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Influence of Manufacturing Conditions on Fatigue Life of Welded Joints

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Abstract

This paper presents a study on the influence of manufacturing conditions on the fatigue life of welded joints of high strength steels P355NL-1 and P355NL-2. Welding conditions were varied by adjusting the welding parameters and component-welding positions for a range of railway bogie welded joints. Prepared joints were then assessed for cracks and porosity defects. It was observed that an increase in welding speed resulted in an increase in crack and pore sizes. The same applied to increase in welding angle. Identified crack sizes ranged from 0.2 to 2.6 mm. Impact of such defects on fatigue life was assessed by evaluating the residual fatigue life of the component using the Paris law for stress amplitude of 150 MPa. The fatigue life of the bogie was estimated to be 6.23×10^5 instead of the required 1×10^6 cycles. It was concluded that manufacturing conditions have a significant effect on fatigue life of high strength steel welded joints. Travel speed and welding angle are critical.

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Keywords: Welded joints; Fatigue life; Critical stress

1. Introduction

The production of most railway components is achieved through welding. Because these critical parts are subjected to dynamic loading, it is very important to establish ways of evaluating the integrity of welded joints. The lack of crack growth monitoring within welded joints has raised concerns over manufacturer's ability to produce safe and durable components. Literature has shown that the quality of welded joints depends on welding parameters such as material properties, heat input, travelling speed, torch angle and cooling rate [1-6]. Pang et al [1] and

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Pramesh et al [2] showed that mechanical behaviour of high strength steels is affected by the change in welding parameters. Pang et al [1] also demonstrated that the hardness in the heat affected zone of a welded joint is inversely proportional to the amount of heat applied. This was deduced from hardness tests of welded joints. Additionally, optical microscopy on the HAZ revealed that an increase in heat input corresponds to an increase in weld bead geometry [1]. Similarly, Yanjiang et al [3] analysed the effect of heat input on fracture toughness of HAZ after welding. This work revealed that increasing the heat input results in a significant decrease of fracture toughness due to the presence of carbide inclusions in weldments. Bamakar and Sawant [4] suggested that optimizing shielding gas composition and welding speed would limit the formation of inclusions regardless of the heat input. Furthermore, Pramesh et al [2] showed that varying the welding speed affects the mechanical properties of the weld. Increasing the welding speed leads to a decrease in tensile strength and subsequently, to an increase in welding defects. Moreover, Pawaria et al [5] also showed the same results, not only due to welding speed, but also to welding current and voltage. The indicated effects of welding parameters on mechanical properties of welded material invariably affects the fatigue performance of the welded joints. Research has provided novel techniques for predicting fatigue life of welded joints. Thermographic methods used by Crupi et al [6] and La Rosa and Risitano [7] while analysing butt welded joints proved to be satisfactory for approximation purposes. The results were accurate to within a standard deviation of 25%. The benefit of using this method is the short time required to approximate fatigue life [6]. In addition to thermographic methods, numerical solutions such as the boundary element method, Kohonen self-organizing map (SOM) and traditional techniques (S-N curves combined with cumulative damage), can be used. One major limitation with these methods is that BEM uses probabilistic fracture mechanics to predict life, S-N curves require the level of stress within the structure to be known, Kohonen's SOM requires acoustic sensors capable of eliminating noise from raw data in order to be more accurate [8], [9]. In this work, fatigue life is predicted using the linear relationship between crack growth rate and stress intensity factor on Paris' crack propagation curve.

2. Experimental programme

2.1. Aim of the experiment

The main aim of the experimental work was to determine the nature and sizes of welding defects produced by welding using different welding parameters and conditions.

2.2. Material

The materials used for this investigation were high strength steels P355NL-1 and P355NL-2. These materials were supplied as rolled plates with chemical compositions shown in Table 1. The filler material used was 1.2 mm ER 70S-6-tungsten electrode wire. The chemical composition of the filler material is summarised in Table 2.

Table 1. Base material chemical composition according to manufacturer certificate

Steel grade	C	Si	Mn	Ni	S	V
P355 NL1	0.18	0.50	1.40	0.50	0.008	0.10
P355 NL2	0.18	0.50	1.40	0.50	0.005	0.10

Table 2. Filler material chemical composition according to manufacturer certificate

Material	C	Si	Mn	P	S
ER 70S-6	0.08	0.58	1.15	0.014	0.1

2.3. Equipment

The plates were cut using Amada FOLB015AJ laser cutting machine with a maximum power of 4 kW and a laser beam length of 1.08 µm. The plates were bevelled using a vertical turet 61V Maximart milling machine 4 kW power rating. Welding was performed on a semi-automatic Lincoln Electric Power MIG 350 MP with a power rating of 60 kW (76 A). Microscopic samples were polished using Ecomet 250 grinder-polisher with a maximum rotational speed of 120 rpm at 15 kW. The microstructures of the welded samples were analysed on an Olympus AX70 microscope equipped with a PLFX 0.5 times macro-objective, an AX-CD Macro (0.5 - 100 times) condenser as well as 2 eyepieces (SWH 10 x - H and 35SWH 10 - H).

