PROCEEDINGS : COFA–1997
©NML JAMSHEDPUR; pp.212-220

Failures of welded joints

D. K. BHATTACHARYA
National Metallurgical Laboratory, Jamshedpur - 831 007.

ABSTRACT

For a failure at a welded joint, the important factors are : (a) presence of defects in the form of physical discontinuities, (b) a bad microstructure, and (c) residual stresses. A few important examples of bad microstructures leading to failures in stainless steel and alloy steels are presented in the paper. Apart from the references cited in the text, a list of general references are included to help the reader to get a better perspective on the conditions under which the failure of a weld joint takes place.

INTRODUCTION

The type of welded joints to be considered in this paper would be fusion weld joints in which metal is molten by creating an arc between an electrode (made of similar alloy as the parent metals or an "inert" metal like tungsten) and the parent metals. This the type of welding process is more common. Fig. 1 shows the different welding processes.

Failure of a welded joint can be of two types : (a) those "failed' during inspection after fabrication, or (b) those failed during service. The defects which may fail a weld joint during service if left in a component undetected are the following: creaks, lack of penetration, lack of fusion, porosity etc. Among these defects, the linear ones such as the lack of penetration, lack of side wall fusions etc. and particularly the cracks are more harmful. Linear defects on the surface or in the subsurface region are again more important because the two modes of failures e.g., fatigue and stress corrosion cracking which are the most prevalent mechanisms of failures in industrial components [1,2] originate from the surface or subsurface regionss.

RESIDUAL STRESS AND MICROSTRUCTURE IN A WELD JOINT

The defects in weld joints are essentially, the physical discontinuities such as cracks which 'offer' their harmfulness by way of creating stress concentrations and degrading the fracture toughness [3]. For a welded joint, there are two other important parameters which degrade the fracture toughness behaviour e.g., (a) residual stress [4,5] and (b) alteration and variation of microstructure across a welded join. Fig. 2

