Analysis of Fatigue Design Recommendations for Aluminum Weldments with Imperfections

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ABSTRACT

The available fatigue data on weld imperfections regarding weld toe angle (WTA) and linear misalignment (LM) in the joints of Al-alloys reported by several workers has been mathematically and statistically analyzed to derive the sets of fatigue design curves for quantitative comparison with those recommended by the Eurocode. It is envisaged that as reference the newly derived design curves can assist in designing under dynamic loading with better understanding of the recommendations compared to the design curves of recommended standards. Further, for the defects like lack of penetration (LOP) and lack of fusion (LOF) the validity and shortcomings of the recommended limits of imperfection of Euronorm are evaluated with respect to the analysis put forward by the newly derived design curves. The critical analysis has proposed certain more preferable logical recommendations on economically acceptable limits of weld defects especially for the high cost intensive structures at high cycle range of 5×10^5 to 5×10^6, which should be verified further with more experimental data in this area prior to its practical implementation.

Keywords: Design recommendations; Fusion welded joints; S-N curves; Aluminum alloys: Weld toe angle; Linear misalignment; Lack of penetration; Lack of fusion; Imperfection limits

INTRODUCTION

Aluminium alloys have gathered wide acceptance in many conventional and advanced engineering applications primarily due to their high strength to weight ratio along with several other merits, when the welding is commonly used as one of the basic means of fabrication of these alloys. However, the weld fabrication of aluminium alloys has often faced number of challenging questions to solve due to its several adverse influences on the integrity of welded structure. Based on the alloy system, the severity of the problems is largely dictated by high affinity of the weld to porosity formation, solidification cracking and the formation of low melting eutectic as well as coarse grain microstructure in the heat affected zone (HAZ) of the arc weld. These problems are in isolation or in combination competitively arising out of high susceptibility of molten weld pool to dissolve hydrogen with practically no solid solubility, high thermal coefficient of expansion (twice than that of steel) and substantial contraction on solidification (typically 5% more than that of equivalent steel weld) [1] and grain boundary segregation of alloying elements primarily by dissolution of precipitates. However, besides these difficulties there are many other problems which significantly influence the fatigue properties of weld joints of structural aluminium alloys and determine their utility in engineering applications under dynamic loading system. They are generally referred as the profile imperfections of weld joints with respect to their considerable influence on stress distribution in it. Such kind of imperfections, especially refer to low outer weld toe angle (WTA), misalignment of welded components, lack of penetration (LOP), lack of fusion (LOF) and undercut, largely arise out of incorrect welding procedure specifications (WPS) and poor welding technique [2]. The weld joints of aluminium alloys become comparatively more prone to occurrence of such kind of profile imperfections primarily due to their high thermal conductivity and rapidly solidifying weld pool [3] and thus, these detrimental features adversely influence the fatigue properties of aluminium weld quite significantly.

The fatigue life is largely dominated by the duration of crack propagation. The cracks of approximately 100 m in length generally initiate during the first 10% of total fatigue life of aluminium alloy. If the measurable crack size is considered as 10-20 m, this aspect of consumption of fatigue life may be reduced to below 1%. It is observed for notched as well as un-notched base material and welded joints [4]. The fatigue behaviour is thus a result of fracture mechanics governed by the stress conditions in critical zones of weld joint and the behaviour of crack propagation. Based on this knowledge the influence of weld defects on fatigue properties can be derived through consideration of fracture mechanics by neglecting the crack initiation time [2]. The weld defects act as a system of rival notches and cracks. Normally the most important stress concentrations arise from the weld geometry itself in fillet welds and butt welds with or without weld reinforcement. That is why very few fatigue failures occurred in service are directly attributed to the effect of weld defects when majority being associated with fillet welds having an inherently low strength. Thus, the goal of economic quality assessment codes is to classify the grades for different weld defects in groups leading to comparable strength values.

Codes for the definition of weld defects, weld quality and derivation of acceptable levels of weld defects have been introduced in several countries. The prEN ISO 10042:2004 [5] defines the dimensions of typical imperfections which commonly occur in general fabrication. It provides three sets of dimensional values denoted as B, C and D categorised for three quality levels as stringent, intermediate and moderate respectively, in order to permit application over wide range of weld fabrication. In IIW document XIII-1965-03 [6] the limits of imperfection are separately defined for certain cases, although to some extent they are covered in fatigue resistance of classified structural details. The IIW document has been found appropriate for an overall view to the problem of fatigue of welds. It is often marked that there is difference in individual fatigue strength values between the IIW document and Eurocode document. It is believed that Eurocode is comparatively more in agreement to the actual results of beam tests. Further there is more or less a direct link maintained between the design curves of prEN 1999-1-3 (Design) [7] through quality levels of prEN ISO 10042:2004 and EN 1090-3 (Execution) [8]. Thus it is observed that, in spite of considering similar sets of data, some differences amongst the specifications with respect to recommended values of allowable defect size partially exists. This may have possibly happened due to difference in conceptual aspects and the gap that still exists in the knowledge base.

In view of the above an effort has been made in this investigation to carry out a comparative study of the fatigue test results of arc welded joints of Al-alloys with the fatigue design recommendations of Eurocode in order to see its applicability for some key varieties of weld imperfections affecting the fatigue life of the joint. The data collected from fatigue failure of weld joints have been classified for analysis with respect to the type of weld imperfections referred as predominant cause of failure. However, in this regard the influence of common range of composition dictating the filler metal properties is assumed to be insignificant in comparison to the influence of imperfections and thus this study can be considered to be valid for most of the weld joints irrespective of the commonly used filler alloys. Fatigue design curves derived from the available data on the effect of weld toe angle and linear misalignments on fatigue behavior are compared to that of Eurocode-9. Quality limit specifications as per prEN ISO 10042 : 2004 for LOP and LOF defects are evaluated to justify their validity with respect to the available data. Relative effect of LOP and LOF defects on the behavior of butt welds with and without reinforcement is also examined. Since the results summarized in the present study have been compared with current standards and codes, they may be recommended for consideration of the designers in evaluation of the performance and reliability of design of weld joints under dynamic loading.

