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Stabilizer Fillet Weld Strength under Multiaxial Loading (Effect of Force, Size and Residual Stress)

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Abstract**—**In this paper, the strength of a stabilizer is determined when the static and fatigue multiaxial loading are applied. Stabilizer is a part of suspension system in the heavy truck for stabilizing the cabin against the vibration of the road which composes of a thin-walled tube joined to a forge component by fillet weld. The component is loaded by non proportional random sequence of torsion and bending. Residual stress of welding process is considered here for static loading. This static loading with road irregularities are applied in this study as fatigue case that can affected in the fillet welded area of this part. The stresses in the welded structure are calculated using FEA. In addition, the fatigue with multi axial loading in the fillet weld is also investigated and the critical zone of the stabilizer is specified and presented by graphs. Residual stresses that have been resulted by the thermal forces are considered in FEA. Force increasing is the element of finding the critical point of the component.

Keywords**—**Fillet weld, fatigue, weld toe crack, weld root crack, S-N curve, multiaxial load, residual stress, combined force.

I. INTRODUCTION

CONNECTIONS in steel structures are particularly exposed to fatigue cracking. Significant geometric effects produce stress concentration and elastic-plastic behavior of connections [1]. The paper presents the analytical analysis of static and low cycle fatigue strength of complex variable loaded component in order to assess durability. The approach based on S-N diagram and rain flow matrix by considering the thermal and residual stresses. Simple thermal analysis of welding process obtains the forces and stresses that cause residual stresses. To find the critical point of the component, horizontal and vertical forces are increased. Finally with this analysis we can reinforce the critical zone. It is important that three different material properties are considered for weld metal, base metal and attachment.

II. WELD STRESS AND STRAIN

A typical geometry of T-joint fillet weld studied here, is shown in Fig. 1. The failure load is related to the tensile strength of the weld metal by the following empirical relationships:

$$R_u = K_w L W \sigma_c \tag{1}$$

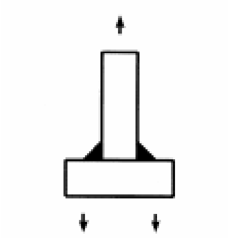

Fig. 1 T joint fillet weld

where, R_u is failure load, K_w is weld constant, L is weld length, W is combined leg length and σ_c is tensile strength of weld metal [2]. Alternatively the failure load has been related to the area of the weld throat, i.e.:

$$R_u = K_a L a \sigma_c \tag{2}$$

where, K_a is a constant and a is a combined throat length. In this empirical relationship, the throat dimension, a, may be expressed as the nominal throat length, i.e. for equal leg length, the throat, a_n, is length/$\sqrt{2}$, or the measured throat dimension (true throat), a_t (which includes any weld penetration, h_p). Hence

$$R_u = K_{an} L a_n \sigma_c \tag{3}$$

$$R_u = K_{at} L a_t \sigma_c \tag{4}$$

When no penetration is present the two constants, K_{an} and K_{at}, will be the same; when penetration exists K_{an} will be grater than K_{at} [2]. As some dilution of the deposited metal by the parent metal will occur during welding the mechanical properties of the weld metal itself, e.g. its tensile strength, σ_c, will lie between the values for the parent and deposited materials. It has been proposed that the tensile strength of the weld metal can be related to the properties of the parent material and deposit by an expression of the form:

$$\sigma_c = K_1[\alpha\sigma_w + (1-\alpha)\sigma_p] \tag{5}$$

where σ_c, σ_p and σ_w are the tensile strength of the weld metal and deposited metal, respectively, α is a dilution factor and K_1 a coefficient which indicates thermal effect. Kato and Morita indicate that the average value of α is 0.6. The effect of dilution is considered to be prominent in the first layer of the weld, which coincides with the severe stress concentration at the root of the weld when the fillet weld is loaded and cracking of this area will decrease the load carrying capacity of the weld [2]. Hence the value of α is valid independent of the size of the weld. The value of K_1 may be affected by the number of layers and welding conditions and thus is an unknown constant. Hence

$$\sigma_c = K_1(0.6\sigma_w + 0.4\sigma_p) \tag{6}$$

Kato and Morita give K_1 as 1.05. Ligtenberg reports

$$\sigma_c = 0.6\sigma_w + 038\sigma_p , \tag{7}$$

which is very little different from the Kato and Morita expression. The expression

$$\sigma_c = 0.5\sigma_w + 0.5\sigma_p \tag{8}$$

is also commonly used. In the following analysis

$$\sigma_c = 0.6\sigma_w + 0.4\sigma_p \tag{9}$$

has been used when the relevant data where reported.