2.4. Procedure

In the work, fracture mechanics principles were applied to determine the influence of welding parameters on fatigue life. Literature about manufacturing and design of locomotive bogies showed that critical points in the structure are located on welded joints [10]. Joints were prepared by welding rectangular plates using predefined welding procedure specifications under normal workshop conditions. In order to reduce the effects of weld contamination; the joints were cleaned by sand blasting. Joint analysis samples were then prepared according to EN 15085-3 for visual examination [11]. Welding defects were identified and classified in accordance to ISO 5817-1:2007 [12]. Metallographic samples were prepared using standard procedures i.e. grinding, polishing and etching according to ISO 17639:2003 [13]. For fracture mechanics based life estimation, initial crack sizes must be known. Identified defects were therefore measured using an optical microscope. This allowed the application of the Paris' equation to estimate the remaining service life. The critical crack size was determined from the recommended design stress of the structure. This computation was applied on the basis of linear crack propagation rate in the crack propagation curve shown in Fig. 1.

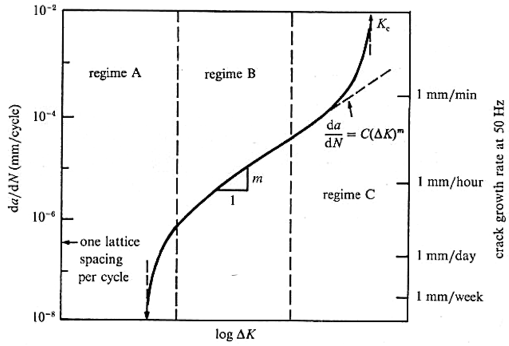


Fig. 1. Crack propagation curve [14]

3. Results

3.1. Joint and defect classification

Fig. 2 (a) shows the summary of joint welding defect distributions within a locomotive bogie. The joints summarised were analysed for defects and these are summarised in Fig. 2(b). Table 3 and 4 show typical sizes for welding defects including their estimated fatigue lives. The average size of each welding defect per class is presented in Fig. 3.

3.2. Microstructure characterisation

Microstructural analysis of the material by optical microscopy can be seen in Fig. 4. The morphology of the structure in Fig. 5 shows that the weld consists of three different zones (base metal, fusion and weld metal zone). The base metal zone is characterised by special orientation of grain boundaries and the weld metal zone by a random orientation of grain boundaries. This special orientation of grain boundaries in the parent material favoured the formation of acicular ferrite due to the non-distortion of grain boundaries during welding. The weld metal, on the other hand, is characterised by the promotion of martensitic structure that results from rapid cooling of the weld and fusion zone. Due to this rapid cooling in these zones, manufacturing defects were observed and most of them were characterised as incomplete fusion, localised porosity and inclusions (see Fig. 6). Compared to the parent material, both the fusion and weld metal zones were subjected to heat and this motivated secondary beta nucleation as well as promotion of Widmanstatten ferrite (lamellae orientation) in their microstructures.

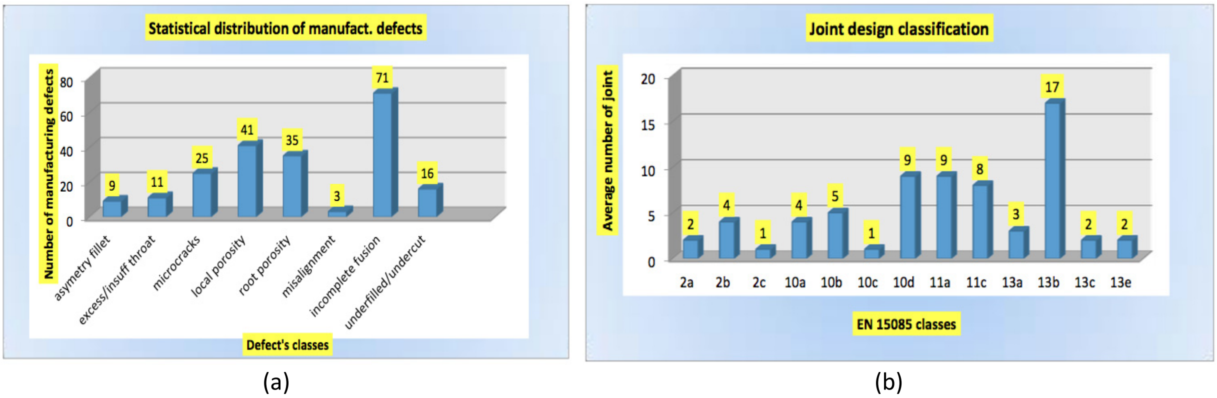


Fig. 2. (a) Statistical distribution of manufacturing defects (b) Joint type distribution