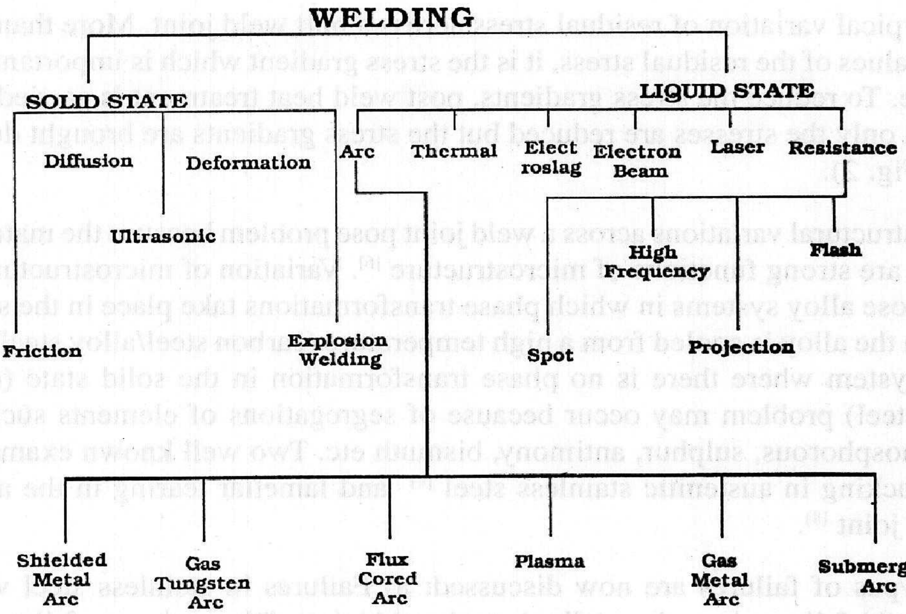

Fig. 1 : Classification of welding processes

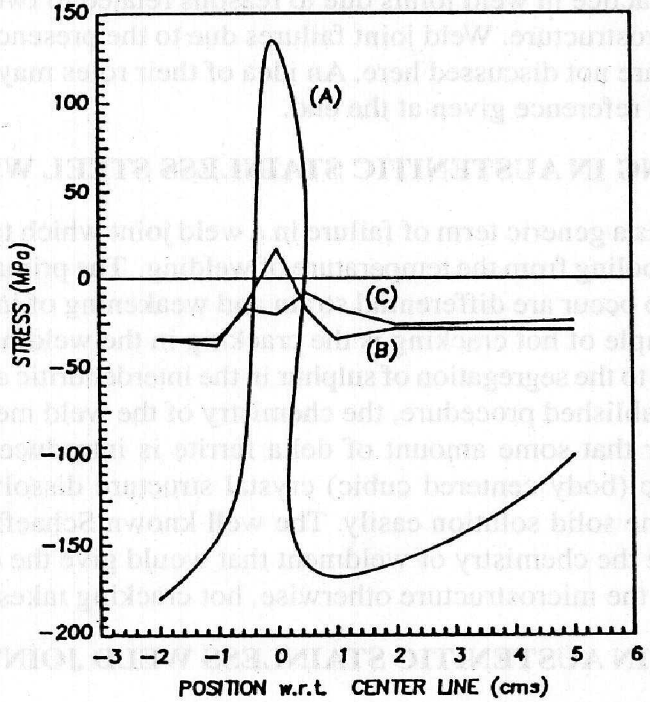

Fig. 2 : Variation of residual stress across the butt weld tube to tube joint of 2.25Cr-1Mo steel. Line (A) is the stress distribution before post weld heat treatment and line (B) and (C) the stress distribution after post weld heat treatment

shows a typical variation of residual stress across a butt weld joint. More than the absolute values of the residual stress, it is the stress gradient which is important for any failure. To reduce the stress gradients, post weld heat treatment is carried out so that not only the stresses are reduced but the stress gradients are brought down as well (Fig. 2).

Microstructural variations across a weld joint pose problem because the material properties are strong functions of microstructure [6]. Variation of microstructure is more in those alloy systems in which phase transformations take place in the solid state when the alloy is cooled from a high temperature (carbon steel/alloy steel). In an alloy system where there is no phase transformation in the solid state (e.g., stainless steel) problem may occur because of segregations of elements such as carbon, phosphorous, sulphur, antimony, bismuth etc. Two well known examples are hot cracking in austenitic stainless steel [7] and lamellar tearing in the alloy steel weld joint [8].

Two types of failures are now discussed: a) Failures in stainless steel weld joints, and (b) failures in carbon (alloy) steel weld joints. Discussion on failures in these two types of alloys would give a general idea on the types of failures that are encountered in practice in weld joints due to reasons related to two typical feature of weld joint microstructure. Weld joint failures due to the presence of defects and residual stresses are not discussed here. An idea of their roles may be found in the list of the general reference given at the end.

HOT CRACKING IN AUSTENITIC STAINLESS STEEL WELD JOINTS

Hot cracking is a generic term of failure in a weld joint which takes place when the weld joint is cooling from the temperature of welding. The primary requirements for such a thing to occur are differential strain and weakening of interfaces. A very well known example of hot cracking is the cracking in the weldment of austenitic stainless steel due to the segregation of sulphur in the interdendritic and intergranular regions. In an established procedure, the chemistry of the weld metal is controlled in such a manner that some amount of delta ferrite is introduced because delta ferrite having bcc (body centered cubic) crystal structure dissolves sulphur and phosphorous in the solid solution easily. The well known Schaeffler's diagram is used to determine the chemistry of weldment that would give the desired quantity of delta ferrite in the microstructure otherwise, hot cracking takes place (Fig. 3).