DESCRIPTION OF THE STATISTICAL ANALYTICAL METHOD

The reported [9-11] data on weld toe angle and linear misalignment has been considered in terms of stress range and number of cycles to failure. The data used in this investigation corresponds to the fatigue tests in which some types of defects under consideration have been responsible for initiation of failure. For most of the engineering applications a fatigue life range may be approximately defined as 1x 10^4 to 5x 10^6 cycles where the relationship between the cycles to failure and fatigue strength can be found linear for all practical purposes [12]. Basic method of analysis has been the estimation of best-fit regression curve ($\log N = -m \log \Delta\sigma + \log C$) of the cycles to failure (N) to the stress range ($\Delta\sigma$) plot of the fatigue data of weld joints using the least square method. The linear analysis of the log-log plot of the N-$\Delta\sigma$ was made at mean regression line of 50% of probability of survival by characterizing it through its slope (m), intercept (logC) and the standard error denoted as standard deviation or square root of variance (S) of the predicted number of cycles for each amplitude.

The standard deviation of logN about mean regression line has been estimated and used to establish the confidence limits based on the assumption that the data conforms to log-normal distribution. A lower 95% confidence limit, which is approximately two standard deviations below the mean regression line, has been considered as a suitable basis for design in reference to the respective recommendation regarding necessity of defining additional material safety factors [12], [13]. It theoretically corresponds to a probability of failure of 2.5% or to a probability of survival of 97.5 % and thus the curves passing through the point, 2SD below mean regression line and having same slope has been drawn. The 95% confidence limit estimation indicates that on 100 statements, which assert that the results are given with a probability of 97.5 %, five could be wrong. Nearest slope from the recommendation of Eurocode-9 (EC-9 recommends slopes of 3.4 and 4.3 in middle cycle range), to the slope of mean regression line has been selected. Central part of the data points mostly belonging to short life span has been estimated. A curve passing through the point which is 2SD below this central part with selected slope has been drawn and used as a basis for comparison with the recommended standard.

The reported data on LOP and LOF have been considered in terms of different defect size (measured after tests) influencing the number of cycles to failure at a given applied stress range. In the light of Eurocode recommendations this data has been transformed to reference strength at 2 x 10^5 cycles for different defect size. This is achieved by considering every individual data point on a design curve of slope 3.4 followed by interpolation of strength at 2 x 10^5 cycles. The slope of 3.4 is recommended for butt weld joint with this kind of imperfections and thus the result of this analysis may be assumed to reflect the validity of standard. In case there are more than two data for same defect size, it is averaged over the reference strength value. The data has been plotted on semi-log scale with fatigue strength on Y-log scale and ratio of defect size to plate thickness (relative defect size) on X-scale. The fatigue behavior of weld joint having LOP and LOF has also been studied with respect to plate thicknesses. An analysis of the comparative influence of weld reinforcement on fatigue properties of the joints has also been attempted through this investigation.

ANALYSIS OF REPORTED DATA

Weld Toe Angle

The effect of weld toe angle, α , as shown in **Fig. 1** on fatigue behaviors of single side butt joint of TIG welded 7020 (AlZn4.5Mg1) and MIG welded 5083 (Al-Mg) alloys have been investigated where they were prepared by using 5183 (S-AlMg4.5Mn) filler rod and 5356 (Al-Mg) filler wire respectively [9, 10]. Although the fatigue data considered for the alloys 7020 and 5083 conforms to different test conditions of minimum to maximum stress ratio R = 0.1 at frequency of 25 Hz and R = 0 at frequency of 33 Hz respectively, they are considered all together in the present analysis. This is as per the recommendations of Eurocode where, for all stress ratios R ≥ -0.25 the enhancement factor for fatigue strength is considered as 1 for weld joints [7, 14]. The fatigue design curves generated or derived for different levels of weld toe angles from 109^0 to 155^0 are shown in **Fig. 2(a-e)**. The plots presented in **Fig. 2(a-e)** show that the increase of WTA enhances the slope (m) and reduces the intercept (logC) as given in Table-I. The correlations of the m and logC with WTA have been shown in **Fig. 3**. The figure shows that the m and logC varies almost linearly with a change in WTA. The variation of fatigue strength at 2x10^5 cycles with the weld toe angle as shown in **Fig. 4** has been derived in reference to the plots depicted in **Fig. 2**. It is observed that most of the data considered in this analysis from **Fig. 2** belongs to the range of about 2x10^5 cycles and hence choosing this as reference point for fatigue strength is realistic for the current analysis.