Table 3. Visual inspection - sizing of manufacturing defects

Fatigue life prediction for visual inspection					
Joint #	Sample #	Defect size (long	Lateral	Transverse	Estimated
ISO Class: 507					
9	2	4	1	25	5.43E+05
9	3	2	1	25	5.08E+05
53	1	4	1	25	5.43E+05
ISO Class: 502 & 503					
53	2	6	0.8	25	5.59E+05
53	3	7	0.8	25	5.64E+05
ISO Class: 512					
4	1	7	14	25	5.64E+05
5	3	18	12	25	5.88E+05
41	2	18	10	25	5.88E+05
41	3	10	15	25	5.75E+05
41	4	5	10	25	5.52E+05
56	1	15	2	25	5.84E+05
56	3	15	2	25	5.84E+05
66	4	14	16	25	5.83E+05

Table 4. Microscopic inspection - sizing of manufacturing defects

Joint Class	Defect #	Longitudinal 2a (mm)	Lateral 2b (mm)	Area (mm^2)
1-001	1	1.49	1.29	1.92
	2	2.34	1.14	2.67
	3	0.36	0.19	0.07
4-002	1	2.01	0.67	0.79
	2	1.96	0.47	0.92
5-003	1	2.16	1.08	0.92
	2	4.67	0.12	0.56
	3	0.28	0.28	0.06
5-004	1	1.26	1.26	0.31
	2	2.63	0.20	0.53
	3	0.39	0.39	0.03

4	0.39	0.39	0.03

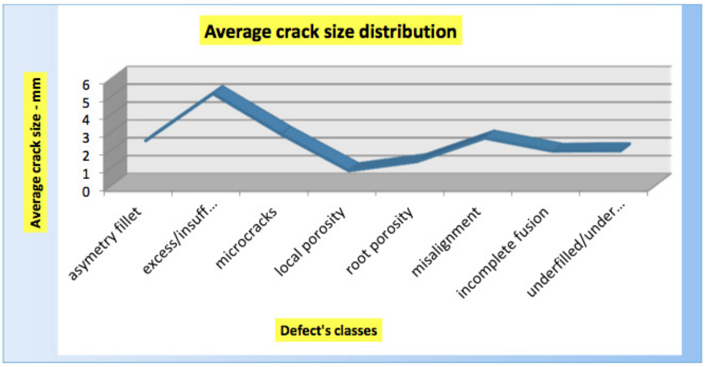


Fig. 3. Average crack size distribution

3.3. Fatigue life prediction

In order to achieve the objectives of this study, data in Table 4 were analysed using endurance limit method and data in the sixth column of Table 3 were obtained. In order to have a better understanding of the influence of welding defects, different stress levels were used and fatigue crack growth curves for each defect class was generated (see Fig. 8 - 10).