III. FATIGUE STRESS BASED CRITERIA (S-N)

Equivalent stress approaches are extensions of static yield criteria to fatigue [3]. The most commonly used equivalent stress approach for fatigue is the octahedral shear stress theory (Von Mises theory). An equivalent nominal stress amplitude, S_{qa}, can be computed according to:

$$S_{qa} = \sqrt{(S_{a1} - S_{a2})^2 + (S_{a2} - S_{a3})^2 + (S_{a3} - S_{a4})^2} \tag{10}$$

Here S_{a1}, S_{a2}, S_{a3} are principle alternating nominal stress with $S_{a1} > S_{a2} > S_{a3}$.

The Von Mises criterion is the most widely used equivalent stress criterion for multi axial fatigue of materials having ductile behavior. If mean or residual stress is present, an equivalent mean nominal stress, S_{qm}, can be calculated based on Von Mises effective stress:

$$S_{qm} = \frac{1}{\sqrt{2}}\sqrt{(S_{m1} - S_{m2})^2 + (S_{m2} - S_{m3})^2 + (S_{m3} - S_{m4})^2} \tag{11}$$

where S_{m1}, S_{m2}, S_{m3} are principal mean nominal stresses [3]. Also the modified Goodman and Basquin equations obtain fatigue life as follows:

$$\frac{S_{qa}}{S_{Nf}} + \frac{S_{qm}}{S_u} = 1 \qquad S_{Nf} = \sigma'_f (2N_f)^b$$

IV. FEM ANALYSIS

Fig. 2 shows the stabilizer that includes of two forged arms and a thin ductile tube matching together with the fillet welds. This component stables the truck cab against applied loads from road irregularities. This model is analyzed in thermal, static and fatigue conditions together and also the weld root and toe is modeled here. A region for places that affected by heat of welding is defined calling heat affected zone (HAZ). Three mechanical properties for arm, tube, weld and HAZ is specified. The strength and elastic modulus of the weld are considered between the parent metal and deposited metal [4].

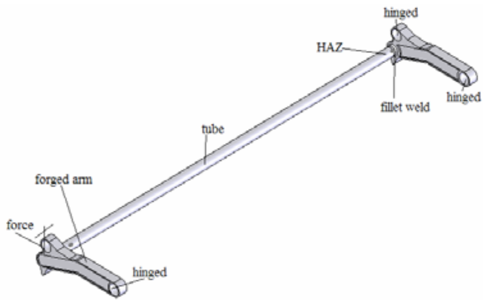

Fig. 2 Stabilizer

The steel is selected for mechanical properties and S-N diagram. Fine mesh modeling are done for the welds and HAZ and illustrated in Fig. 3.

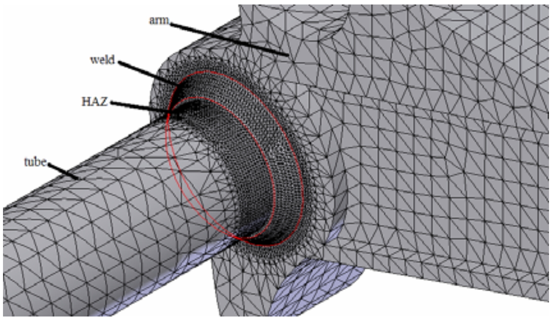

Fig. 3 Detail of weld mesh

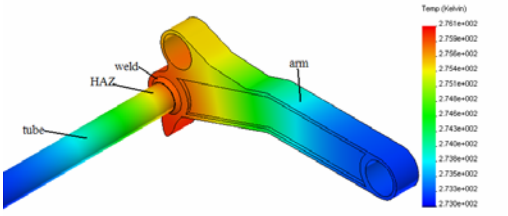

Fig. 4 Thermal analysis

The initial temperature of the welds, are 1800°K and the other part of the component and ambient temperature are 273°K which is considered as a critical condition. The results of the analysis of this study use for the residual stress. The convention between component and environment is $h = 15w/m^2k$ [4]. The results are shown in Fig. 4. The variations of temperature on weld toe on forged arm and tube are shown in Figs. 5a and 5b, respectively.