Linear Misalignmet

The effect of misalignment on fatigue behavior of single sided butt weld joints has been investigated by employing the reported data on the joints of 1 and 2 mm thick plates of Al-alloy 7020 (AlZn4.5Mg1) prepared by using the TIG welding process and 5183 (S-AlMg 4.5Mn) filler rod [9,10]. The design curves for different levels of linear misalignment exist in the two different plate thicknesses have been established as shown in Fig. 5 where, e is the eccentricity and t is the plate thickness (BS PD6493). The correlation of the linear misalignment with the fatigue strength estimated from the design curves (**Fig. 5**) at 2x10^5 cycles has been established as shown in **Fig. 6**. The figure shows that the increase in misalignment defined by the ratio (e/t) almost linearly reduces the fatigue strength of the weld joint. Taking into consideration the secondary bending moment caused by the introduction of linear misalignment, a relevant fatigue design curve has also been established with the same data as shown in **Fig 7**. This curve represents a common design curve for all values of misalignments. The critical stress generated in weld joint due to bending moment is estimated by using the expression given [15] as

$$\Delta\sigma_{eff} = \Delta\sigma \times (1 + 3 \times \frac{e}{t}) \quad ....(1)$$

Lack of Penetration and Lack of Fusion

The effect of LOP and LOF on fatigue behaviour of the weld has been investigated by using the reported data about double V full seam butt weld of 9.5 and 24.5 mm thick plates of Al-alloy 5083-O (AlMg4.5Mn) prepared by MIG welding employing 5183 (S-AlMg4.5Mn) filler wire [9, 11]. The fatigue data obtained from the weld joints of the plate thicknesses of 9.5 and 24.5 mm were subjected to testing at two different stress ranges of 83 and 131 MPa respectively at a given frequency of 5-10 Hz with a stress ratio, R = 0. The influence of relative defect size, defined as a ratio of defect width (as shown in **Fig. 8,** which also shows how LOP and LOF are identified in weld joint) to plate thickness, on the reference fatigue strength at $2x10^5$ cycles has been analyzed for two cases of LOP defect as reinforcement removed (RR-LOP), and reinforcement intact (RI-LOP) and for LOF defect in reinforcement removed (RR-LOF) butt weld as shown in **Figs. 9, 10 and 11** respectively. The **Fig. 12** shows the comparison of the effect of these defects on fatigue strength of the reinforcement dressed and undressed welds.

COMPARATIVE ANALYSIS WITH PRESCRIBED STANDARDS

Effect of Weld Toe Angle:

In order to indicate applicability of appropriate fatigue strength curve for the fatigue assessment, the EC-9 standard [7] has defined 'Detail Category' with respect to particular fatigue initiation site arising from fluctuating stress in fixed direction. Each design curve is defined by the fatigue strength at $2x10^6$ cycles and its slope (m). With the objective of performing comparison between recommended design curves and established design curves the detail category of butt joint welded from one side with full penetration without backing has been chosen, where the Class 45 MPa-4.3 represents the best quality in this category.

The fatigue design curves generated **(Fig. 2)** for weld toe angle show significantly higher slopes (Table-I) than those recommended by EC-9 for best quality class B weld joint. For WTA greater than 150^0, the values of slope greater than 6 are observed when the EC-9 suggests requirement of WTA> 150^0 for class (B) weld joint based on the fact that at a larger WTA its effect is practically insignificant. This seems to be a valid assumption because the slopes of the design curves for WTA < 150^0 are decreasing significantly up to a value about 4 at WTA = 109^0 , when the WTA < 130^0 considerably enhances the failure initiation by providing a significant mechanical notch effect at the weld toe. It is observed that at WTA < 120^0 the strength decreases significantly due to predominant role of notch effect at weld toe and the situation becomes stable with no further decrease in strength at certain value of WTA of about 90^0-100^0 stating that the critical stresses at the joint may have entered into the plastic region and dictating the joint strength overruling the effect of WTA. In this line of understanding it may be seen from **Fig. 3** that the intercept (logC) decreases with the increase in weld toe angle. Thus it may be concluded that with the increase in WTA the design curves become shallower and hence permit the weld joint to bare more stresses enhancing the fatigue strength by rapidly reducing the adverse influence of WTA on fatigue strength at an angle more than about 150^0 as shown in **Fig. 4**. At this stage the mechanical effect of notch at weld toe becomes insignificant and the material properties primarily govern the failure by damage accumulation.

The following empirical relationship is derived from the established design curves for the estimation of life of a given sample with known stress range and weld toe angle.

$$\log N = (2.53 - 0.06 \times WTA) \times \log\Delta\sigma + (4.01 - 0.07 \times WTA) \quad .... (2)$$

The fatigue strength can also be estimated with the help of the following empirical equation.

$$\Delta\sigma_{ref,2\times10^5} = 40 \times e^{0.00664 \times WTA} \quad ..... (3)$$

For this kind of weld joint the class 45-4.3, EC9 allows fatigue strength of 76.86 MPa whereas the design curves generated in this investigation permit strength of about 110 MPa. This also shows the conservative approach of EC-9 allowing high safety margin. This is especially true in case of high cycle region where safety margin provided by the Eurocode is so high that it may not be always economical to consider due to high cost of fabrication of structures.

Effect of Linear Misalignment

Although in principle the linear misalignment in weld joint is not permitted, but the studies have been found effective to qualify the class 45-4.3 weld joints on the basis of their fatigue strength at a given misalignment ratio with respect to the standard prescribed in EC-9. It is observed **(Fig. 6)** that fatigue strength of the weld joint is reduced to about 50% when a misalignment of 45% of the plate thickness is introduced. Practically the misalignment greater than 50% of plate thickness cannot be permitted in any fatigue class specified in EC-9. For good quality weld joints misalignment less than 10% is generally considered for design purpose which is also favoured by the recommendations of IIW [6]. The linear regression analysis of correlation of the misalignment ratio (**e/t**) with the fatigue strength at 2×10^5 cycles has been found as follows with a standard deviation of 0.098 from the mean line of regression.

$$\Delta\sigma_{ref,2\times10^5} = 120 - 155\times(e/t) \quad ...(4)$$

This relationship represents the variation of strength with misalignment at 50% probability of success. However, for safety to general practical purpose a relationship which is two standard deviations (2SD) below this line may be considered more realistic and accordingly by statistical calculations this relationship can be expressed as

$$\Delta\sigma_{ref,2\times10^5} = 90 - 155\times(e/t) \quad ...\ (5)$$

This correlation represents the variation of fatigue strength with misalignment at 97.5% probability of success, which can be used in practice to estimate the allowable defect size at design stage.

