D. Thesis, University of Birmingham, 1970.
22. Unger, A. M., et. al., Welding Journal, Research Supplement, 22(3), 135-s, 1943.
23. Hess, F. W. and Ringer, R. L., ibid, 17(10), 39-s, 1938.
24. Spraragan, W. and Giordori, M.A., ibid, 23(7), 305-s, 1944.
25. Tylecote, R. F., ibid, 20(8), 359-s, 1941.
26. Nikolaev, G. A. and Nikolaev, B.P., Autog, Delo,10(5), 3, 1933.
27. Brown, H. W., The Welding Journal, Research Supplement, 23(8), 458-s, 1944.

28. Beevers, A., "Post Weld Heat Treatment of Spot Welds in Low Alloy Hardenable Steel", BWRA Report A3/12/61.
29. Hess, W. F. and Herrschaff, D.C., The Welding Journal, Research Supplement, 22(10), 451-s, 1943.
30. Beevers, A. and French, E. J., British Welding Journal, 9, 543, 1962.
31. Bibber, L. C. and Heurchkel, J., The Welding Journal, Research Supplement, 22 (12), 616-s, 1943.
32. Pollard, B., ibid, 53(8), 343-s, 1974.
33. French, E. J. and Wells, A. A., British Welding Journal, 4, 514. 1957.
34. Gelman, A. S., Autog. Delo, 12(4), 1, 1941.
35. Marshal, H. and Hartman, E. C., The Welding Journal, Research Supplement, 26(4), 233-s, 1947.
36. Welter,G.,ibid,28(9),413-s,1949.
37. Welter, G., ibid., 27(6), 285-s, 1948.
38. Johnson, I. W., ibid, 39 (3), 89-s, 1960.
39. Welding Research Council, ibid, 19(9), 334-s, 1940.
40. Hess, W. F. et. al. ibid, 25(6), 326-s, 1946.
41. Unger, A. M., et al., ibid, 22(3), 135-s, 1943.
42. Marshal, H. and Hartman, E. C., ibid, 31(4), 183-s, 1952.
43. Welter, G., ibid, 29(11), 565-s, 1950.
44. Welter, G. and Choquet, A., ibid, 38(4), 145-s, 1959.
45. Benson, L. E., "Residual Stresses in Metals and Metal Construction", Reinhold Publishing Corporation, p. 75, 1954.
46. Weck, R., "Symposium on Internal Stresses in Metals and Alloys", The Institute of Metals, p. 119, 1948.
47. Gurney, T. R., "Fatigue of Welded Structures", Cambridge Press, p. 143, 1968.
48. Wilson, W. M., Flexural Fatigue Strength of Steel Beams, University of Illinois, ESS Bull. No. 377, 1948.
49. Thum, A. and Erker, A., "Handbook of Experimental Stress Analysis", John Wyle & Sons, Inc. New York, 1938.
50. Norton, J. T. and Rosenthal, D., The Welding Journal, Research Supplement, 22(1), 63-s, 1943.
51. Norton, J. T. et. al., ibid, 25(5), 729, 1946.
52. Buhler, H. and Buchholtz, H., "Handbook of Experimental Stress Analysis", John Wyle & Sons Inc., New York 1950.
53. Schmidt, R. ibid.
54. Welter, G. and Choquet, A., The Welding Journal, Research Supplement, 33(2), 91-s, 1954.
55. Welter, G. and Choquet, A., ibid, 33(3), 134-s, 1954.
56. Welter, G., et. al., ibid, 33(3), 509-s, 1954.
57. Welter, G. ibid., 34(3), 1955.
58. Chandel, R. S. and Garber, S., Metals Technology, 1(9), 418, 1974.
59. Chandel, R. S. and Garber, S., ibid, 4(1), 37, 1977.
60. Houldcraft, P. T., Welding Process Technology, Cambridge University Press, 1977.
61. Chandel, R. S., Ph.D. Thesis, Department of Industrial Metallurgy, University of Birmingham, U.K., 1975.

The Registration of Newspapers (Central Rules) 1956.
Statement about ownership and other particulars about newspaper :
Indian Welding Journal (English).
FORM IV

1. Place of publication	3A, Loudon St, Flat 4B/N, 4th Floor Cal-700017.
2. Periodicity of its Publication	Quarterly.
3. Printer's Name	A. C. Lahiri
Nationality	Indian
Address	3A, Loudon St, Flat 4B/N, 4th Floor Cal-700017.
4. Publisher's Name	A. C. Lahiri
Nationality	Indian
Address	3A, Loudon St, Flat 4B/N, 4th Floor Cal-700017.
5. Editor's Name	A. C. Lahiri
Nationality	Indian
Address	3A, Loudon St, Flat 4B/N, 4th Floor Cal-700017.
6. Name and address of individual who owns the newspaper and partners, shareholders holding more than one per cent of the capital.	The Indian Institute of welding, 3A, Loudon St, Flat 4B/N, 4th Floor, Cal-700017.

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