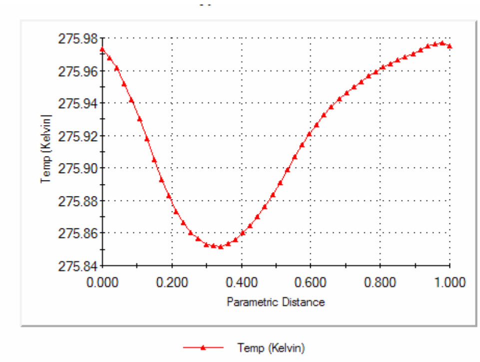

Fig. 5a Temperature on toe on arm

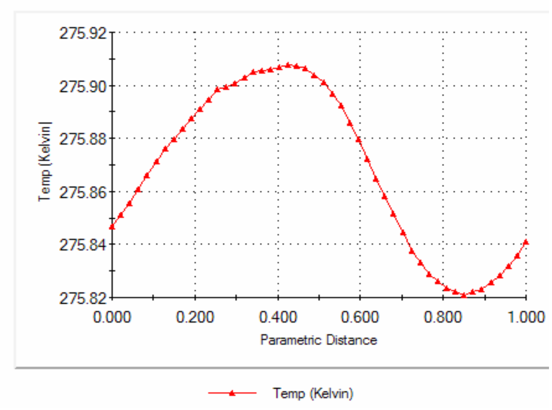

Fig. 5b Temperature on toe on tube

The transient heat transmission in the welding process should be investigated in order to obtain residual stress. Because of variation of temperature in the elements, there is some resistance against the elongation of the component and accordingly, have a residual stress in some parts near weld [5]. After a few time, the heat of the weld transmits to the arm and tube but all over the tube, doesn't have the same temperature and it is the reason of resistance against the elongation and residual stress. Then, using the thermal results as the input of static study obtains the stress due to temperature variation.

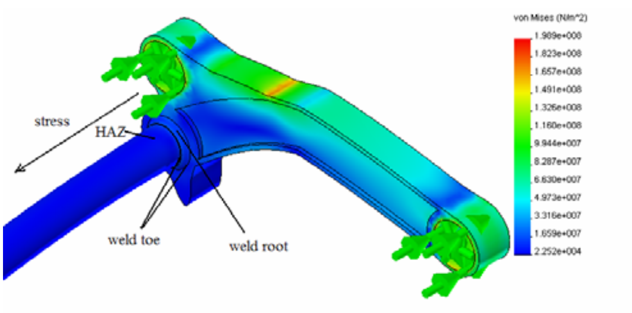

Fig. 6 Residual stress due to temperature

Variations of stress on the weld toe on the tube, is shown in Figs. 6 and 7. The residual stress has the maximum value 22MPa as can be seen in these figures. The toe and root of weldment are indicated along with three basic weldment regions [6]:

1- Parent or base metal (BM)
2- Deposited weld metal (WM)
3- Heat affected zone (HAZ)

In addition, a forth region, a fusion zone, exists between the deposited weld metal and the heat affected zone. These four regions have different microstructures, residual stresses, discontinuities and monotonic strength, ductility and fracture toughness properties. There are essentially basic ways of improving weldment fatigue resistance:

1- Improve the actual welding procedure
2- Alter the material microstructure.
3- Reduce geometrical discontinuities
4- Induce surface compressive residual stress.

It is very important that fatigue resistance is less dependent on ultimate tensile strength of base metal and mean stress and more dependent on applied stress range and class of weld and we must reduce stress concentration by dressing fillet welds and avoiding undercuts.

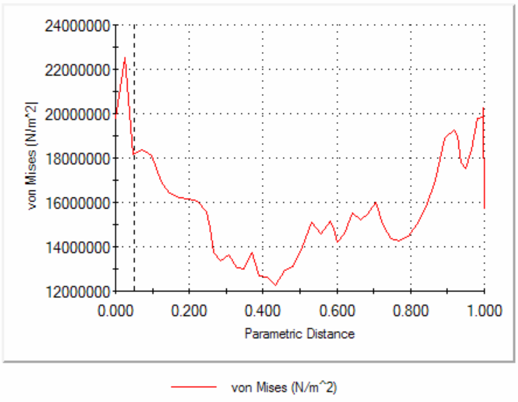

Fig. 7 Stress on weld toe on tub

Then, the results of residual stress as an input for static study with force 200N in direction of tube axes and perpendicular to it are used as the force of the road.