WELD DECAY IN AUSTENITIC STAINLESS WELD JOINTS

While the segregation of sulphur, phosphorous, antimony etc., in the liquid weld metal in austenitic stainless steel weld causes hot cracking under restraint in austenitic stainless steel weldment, the segregation of carbon at the grain boundaries in the HAZ of a stainless steel weld joint creates a sensitized microstructure (Fig. 4) and leads to weakened grain boundaries against corrosion and stress corrosion cracking. The reason is the reduction of chromium at the grain boundaries since the segregated carbon takes up the carbon forming chromium carbides. Sensitization is a phenomenon that has its highest tendency in a temperature range of 550–750°C. Therefore, if one considers the cooling pattern in the HAZ region, sensitization should take place in a narrow region (Figs. 5 and 6). The presence or absence of sensitization is often verified by a standard procedure (ASTM Standard A262–70 Practice E). The test consists of exposing a rectangular strip in boiling and acidified (by adding sulphuric acid) copper sulphate solution mixed with copper turnings for 24 hours. After the exposure, the strips are bent into 'U' shape. The nature and extent of cracks if developed reflect the tendency for IGSCC. In Fig. 7, the orange peel structure in a narrow band signifies sensitization in a narrow band away from the weld/parent metal interface similar to what are indicated in Figs. 5 and 6. Fig. 8 shows a stress corrosion crack formed along sensitized grain boundness of the HAZ of a 316 type stainless steel.

LAMELLAR TEARING IN STEELS

'Lamellar tearing' is another example in which the strains generated during welding process creates strain concentration at regions of weakness. In this case, the regions of weakness are the elongated sulphide inclusions. The situation is worse if there are weld defects from where the crack fronts can be initiated. The inter-inclusion regions are fractured because they are not able to withstand the load concentration. Fig. 9 shows an example of lamellar tearing [10].

STRESS RELIEF CRACKING

In Fig. 2 the efficacy of stress relief annealing was demonstrated for a ferritic steel. For an austenitic stainless steel, a stress relief annealing may lead to cracking because, by their lower thermal conductivity and higher coefficient of thermal expansiion much higher levels of residual stresses are generated in the austenitic stainless steel weld joints. Due to the same two reasons, annealing intended for relieving of the residual stresses may in fact, induce new residual stress. If in addition, the microstructure is not conducive to relieve the newly introduced residual stress, cracks may appear at the weld/HAZ interface or in the HAZ.

DELAYED CRACKING BY HYDROGEN

Often cracks are initiated at the weld/HAZ interface or in the HAZ after the welding operation has been finished and the weld joint has cooled down to room temperature. These incidences of cracking due to the influence of hydrogen taken up in the weld pool and diffusing to the HAZ under a temperature and strain gradient,

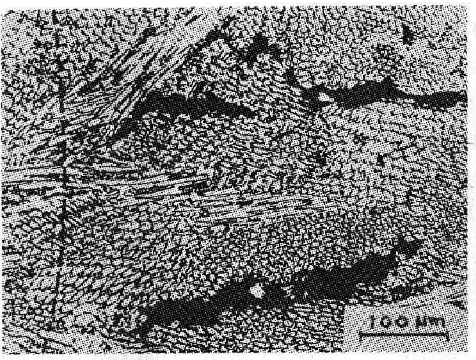

Fig. 3 : Typical appearance of hot cracks in stainless steel weld metal.

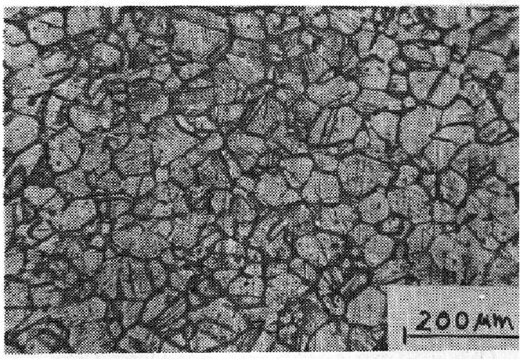

Fig. 4 : A fully sensitised micrsotructure in a AISI 304 stainless steel specimen. the balckened grain boundaries are the areas where carbon segrigated and formed chromium carbides