The design curve based on the critical stress generated by secondary bending moment due to misalignment in weld joint, shows **(Fig. 7)** quite high fatigue stresses in the low cycle regime. But it may be remembered that the weld joint may fail at stresses much below this mathematically derived values if the stress which critically developed due to misalignment exceeds yield stress of the material. However, for the middle cycle range the slope of the design curve found as 5.9 is again significantly higher than the maximum value of slope recommended as 4.3 by the EC-9. The EC-9 and the established design curves can be good design consideration in the range of about 10^4 to 5×10^5 cycles. But coming to the high cycle regime it is observed that the safety margin recommended by the EC-9 is considerably high and it shows conservative approach. In the range of 5×10^5 to 5×10^6 cycles the design curve of the data points shows a comparatively shallower slope to that of the lower cycle regime, when EC-9 recommends a common slope in the region from 10^4 to 5×10^6 cycles. From the above observation it may be suggested to use different slopes in the range of 5×10^5 to 5×10^6 cycles. It may not have much significance in dealing with low cost fabrication, but it may be significant in designing a structure of high cost fabrication more economically by reducing the application of costly sophisticated methods of production and use of large quantity of cost intensive special class materials to satisfy the requirements of specified standards.

Effect of Lack of Penetration and Lack of Fusion

The lack of penetration lowers the fatigue strength more markedly than tensile strength of weld joint primarily due to introduction of a notch effect. Reinforcement tends to overrule the influence of a small lack of penetration in degradation of fatigue properties [13], when the lack of penetration becomes significantly more harmful in weldments with dressed reinforcement [11, 16]. Analysis of Kosteas [12] on aluminium welds shows that for as-welded joints the acceptable LOP size may be of the order of 1-2 mm which is also in agreement to the fracture mechanics analysis [14]. For reinforcement removed butt joints this limiting value reduces below 0.5 mm for sound welds [12]. The more resistance to failure offered by the reinforcement intact welds containing lack of penetration than that of the reinforcement removed welds is in agreement to the observation of **Fig. 12** showing a comparatively higher strength in reinforcement intact joint than that of the reinforced removed one at a given ratio of defect width (w) to the plate thickness (t). This is possibly due to partial enhancement of load bearing area over compensating that diminished by the defect. However, in this regard it may be remembered that reinforcement should not be large enough to introduce notch effect which may predominantly act as a crack initiation site by providing excessive stress concentration. As the study has been carried out by considering the weld toe angle of more than 150^0, the adverse effect of WTA on this analysis can be neglected on the basis of the observations on WTA as stated earlier in **section 4.1.** The out come of the current analysis may be realized as for a given defect size of about 20% of plate thickness the fatigue strength of weld joint reduces by about 40% in reinforcement intact welds, while the corresponding reduction in strength for reinforcement removed weld joints is about 60%.

Lack of fusion in weld is likely to be intermittent and variable in size with planer shaped flaw and act much like LOP. Its effect on fatigue strength of dressed welds depends strongly on the size, shape and position of defect in weld [13, 2]. But the lack of fusion is not as effective as lack of penetration in degrading the fatigue properties of weld joint. It is also seen from the **Fig. 12**, that at a given relative defect size the fatigue strength shown by the weld is comparatively higher in case of LOF than that of LOP possibly because the notch sensitivity of LOF is less compared to that of LOP in both the plate thicknesses. About 90% of fatigue life is dominated by crack propagation from an initial crack length of 100 μm [4] and for welded joints with imperfections like LOF it may be evaluated by neglecting the crack initiation time [2]. The lack of fusion takes more time to grow to macro size which delays the initiation of failure, when the opposite surfaces of a LOF imperfection are pressed together by residual stresses resulting in higher fatigue life [12]. The **Figs. 9-11**, shows that in all the three cases of RR- LOP, RI- LOP and RR-LOF the weld joints respond to cyclic loading in similar manner over the whole range of relative defect size where the increase of relative defect size logarithmically reduces the fatigue strength of weld joint. It is observed that for a given relative defect size, the weld joints with lower plate thickness (9.5 mm) offer comparatively more resistance to fatigue failure and its difference from that of the higher plate thickness (24.5 mm) reduces with the increase of relative defect size. Above observation shows that the influence of LOP and LOF on the behavior of weld joint is independent of plate thickness, rather it depends upon actual defect width. However, in the prEN ISO 10042:2004 the limits of imperfections for such defects are defined on the basis of relative defect size and same limits are specified for all plate thicknesses above 0.5 mm. It demonstrates the appreciable dependency of the LOP and LOF containing weld joint on the plate thickness, which is in contrast to the observations of the current investigation. It may be noted that the smallest defect size investigated in this study is 500 μm. The effect of plate thickness comes into picture for lower defect size as it is obvious that thicker plate (24.5 mm) can have higher fatigue strength than its counterpart of lower thickness (9.5 mm) for zero defect size. Thus, results of this study infer that there is a critical defect size, which can not be evaluated within the range of data available for this study, above which the effect of plate thickness does not play predominant role in deciding fatigue properties of weld joint. This issue has not been addressed by recommendations of prEN ISO 10042:2004 and should be carefully taken into considerations by the designers following this standard.

