Simulation of Cyclic Stress-Strain Behavior of S960 at Weld Toe by means of Finite Element Method

Mohammad Dabiri, Timo Björk

Abstract

The cyclic stress-strain response of S960 at the toe of fillet-welded joint has been simulated by means of finite element method in order to gathering the needed data for fatigue life prediction process. The Femap software (Version 11.0.0) with NX Nastran 8.5 as its solver has been used in this simulation work. Since the special emphasis is on analyzing the cyclic behavior of weld toe and the softening effect on its cyclic behavior, for making a more accurate and realistic simulation, the 3D finite element model has been analyzed in two different categories: homogeneous (no softening) and inhomogeneous (with softening). The final cyclic stress-strain curve (CSSC) based on the stress and strain changes at weld toe for both cases have been obtained and compared.

Keywords: Cumulative damage fatigue; Numerical simulation; Cyclic stress-strain curve; Softening; Weld toe; Ultra high strength steel

1. Introduction

Most mechanical components contain structural discontinuities and more local notches that result in localized regions of stress concentration. In order to conduct fatigue analyses of notched components it is often necessary to accurately characterize cyclic states of stress and strain where considerable localized plasticity can occur. The detailed evaluation of stress-strain at a notch like weld toe, is a formidable problem. For a more refined analysis, finite element codes are commonly utilized by engineers. Fully reversed load histories which can be set in different methods are applied to finite element models to analyze their cyclic responses. Among these methods, the incremental step and multiple step tests can be named which have widespread use in experimental tests. In this study, these load histories have been changed to a modified load history used in FE modeling section.

Based on a comprehensive study [1], the effect of HAZ in compare to stress concentration factors caused by geometry of weld toe on fatigue strength is insignificant and negligible. However, the hardness reduction because of softening can lead to a big change in cyclic response of weld toe. This matter has been analyzed and addressed in this study as well.

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2. Material Properties

The material used in this study, is a Rautaruukki Corporation product known as Optim QC. This family of ultra-high-strength steels offers high strength and good workshop properties and is not directly compliant with any standards for structural steels. The grade 960QC has been chosen in this study and its properties can be seen in Table 1.

The measured values in Table 1 have been used in modeling in order to get realistic results. For defining the material behavior in FE modeling, the cyclic material parameters are needed which have been gained according to uniform material law [2]. For steels, cyclic strength coefficient (H') can be obtained according to (1).

$$H' = 1.65\sigma_u \qquad (1)$$

where σ_u is the ultimate tensile strength. The cyclic strain hardening exponent (n') can be considered as 0.15 for steels [2].

3. Hardening rules

Two or more plasticity relations are embedded in commercial codes (isotropic, kinematic, and combination) in finite element software. Both of these methods utilize von Mises yield surface and may give similar or identical results for monotonic loading but can give different results for a load reversal. Some tests had been done numerically to illustrate the difference between these two [3].

A kinematic hardening rule predicts that reversed yielding will occur once the stress has changed by the amount of $2\sigma_0$. However, the isotropic rule predicts that reversed yielding will not occur until a compressive stress equal to $-\sigma_0$ is reached. This fundamental difference between the two approaches is responsible for substantial discrepancies when each are used to model cyclic stress-strain response in identical finite element geometry [3]. Therefore, kinematic hardening predicts the *Bauschinger effect* while isotropic hardening does not.

Table 1: Mechanical properties of BM

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Impact Strength	
			Temperature (°C)	Charpy V ($\frac{J}{cm^2}$)
Nominal 960	Nominal 1000	7	-40	34
Measured 1002	Measured 1126	12.5	-40	50

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4. FE modeling

The purpose of simulating the cyclic stress-strain response is to determine the parameters necessary for cumulative damage fatigue analysis. Information such as stress amplitude, mean stress, elastic and plastic strain can be determined for each reversal in the load history. The use of finite element method for obtaining the design stress information which is needed to perform a fatigue life calculation requires good understanding of the principles of the FEM and the concept behind the fatigue assessment methods.

In order to improve the accuracy of fatigue life prediction, the simulation of cyclic stress-strain evolutions is an essential step and to calculate local strain, finite element method is adopted as a powerful numerical tool for the local strain analysis. The simulation has been done by Femap software (Version 11.0.0) with NX Nastran 8.5 as its solver. The geometry, modeling methods, and loading methods have been explained in their separated sections. The weld toe geometry has to be modeled precisely in order to obtain reliable results for the notch strain and it should be noted that the strain in weld toe region is influenced by the mesh size, so mesh size should be fixed as a reference model.

4.1 Specimen geometry

The geometry and dimensions in front and top views are as shown in Fig. 1. The model is a non-load carrying cruciform-welded joint. Thanks to having three planes (XY-XZ-YZ) of symmetry, it is possible to just model one eighth of the specimen. It helps having a perfect mesh sizing and quality at weld toe and getting the results faster. After dividing the model into eight, the final model would be like the Fig. 2. Because of having clamps in the experimental test, the flat tip surface has been cut in modeling and just the free part has been considered. Based on previous research [4], modeling no contact between non-welded roots leads to conservative results, but the weld root has been modeled as a sharp edge root with 0.1 mm gap to make the more realistic simulation.