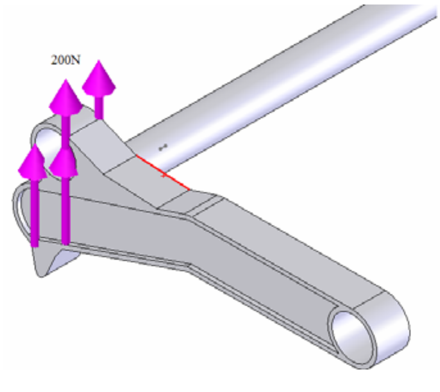

Fig. 8 200N force on forge arm

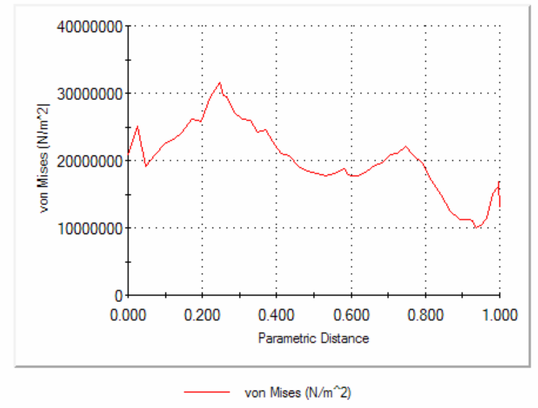

Fig. 9 Stress combination of heat and force

This applying force is showed in Fig. 8 and the related stress is showed in the Fig. 9. The force 200N in the direction of the tube axes is applied as shown in Fig. 10. The stress on the weld toe similar to pervious result is shown in Fig. 11. As can be observed from Figs. 9 and 11, the stress of perpendicular force is higher than parallel force. The results of static analysis are used as an input of fatigue study. SAE suspension and transmission load for perpendicular and parallel force to the tube are used here and showed in Figs. 12 and 13 [3].