According to fracture mechanics the failure originated from such defects largely depends upon the defect/crack size and its sharpness. Using fracture mechanics fundamentals this flaw size can be correlated to strength of the weld joint. Thus, the concept of euro norm specifying the requirement of same relative defect size for all plate thickness seems to be inappropriate to deal with the problems of weld joint containing LOP and LOF. Considerable efforts are on to evaluate fatigue behavior of weld containing LOP and LOF using fracture mechanics approach.

CONCLUSIONS

The present investigation carried out on the fatigue behavior of weld joints of Al-alloys in middle cycle range on the basis of reported data on imperfections regarding weld toe angle, linear misalignment, lack of penetration and lack of fusion may be concluded as follows.

1. Regarding fatigue strength at a given life cycle with respect to both the weld toe angle and misalignment the comparatively shallower design curves obtained in the present analysis permit more stresses in weld joint compared to those proposed by the Eurocode with relatively steeper slopes providing more safety margin in high cycle region but may not be always economical especially for high cost intensive fabrication of structures.
2. Critical stress generated due to additional bending moment at linear misalignment in weld joint exceeding 50% of plate thickness put limit on permissible applied stress making it impractical to use. In low cycle region it should not exceed yield stresses and in high cycle regime it should conform to design requirement.
3. In high cycle range of 5×10^5 to 5×10^6 cycles the fatigue strength becomes comparatively shallower, which may be considered beneficial in designing of high cost intensive fabrication of structures by compromising the requirements of costly special class of materials.
4. Aluminum welds containing lack of penetration offer more resistance to fatigue failure when they are having weld reinforcement compared to that of reinforcement removed welds, if the notch effect at weld toe is not

playing a predominant adverse role in this regard.

5. At a given relative defect size the increase of plate thickness offers relatively less fatigue strength because of on setting of more significant primary role of the actual defect size.
6. Regarding resistance to fatigue failure the influence of lack of fusion is less significant compared to that of lack of penetration primarily because it takes more time to grow to a critical size for failure.

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Table 1 : Characteristics of the fatigue strength at different WTA

Avg. Weld Toe Angle (°α)	Slope (m)	Intercept (logC)	Standard Deviation (S)
155.0	7.0	0.1413	0.25
151.0	6.5	0.1631	0.30
133.5	5.7	0.1853	0.19
128.5	5.0	0.2003	0.24
109.0	4.2	0.2408	0.10

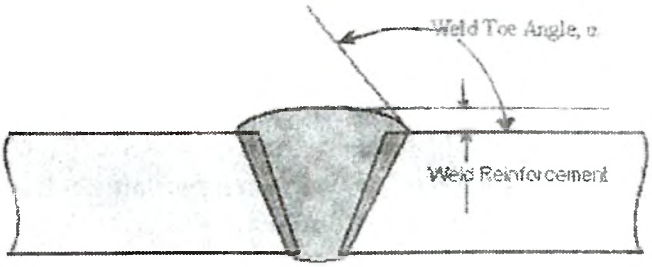
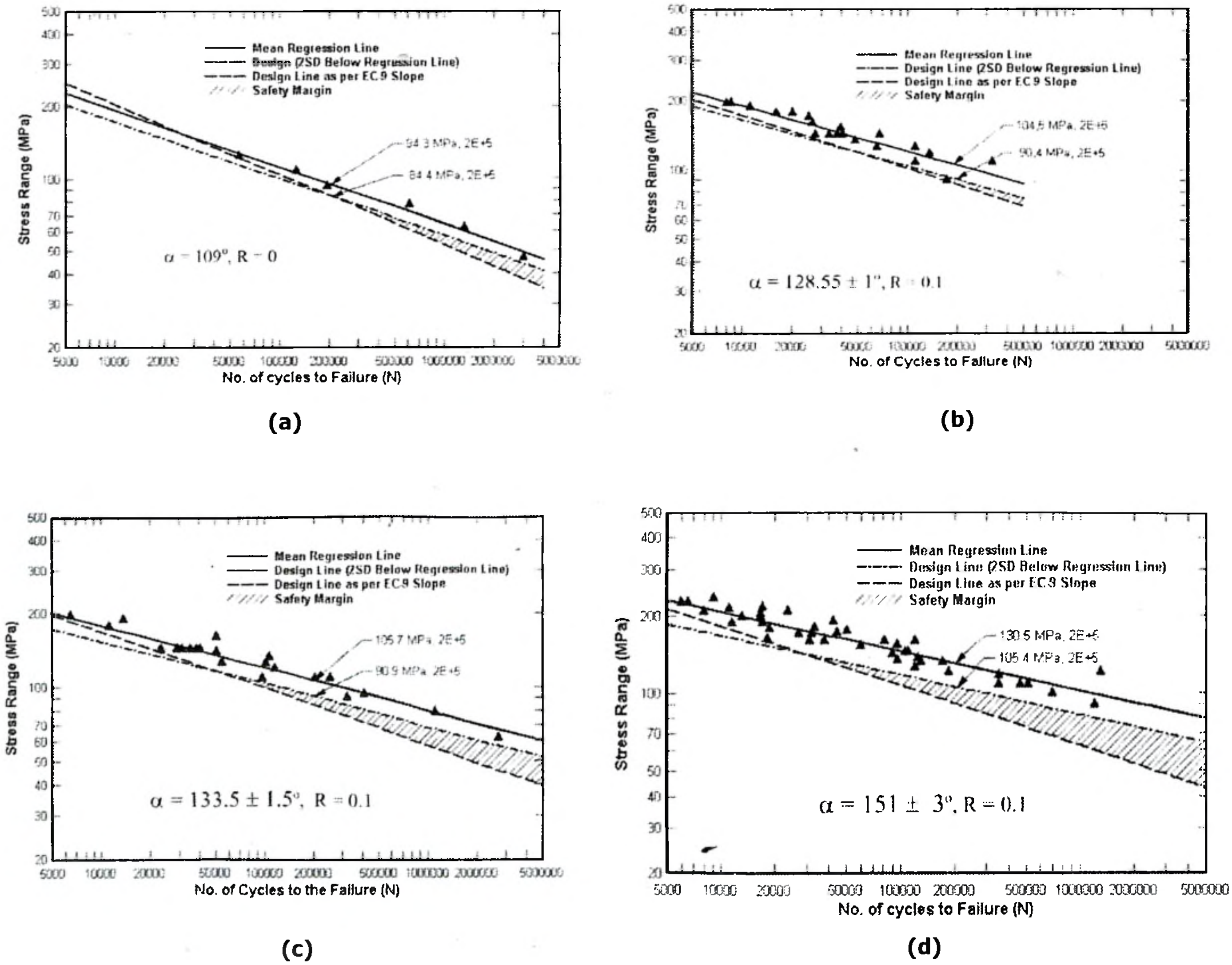