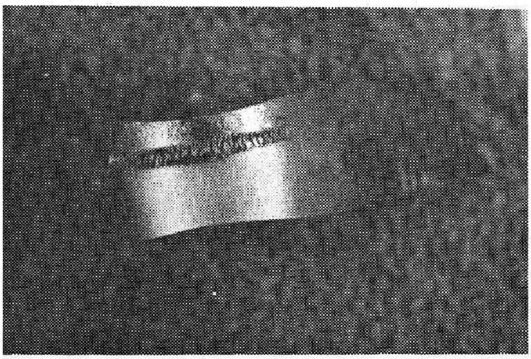

Fig. 5 : Time temperature relationship during cooling after a weld pass in a butt weld joint in AISI 304 stainles steel

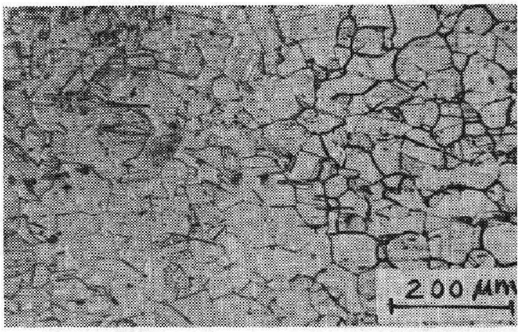

Fig. 6 : Microstructure at the HAZ of a weld joint of AISI 304 stainless steel. Left side of the mcirograph near to the weld parent metal interface is not sensitised but on the right hand side sensitisation is clearly seen.

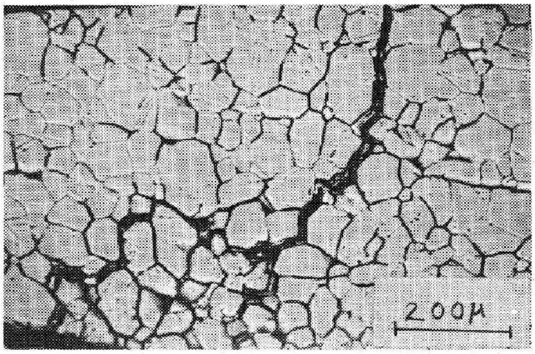

Fig. 7 : Orange peel structure in a narrow band in which cracks were generated in a 'U' bent strip subjected to ASTM test A 262-70 (Practice E) for sensitisation

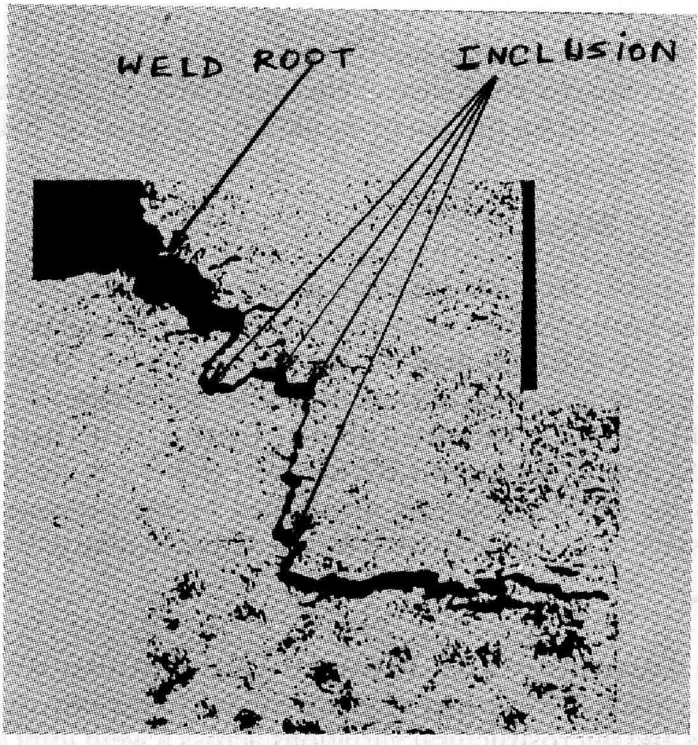

Fig. 8 : A stress corrosion crack along the sensitised grain boundaries of a 316 stainless steel.