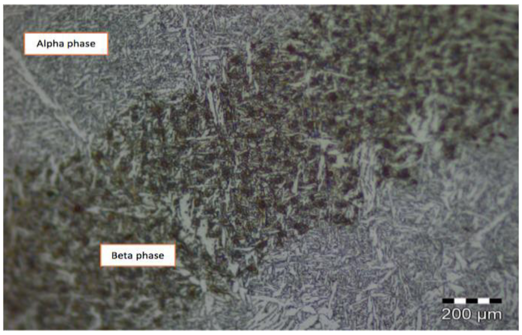


Fig. 4. Optical micrograph of parent material

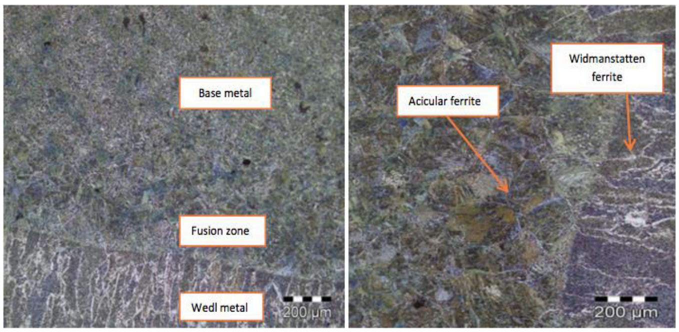


Fig. 5. Micrograph showing phases within weld joints

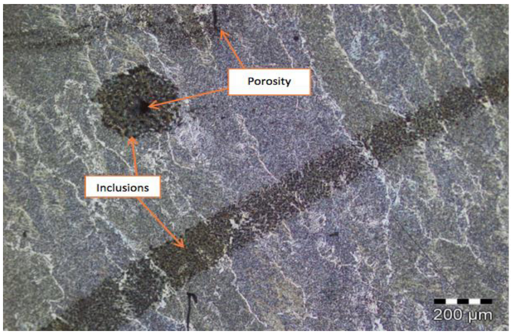
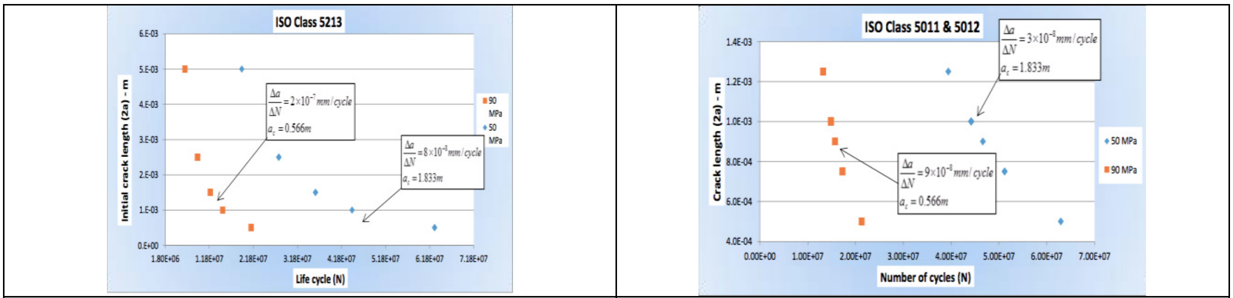


Fig. 6. Optical micrograph showing localised porosity and inclusions within weld metal

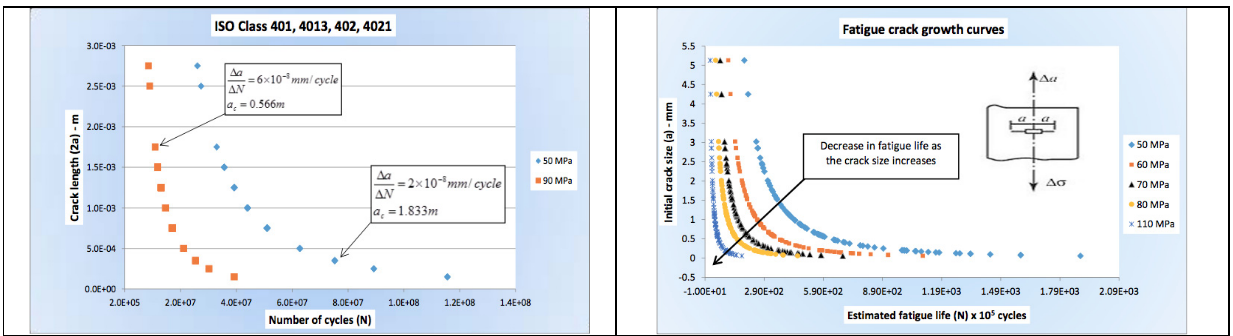
4. Discussion

From Fig. 2(b), it can be seen that the structure of a locomotive bogie is made of 67 different joint designs. These joints can be classified into 13 different classes according to EN 15085. Most of these joints are critically stressed. Double fillet joint is the most dominant class as it can support twice the load supported by any other joint type. The high number of double fillet joints in the bogie is expected given the high loading levels in the bogie. Fig. 2(a) revealed that the structure contained 211 manufacturing defects classified into 8 different classes. Incomplete fusion (lack of penetration) was the most dominating class with 71 defects and an average crack size of 2 mm. The largest crack size was found to be 6 mm long and was found in insufficient throat thickness related defects. Microscopic analysis revealed that clustered porosity 1.35 mm sizes were embedded in the weld metal.