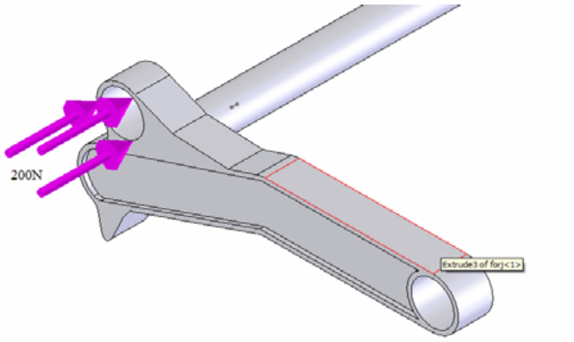

Fig. 10 200N force on arm

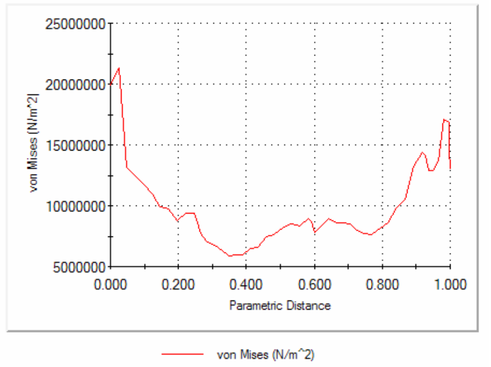

Fig. 11 Stress on toe on tube

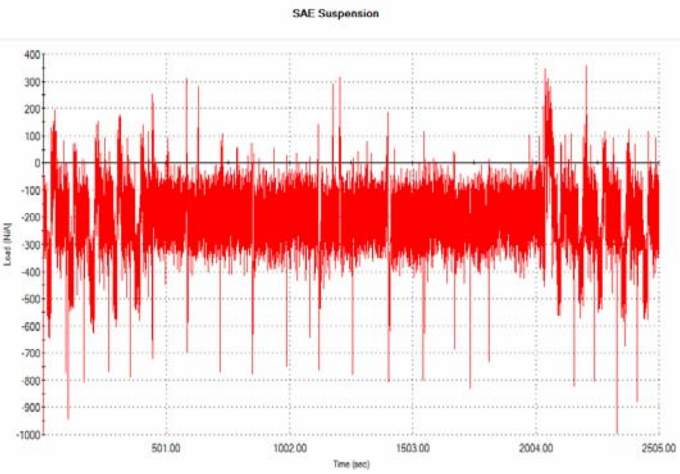

Fig. 12 SAE suspension load

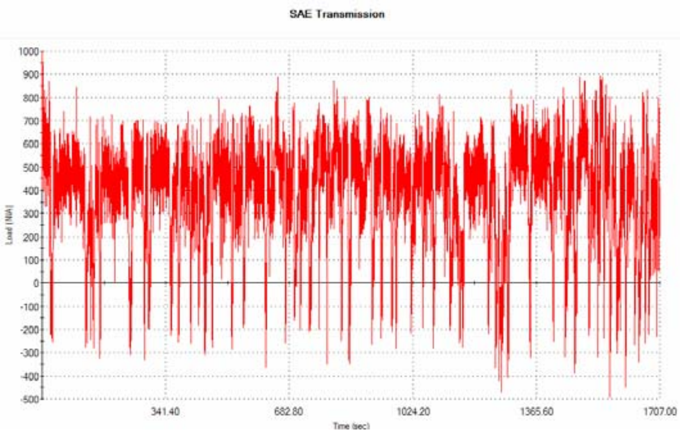

Fig. 13 SAE transmission load

Von Mises stress and Gerber mean stress correction and infinite life of 10^6 are used in this study [7]. The scale factor 0.1 that means the force of 20000N moves along these two SAE diagram for analyzing the fatigue life is entered in the modelling.

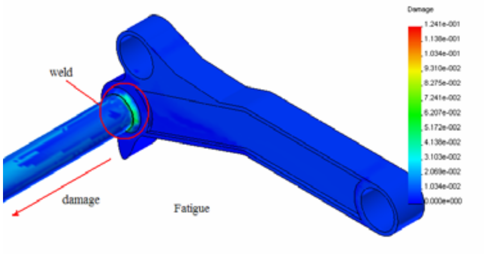

Fig. 14 Failure on weld toe due to fatigue (right)

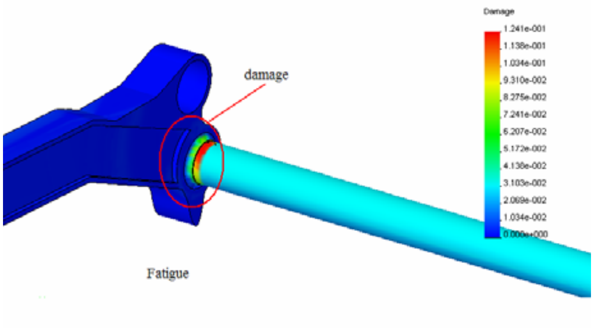

Fig. 15 Failure on weld toe due to fatigue (left)

This scale factor helps to see better from which place crack can grow. The Figs. 14 and 15 show the failure positions in the component. Also, Figs. 16 and 17 represent the random location results to be understood that crack probably grows from the weld toe on tube or HAZ region. As can be observed from Figs. 16 and 17, the most value of damage and the least of fatigue life are in the weld toe. This fact is also indicated in [8], i.e., the weld toe is the most critical location.

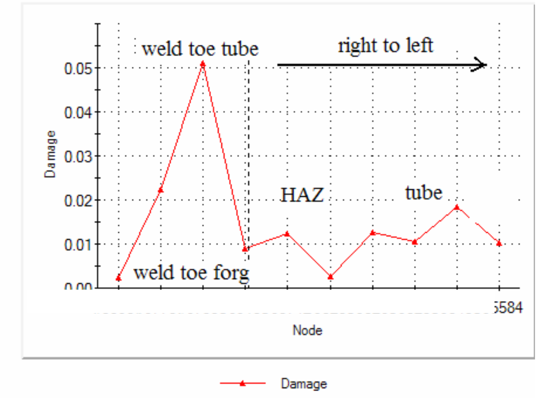

Fig. 16 Damage on component (right)

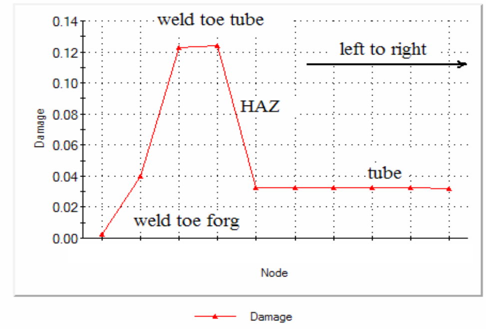

Fig. 17 Damage on component (left)

Rainflow [9] chart is used for cycle counting as shown in Figure 18, and 155 cycles for the worst node to bear these loads is achieved after fatigue analysis is done.