4.2 Loading method

It is not possible to control the strain amplitude and keep it in desired range at weld toe by software and strain is only available in post-processor after solution. To overcome this problem in finite element software, a method called 'soft sensor' has been suggested which has a similar function as a strain gage is applied in experimental test [5]. In this study, the displacement has
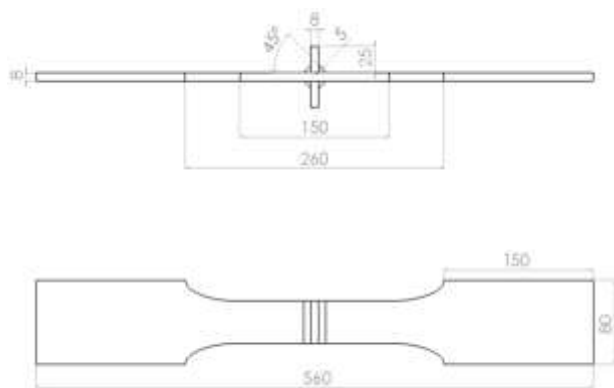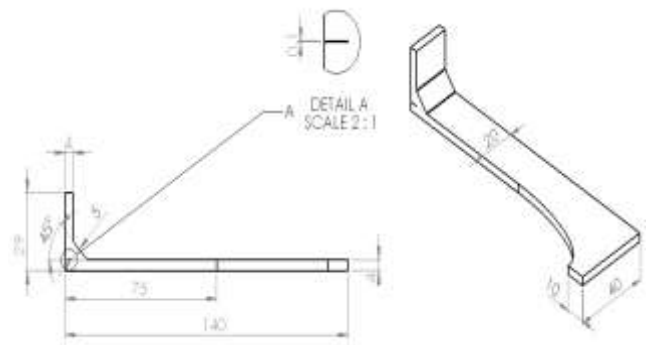

Fig. 2: Specimen geometry used in FE modeling

been used as the load input with narrower cycles of displacement to keep the material behavior in plastic zone and get the more distinctive loops, considering the material behavior. Thanks to using the numerical method, there is no need for repetition of cycles for getting the hysteresis loops and one block from zero to maximum would be satisfactory (Fig. 3). Two first steps have been merged to enter the model into the plastic zone faster.

4.3 Homogeneous model (no softening)

As the first step, the behavior of material has been defined by using the Ramberg-Osgood relationship (2). This relationship cannot be solved explicitly for stress. It provides a single smooth curve for all values of σ and does not exhibit a distinct yield point.

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{H'}\right)^{\frac{1}{n'}} \qquad (2)$$

where H' and n' are standing for cyclic strength coefficient and cyclic strain hardening exponent, respectively and have been replaced by value from (1). E is Young's modulus which has been considered 210 GPa. After substitution of the values, the material behavior curve can be gained. However, the yield strength may be defined by aid of some methods, such as *offset method* [6]. In this method, a straight line is drawn parallel to the elastic slope, E, but offset by an arbitrary amount.

The most widely used and standardized offset for engineering metals is a strain of 0.002. Note that the offset strain is a plastic strain and would be the unrecovered strain. Therefore, using this method can give us a distinct yield strength. This value (732 MPa) can be considered as cyclic yield strength of material which is less than monotonic value.
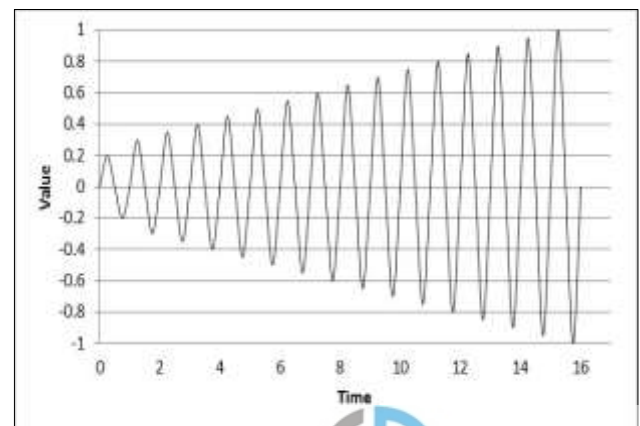

Fig. 1: Geometry and dimensions (mm) of the specimen

Fig. 3: Load history used in FE modeling

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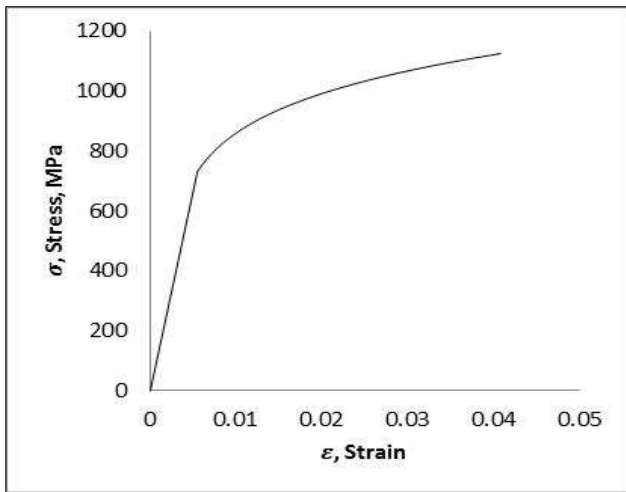
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Fig. 4: Base material behavior curve

$$\sigma'_0 = H' (\varepsilon)^{n'} \qquad (3)$$

The final base material behavior curve has been gained as shown in Fig. 4. The elastic part has been considered as a straight line to overcome the errors during simulation in software.