(a) (b)

Fig. 7. Estimated fatigue lives (a) Undercut defects (b) Cracks



(a) (b)

Fig. 8. (a) Fatigue crack growth curve for lack of fusion defects (b) Effects of stress variation on fatigue life

Data in Table 3 shows that manufacturing conditions affect the quality of the product. Varying the manufacturing parameters results in various types of manufacturing defects. Components manufactured under the same conditions must exhibit similar features such as nature and size of defects. Samples 2 and 3 of joint number 9 showed that a slight variation in welding parameters led to 2 completely different results. Since the 2 samples were obtained from 1 welding sample, they were expected to have identical features but in Table 3, the overall size of the defects in sample 2 differ from those in sample 3. This could be due to a slight change in travelling speed or torch angle. Although the same could have been achieved by altering any of the other parameters, only the torch angle and traverse speed were controlled during the process as they depend on the welder's skill. This observation was also made for joint 53 where the defect observed in sample 2 differs from that in sample 3. In the same manner, samples 3 and 4 in joint 5 of Table 4 have different number and size of defects even though they were produced under similar conditions and were cut from 1 welded sample. Such inconsistencies result from an uncontrolled variation of welding parameters (in this case travelling speed and torch angle). This also depends on the physical and psychological state of the welder and therefore cannot really be controlled in a manual process. In some instances, the welder may be in good state but due to the ease of welding (access to the point of weld), the operator may naturally and unconsciously alter these parameters. It was also observed that defect class varies with an increase or decrease in travelling speed or torch angle. Table 3 shows that joint 53 sample 1 contains a crack-like defect, but as the torch was travelling along the welding specimen, the defect type changed into a circular defect. One explanation is that the travelling speed of the touch decreased thus allowing for the filler material to partially fill the root gap. After examining the joints visually and using a microscope, it was observed that most insufficient throat thickness related defects resulted from processes with incorrect root gap. For example, in joint 44, the root gap specified by the welding engineer is 1 mm but during the welding process, the welder used a gap of 2 mm while keeping the amount of filler material and travelling speed constant. In this case, the material would not be enough to fill the gap and hence a lack of penetration defect will be introduced. The aim of this investigation was to study the effect of stress levels on the rate at which such defects would grow within the structure. From Fig. 7 and 8, the rate of growth of defect are shown to depend on the stress level as well as the geometry of the defect. Defects produced by voids (porosity, lack of penetration) tend to grow at a lower rate compared to those having sharp edges such as micro cracks and linear misalignments. This is due to cracks having sharp edge stress raisers. In cracks, the radius of curvature at which the induced stress acts upon the material tends to be very small (close to zero) which magnifies the stress. The local stress level at the crack tip therefore exceeds the yield strength of the material leading to extensive plastic deformation in the crack tip zone and hence higher stress intensity factor and crack growth rate. This is observed by direct comparison of graphs in Fig. 7(a) where the cracks grow at a rate of 8×10^{-8} mm/cycle compared to undercut defects, which grow at 3×10^{-8} mm/cycle when subjected to a 50 MPa stress level. In Fig. 7(b), the rate at which porosity (lack of penetration) grows is found to be 2×10^{-8} mm/cycle. Comparing the three classes of defects, it may be said that void defects grow at a lower rate compared to other types of defects. From Fig. 8(a) and (b), the number of cycles before failure is inversely proportional to the initial size of the defect as well as the stress level applied. As the stress level increases, the number of cycles before failure decreases. This is expected since the material is stressed more approaching the yield strength of the material. It is also expected that as the initial crack (defect) size increases, the number of cycles before complete failure decreases. This phenomenon can be explained by the amount of material needed to be removed in order to attain the critical size for complete failure has actually decreased. This can also be observed in the Fig. 8, where at 50 MPa the rate was 3×10^{-6} mm/cycle and at 150 MPa, the rate was 2×10^{-2} mm/cycle.

5. Conclusion

This work conducted to assess the effect of weld manufacturing parameters on the fatigue performance of railway bogies. Results showed that the change in travelling speed and torch angle caused the sizes of consecutive defects to vary. Based on whether these parameters increase or decrease, the size and type of manufacturing defects vary. As the welding gun travelling speed increases, the size of the crack and pores also increases. It can therefore, be concluded that an increase in travelling speed or torch angle produces more undesirable manufacturing defects in the bogie (incomplete fusion and cracks). This phenomenon is expected to have an effect on the fatigue life of the structure. The expected welded joint life in the design of railway bogie is expected to be more than 10^8 cycles. The fatigue prediction analysis conducted on the identified and quantified defects in the railway bogie structure resulted in average lives of 6.23×10^5 cycles when subjected to a stress level of 150 MPa. This is the recommended design load for such structures. Based on this finding, it can be concluded that the welding process parameters used were not adequate for the manufacturing of this structure. It is recommended that the welding parameters be closely monitored especially in maintenance related weldments to minimise defects and hence assure welded joint design life.

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