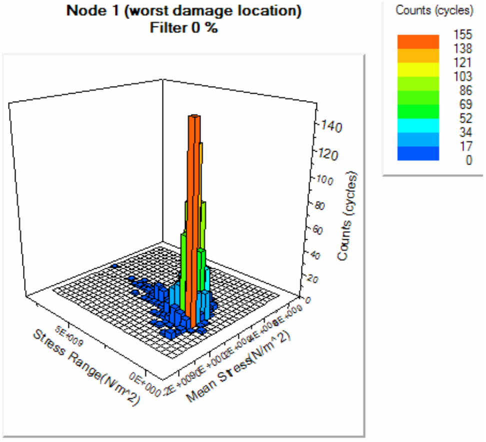

Fig. 18 Rain flow chart of component

Fig. 18 shows that weld toe and weld root tolerate the most stresses and are the worst place that must be fractured. This result is also verified by [10].

V. Effect of Increasing in Leg Length of Weld

In this section the effect of increasing the leg length of the weld on strength of the weld and component is investigated. The weld leg length is changed from 6mm to 10mm that shown in Fig. 19.

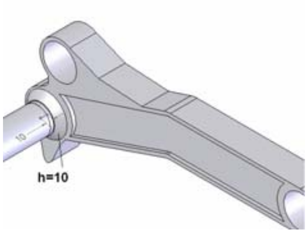

Fig. 19 Weld with leg length 10mm

The position and value of forces and procedure of analysis are the same as the pervious investigation of weld with leg length 6mm. the accuracy of weld meshing and the number of nodes and elements are very important. Mesh size in weld and HAZ region is fine in compare with the other regions as shown in Fig. 20.

Fig. 20 Procedure of meshing

Thermal analysis of the weld with leg 10mm is shown in Figs. 21 and 22. These Figures show that the temperature near the weld and HAZ is higher than other regions.

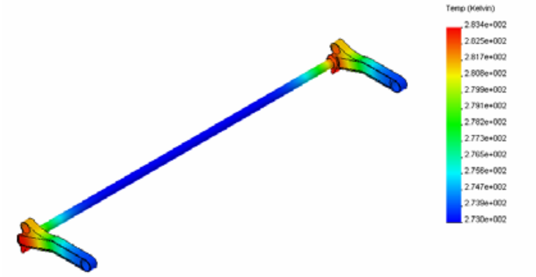

Fig. 21 Thermal analysis of weld with leg 10mm

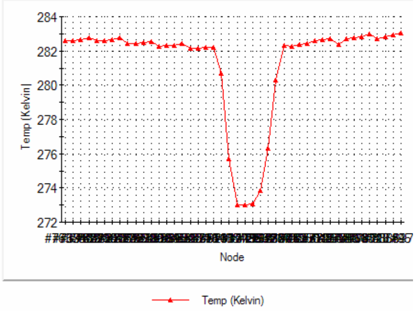

Fig. 22 Thermal analysis of weld with leg 10mm (random from right to left)

In the next step the hinge restraints of the component are considered. The heat of welding process is caused component elongation. This elongation causes force and stress in component especially in sharp edges. Theses stresses are residual stresses that shown in Fig. 23.

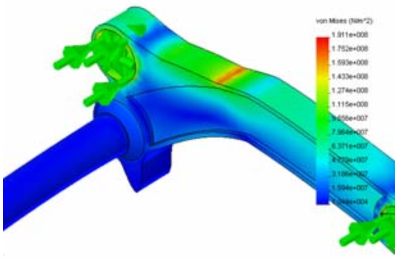

Fig. 23 Residual stress

The residual stresses on the weld toe on tube and forge arm are shown in Figs. 24 and 25 respectively.