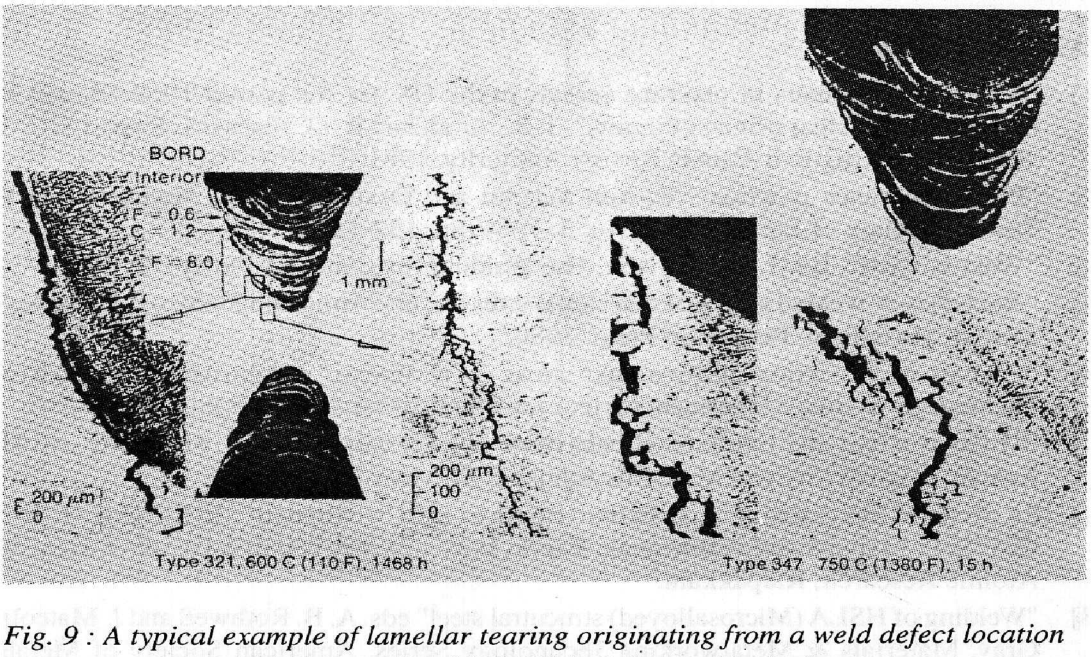

Fig. 9 : A typical example of lamellar tearing originating from a weld defect location and propagating with the aid of elonated inclusions

take place after varying incubation time periods. Fracture toughness of the HAZ is very important to achieve a resistance againest this kind of cracking. This topic is not further discussed since a full paper would be presented on hydrogen assisted cracking in this workshop.

LOCAL BRITTLE ZONE

Local brittle zone (LBZ) in the HAZ of a carbon steel or alloy steel is that zone which can initiate brittle fracture at low stress levels. It should be appreciated that not all regions in the HAZ are bad for the performance of a weld joint against mechanical loading or corrosion degradation. It is only a narrow zone (in most of the cases) in a HAZ which is harmful. Different types of steels have different types of LBZ. For AISI 304 SS a type of LBZ has already been discussed (weld dcay). For alloy steels the problems can be manifested by the presence of deleterious microstructure such as coarse grain martensite, upper bainite etc. [3].