Fig.1 : Schematic diagram of the weld toe angle considered



(a)

(b)

(c)

(d)

Fig. 2 : Fatigue strength curves generated for different weld toe angle of single sided transverse butt weld of various Al-alloys ; (a)-(d) TIG welds of Al alloy 7020 (filler alloy 5183) for plate thicknesses of 1mm and 2mm and

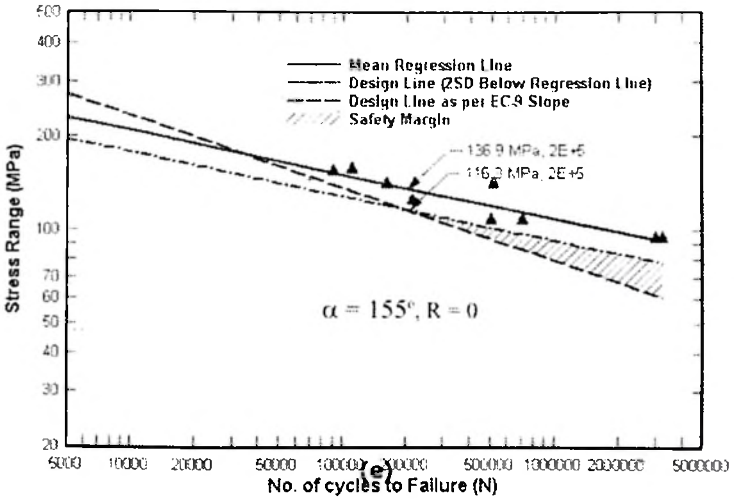


Fig. 2 : Fatigue strength curves generated for different weld toe angle of single sided transverse butt weld of various Al-alloys ; (e) MIG welds of Al alloy 5083 (filler alloy 5356) for plate thickness of 9.6 mm [9, 10]

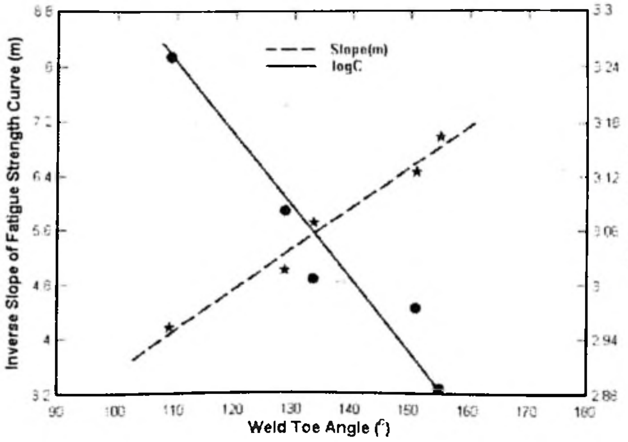


Fig. 3 : Effect of weld toe angle on slope and intercept of mean regression line.

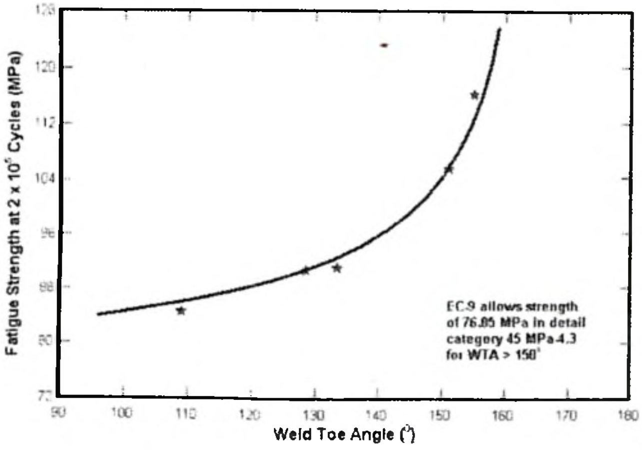


Fig. 4 : Effect of weld toe angle on fatigue strength of weld joint at 2 x 10^5 cycles.