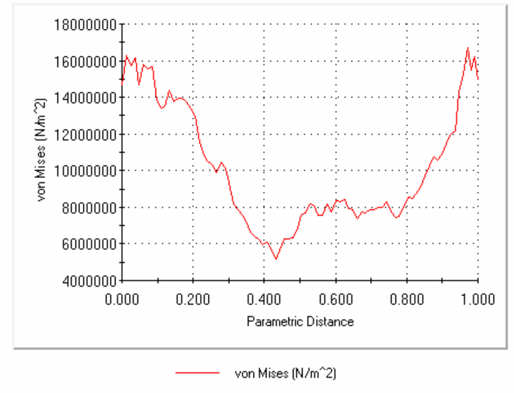

Fig. 24 Residual stress on weld toe on tube

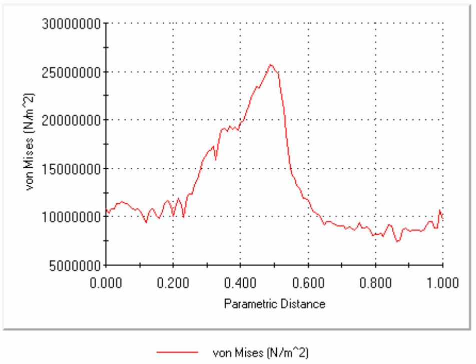

Fig. 25 Residual stress on weld toe on forge arm

These figures show that the increasing in weld leg length, decrease the stress on weld toe on tube and increase the weld strength and the stress on the weld toe on forge arm. These results show the increasing in weld strength and transferring the stress to forge arm.

Then these results are used as an input data for static study. Vertical and horizontal road forces are considered individually that the results have been shown in Figs. 26 to 29.

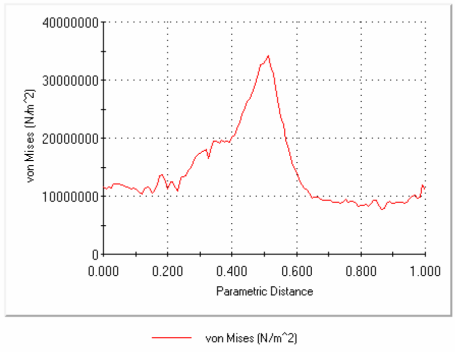

Fig. 26 Stress on weld toe on forge arm (vertical force)

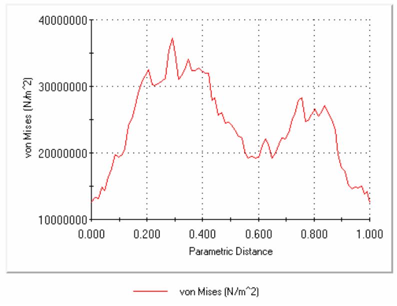

Fig. 27 Stress on weld toe on tube (vertical force)

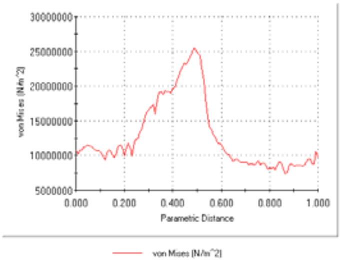

Fig. 28 Stress on weld toe on forge arm (horizontal force)

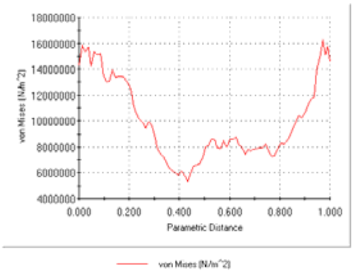

Fig. 29 Stress on weld toe on tube (horizontal force)

If these diagrams are considered the following results are obtained:
1- The increasing in weld leg length is caused in increasing the stress in weld toe on forge arm that means the stress transfers from tube to arm.
2- Stress range is decrease compare with the leg length 6mm.
3- With increasing in leg length, the stress progress in weld is decreased that cause the increasing in life and strength of the weld.

Then the fatigue life is investigated as shown in Fig. 30.

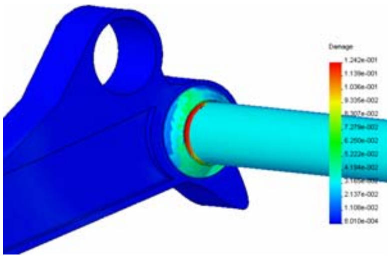

Fig. 29 Fatigue damage with leg length 10mm

The number of cycles that caused failure is calculated with Rainflow procedure that shown in Fig. 31.