CONCLUSION

Through the discussion of a few important types of failures in welded joints an attempt has been made in this paper to given an idea of the important factors such as residual stress and microstructural variations across a weld joint and segregation of elements at weak regions such as grain boundaries, dendritic arms etc. For any type of weld failures there has to be a bad microstructure. This can be present in a narrow zone in the HAZ from where cracks may start.

REFERENCES

[1] "A survey of defects in pressure vessels in the UK for the period 1962-78, and its relevance to nuclear primary circuits", T. A. Smith and R. G. Warwick, Report SRD R 203, United Kingdom Atomic Energy Authority, 1981.

[2] "Plant maintance practice", Yoshito Sakami and Osamu Nishida, Non-Destructive Testing Society of Japan, Vol. 2, No. 3. 1984, pp. 152-157.

[3] "Weld failures", Ed. J. D. Harrison, The Welding Insititute, Londong UK, 1989.

[4] "Analsysis of welded structures Residual stresses, distortion and their consequences", Koichi, Masubichi, Pergamon Press. 1980.

[5] "Control of distortion and residual stress in wldments", Materials metalworking Technology Series, Amnerican Society for Metals, Metals Park, Ohio, 1977.

[6] "Microstructure and mechanical behaviour of materials", Ed. Gn. Haicheng and He Jiawen, Engineering and Materials Advisory Services Ltd., 1986.

[7] "A reviw of hot cracking in austenitic stainless steel weldments", V. Shankar, T. P. S. Gill, S. L. Mannan and P. Roriguez, Report IGC-119, 1991, Indira Gandhi Centre for Atomic Research, Kalpakkam.

[8] "Welding of HSLA (Microsalloyed) strucutral steel" eds. A. B. Rothwell and J. Matcolm Gray, Materials & Metalworking Technology Series, American Society of Metals,

Metals Park, Ohio, USA, 1984.

[9] "Corrosion engineering (Book)", M. G. fontana and N. D. Greene, McGraw Hill International Book Co., 1982, pp. 48-64.

[10] Metals Handbook, 9th ed. Vol. 11 'Failure analysis and prevention", American Society for Metals, Metals Park, Ohio, 1986, pp. 665.

[11] "Alloys for the eighties", H. N. Landers Climax Molybdenum Company, pp. 100, 1981.

[12] Defective Weld Caused Tragic Death. MET. CONSTR. 16(2), 85 Feb. 1984.

[13] Application of Life Prediction Methods to As-Welded Steel Structures, Leever, RC, Conference : Advances in Life Prediction Methods, Albany, N. Y., U.S.A., 18-20 Apr. 1983. Publ : American Society of Mechanical Engineers, USA 1983.

[14] Life Prediction of Dissimilar Weld Joints for boiler Tubing. Setoguchi, K; Daikoku, T; Masuyama, F; Haneda; H; Muraishi, K; Conference : Advances in Life Prediction Methods, Albany, N.Y., USA, 18-20 Apr. 1983, Publ : American Society of Mechanical Engineers, USA 1983.

[15] Stress Relief Cracking in Cr-Mo-V Steels. Edwards, R.H.; Barbaro, F.J.; Gunn, K.W.; MET. FORUM 5(2), 119-129 Autumn 1982.

[16] Metallurgical Failures in Fossil Fired Boilers, (Book). French, D. N. Publ : John Wiley & Sons, Inc. 1983.

[17] Fatigue Weld Failure Causes Explosion of Air Receiver. Sissom, I.E; Scardina, J.T., ENG. FRACT. MECH. 17(5), 405-414 1983.

[18] Metallographic Investigation of Defects on Welded Vessels in High-Strength Fine-Grain Structural Steel. Dieser, K, Prakt. Metallogr. 19, (11) 623-638 Nov. 1982.

[19] Environment-Sensitive Fracture : Material and Welding Considerations. Gooch, T. G., Met. Technol. 9,(6), 210-215, June 1982.