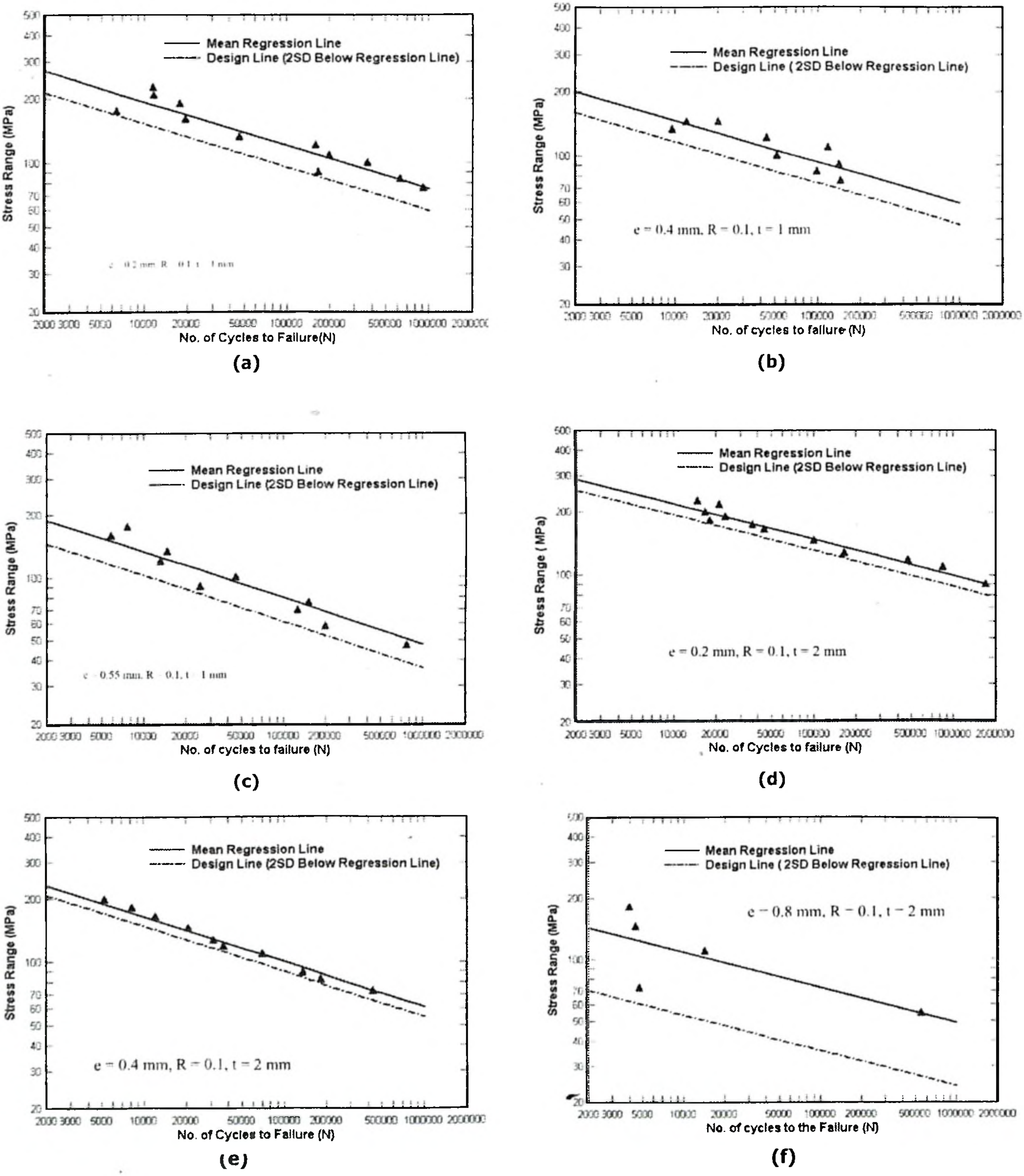


Fig. 5. Fatigue strength curves for different levels of misalignment of single sided transverse butt TIG welds Pof 7020 Al alloy using 5183 filler alloy [9, 10].

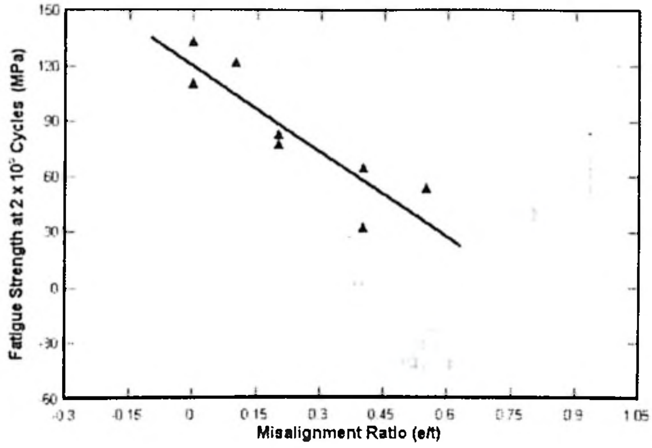


Fig. 6. Effect of misalignment ratio (e/t) in aluminium weld joint on its fatigue strength at 2x105 cycles.

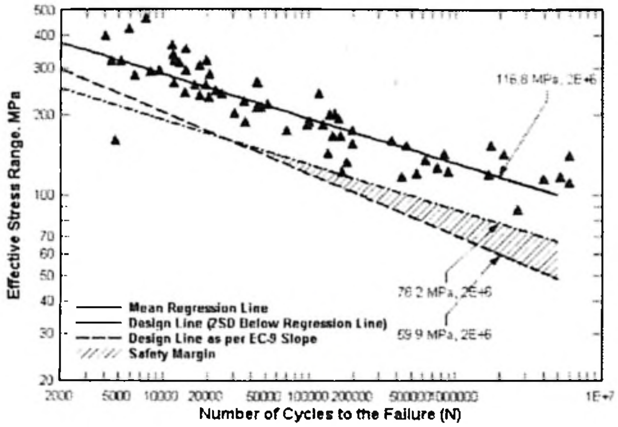


Fig. 7. Fatigue strength curve for linear misalignment i consideration of secondary bending moment caused by eccentricity.