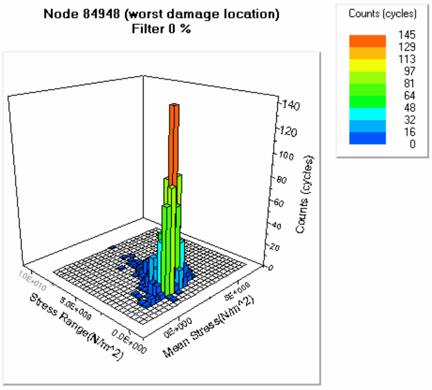

Fig. 29 Rainflow diagram with leg length 10mm

The increasing in weld leg length is caused of increasing in weld strength and decreasing in stress progress in weld. Also the strength of the component may not increase because of sharp edges of the component and stress concentration. For increasing component strength, the reinforcement and stiffeners should be designed. The increasing in weld and component strength must be happened together.

VI. ANALYSIS OF RESULTS

1- Improper overlapping of the weld metal bead at the end and start of the fillet weld resulted in multiple notches in weld metal.
2- Welding of materials with different thickness resulted in deposition of excess weld metal and in the weld bead solidifying in the direction of higher heat flow [11].
3- Cracks initiated from the notches an propagated along the sensitized grain boundaries.
4- The presence of continuous network of grain boundary carbide precipitates in HAZ caused the embrittlement of this zone.
5- The presence of beach and rachet marks on the fracture surface indicates that the failed part subjected to fatigue.
6- Crack may be generated from the weld toe or weld root because of stress concentration.
7- Defining the scale factor and increasing the value of vertical and horizontal force result in recognizing the critical points of weld and component.
8- the increasing in weld leg length is caused in increasing the strength and decreasing stress progress in weld.

VII. CONCLUSION

These failure analysis shows that welded joints between materials of different thickness need to be carried out with extra precautions as follows:
1- Choice of suitable joint design to ensure equitable distribution of heat across joint.
2- Use of low heat input during welding, even if low carbon stainless steels are used, for avoiding sensitization in the HAZ.
3- There is high stress in the weld toe that consequences crack and fracture generation.

4- It is recommended to reduce stress concentration by rounding the edge of fillets and heat treatment of weld and use of the proper material [11].

5- It is recommended that use the weld with higher leg length and use heat treatment in weld region for releasing the stresses.

REFERENCES

[1] Kato, B., Morita, K., The strength of fillet welds, International Institute of welding Document; Vol. 10, 267-69, 1996.

[2] Mellor, B.G, Rainy, R.C.T., Kirk, N.E., The static strength of end and fillet weld connections, Material and Design, Vol. 20, 193-205, 1999.

[3] Stephens, R., Fatemi, A., Fuchs, H., Metal fatigue in engineering, 2nd edition, USA, 2001.

[4] Cieslak, M.J., Ritter, A.M., Savage, W.F., Solidification cracking and analytical electron microscopy of austenitic stainless steel weld metals, Weld Journal, Vol. 61(1), 1s-8s, 1982.

[5] Ho, N., Lawrence, F.V., Predicting the notch root stress of weld from remote strain measurements, Urbana-Champaign: University of Illinois, 1996.

[6] Bulter, L.J., Kulak, G.L., Strength of fillet welds as a function of direction of load, Weld Journal, Vol. 36, 231s-234s, 1971.

[7] Gurney B., Fatigue of welded structures. Cambridge, UK, Cambridge University Press, 1979.

[8] Sleczka, L., Low cycle fatigue strength assessment of butt and fillet weld connections, Journal of Constructional Steel Research, Vol. 60, 701-712, 2004.

[9] Taylor, D., Barrett, N., Lucano, G., Some new method for predicting fatigue in welded joints, International Journal of Fatigue, Vol. 24, 509-518, 2002.

[10] Teng, T., Fung, C., Chang, P., Yang, W., Analysis of residual stresses and distortion in T-joint fillet weld, International Journal of Pressure Vessels and Piping, Vol. 78, 523-528, 2001.

[11] Das, C., Bahduri, A.K., Ray, S.K., Fatigue failure of fillet welded nozzle joint, Engineering Failure Analysis Journal, Vol. 10, 667-674, 2003.