[20] Foresnsic Metallurgy – Some aspects of failure analysis, Whalley, B. G., Metall. Mater. Technolo, 14 (10), Oct, 1982, pp. 480-82.

[21] Microstructure — Toughness Relationship in a C-Mn Weld Metal. Tweed, J.H.; Knott, J.F., Conference : Fracture and the Role of Microstructure, Vol. 1. Fracture and Fracture Toughness, Leoben, Austria, 22-24 Sept. 1982, Publ. : Engineering Materials Advisory Services Ltd., UK.

[22] Is It Good Enough? Tolerances for Welded Ship Structures. Johansson, B. G.; Kjellander, S. L.; Leide, N. G.; MET. CONSTR. 14, (3), 122-126 Mar. 1982.

[23] Weld Failures : They could be the result of violating simple design principles - II. Blodgett, OW, WELD. J. 61, (4), 25-31. Apr. 1982.

[24] Some defects – Do – some defects don't, Burclekin, F. M. Met. Constr, 14(2), Feb, 1982, pp. 91-94.

[25] Influence of Welding Procedure on Stress-Relief Cracking. II-Repair Evaluation in Cr-Mo-V Steels. Myers, J.; Clark, J. N.; MET. TECHNOL. 8(10), Oct. 1981, pp. 389-394.

[26] A study of the Significance of Weld Discontinuities in Shipbuilding. Sandor, I.W., MATER. EVAL. 39(6), May 1981, pp. 533-536,.

[27] Weldments : Physical Metallurgy and Failure Phenomena. Christoffel, R. J., Nippes, E. F.; Solomon, H. D., Author Affiliation : American Society for Metals, TMS/AIME, American Welding Society. Bolton Landing, Lake George, N.Y., 27-30 Aug. 1978, Publ

: General Electric Co., 1979.

[27] Can Industry Afford the High Cost of Weld Repair ? Trving, R. R., TRON AGE 223, (13), 49-55 7 Apr. 1980.

[28] A Study on Microstructure and precipitate in HAZ and Reheated Zone of Weld Metal of Structural Steel. Kikuta, Y; Araki, T; Ohkubo, A; Yoneda, M; Suga, T., Conference : Criteria for Preventing Service Failure in Welded Structures, Tokyo, Japan, 26-28 Sept. 1978. Publ : The Japan Welding Society, 1978.

[29] Fatigue Life Estimation of Structural Members Containing an Internal Flaw. Kawahara, M; Kurihara, M; Arakida, F., Conference : Criteria for Preventing Service Failure in Welded Structures, Tokyo, Japan, 26-28 Sept. 1978, Publ : The Japan Welding Society, 1, 1973.

[30] Avoid Martensite When Welding Rebar. Firth, M; Williams, W. M., MET. PROG., 115(4), April 1979, pp. 38-40

[31] Stress Corrosion Cracking in Duplex Stainless Steel Weldments. Baeslack, WA; TTT; Duquette, D. J., Savage, W. F., Weld. J., 57(6), June 1978, pp.175s-177s

[32] Failure Examination - Faulty Design, Weld Defect-Fracture of a Cross on a Church Steeple. Naumann, Friedrich K; Spies, Ferdinand, PRAKT METALLOGR.,12(5), May 1975, pp. 268-271.

[33] Failure examination defect, Faulty heat treating investigation of worn chain links, Naumann, Friedrich K., Spries, Ferdinand, Prakt Metallogr, 12(8), August 1975, pp. 443-445.

[34] Failure Examination - Welding Defect, Unsuitable Material - Pipe Fracture During Welding. Naumann, Friedrich K; Spies, Ferdinand, PRAKT METALLOGR., 12(6), June 1975, pp. 329-332.

[35] The Significance of Flaws. Garwood, S. J.; Mudge, P. J., Author Affiliation : The Welding Institute, Conference : Non-Destructive Testing, London, UK, 7 June 1989, Publ : The Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB, UK, 1989.