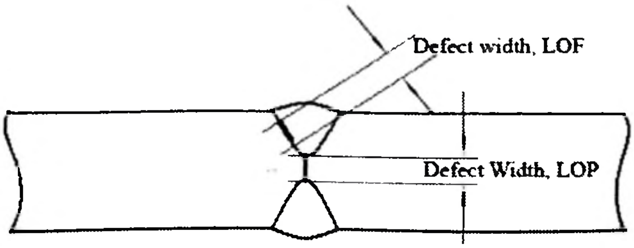


Fig. 8. Definition of defect width incase of Lack of Penetration (LOP) and Lack of Fusion (LOF) defects in butt weld.

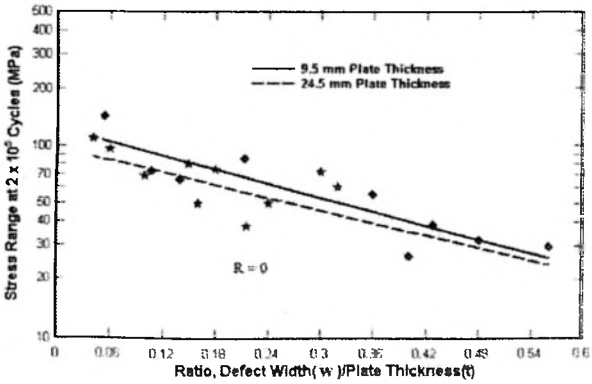
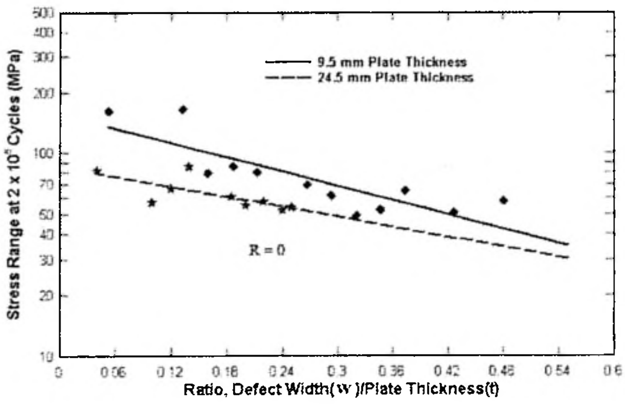


Fig. 9. : Influence of LOP defect with respect to plate thickness on fatigue strength of reinforcement removed double V- butt MIG weld of 5083-O Al alloy using 5183 filler alloy. [9, 11]



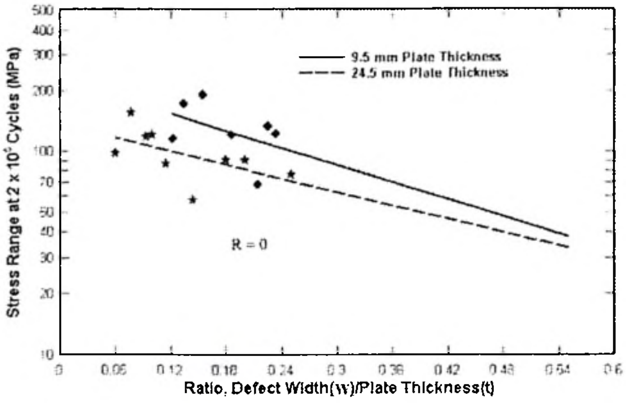


Fig. 10. Influence of LOP defect with respect to plate thickness on fatigue strength of reinforcement intac double V- butt MIG weld of 5083-O Al allo using 5183 filler alloy. [9, 11]

Fig. 11. Influence of LOF defect with respect to plate thickness on fatigue strength of reinforcement removed double V- butt MIG weld of 5083-O A alloy using 5183 filler alloy. [9, 11]

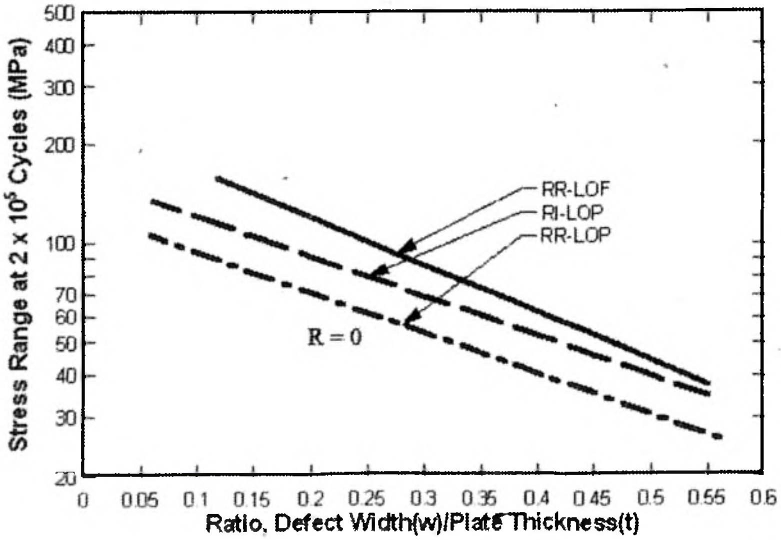


Fig. 12. Comparisons of the influence LOP and LOF defects on fatigue strength at $2x10^5$ cycles.