The displacement has been used as the applied load with mentioned histories in section 4.2. The most important part is putting a refined mesh on the desired place. Because of using the displacement as the load, the area from clamp to weld toe should be modeled. Otherwise, the effect of this part on the weld toe strain would be missed. The rough mesh has been put on no-desired areas (Fig. 5), such as back of attachment, root, and areas close to clamps to decrease the calculation time. The model contains 47830 tetra 10-noded solid elements and 72020 nodes. The toe angle is 45 degree and the radius has been considered as 0.5 mm in order to have the maximum similarity to the real test. As mentioned, the strain at weld toe is sensitive to the mesh size and density. Therefore, double attention is demanded to mesh the weld toe area. The choice of mesh size is decided after considering available computer capability.
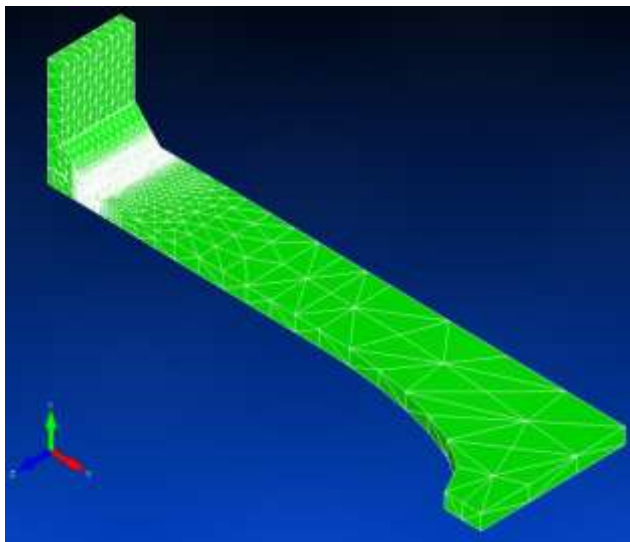
4.4 Inhomogeneous model (with softening)

The same material behavior has been modeled for this case, but because of taking the softened area into consideration in heat affected zone, new material behaviors should be modeled for special areas. The softened area has been considered and new material behavior has been defined for this area based on the changes in hardness. The hardnesses and areas can be seen in Table 2 and Fig. 6, respectively. The average values have been used to get the new tensile strength for areas. The width of areas is 0.5 mm and (4) can be used in order to get the tensile strengths [7].

$$0.5\sigma_u = 1.6H_V \qquad (4)$$

These tensile strength values can be obtained by ISO 18265 as well. After getting the new tensile strength values, the (1) can be used to obtain different cyclic strength coefficients for these areas. All the obtained values have been collected in Table 3.

Finally, the Ramberg-Osgood relation (2) has been used to define the behavior of material in softened areas. The ISO values have been considered in calculations. The same method (offset method) has been used to determine the yield strengths. The cyclic yield strengths are 732, 678, 673, and 611 MPa for main plate, area1, 2, and 3, respectively. The main material behavior along with three softened areas curves have been illustrated in Fig. 7.

Table 2: Different hardnesses

Area		1	2	3
Hardness (HV)	Starting point	319	330	314
	Ending point	330	314	271
	Average	324.5	322	292.5

Fig. 5: Meshing outline
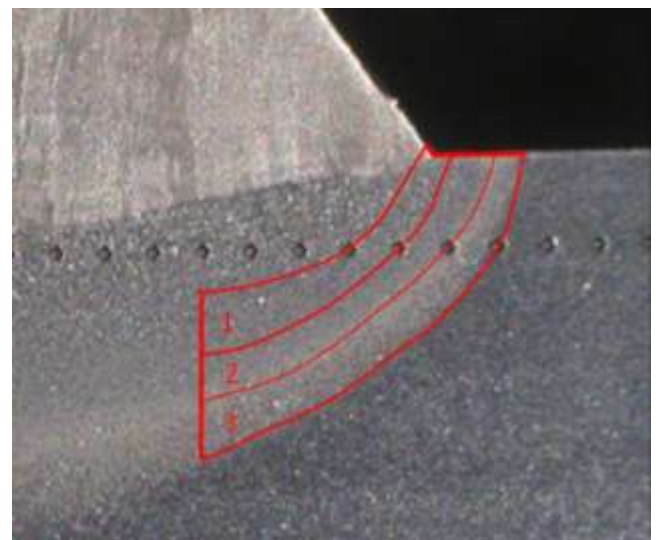
Fig. 6: Softened areas under weld toe

Table 3: Different tensile strengths

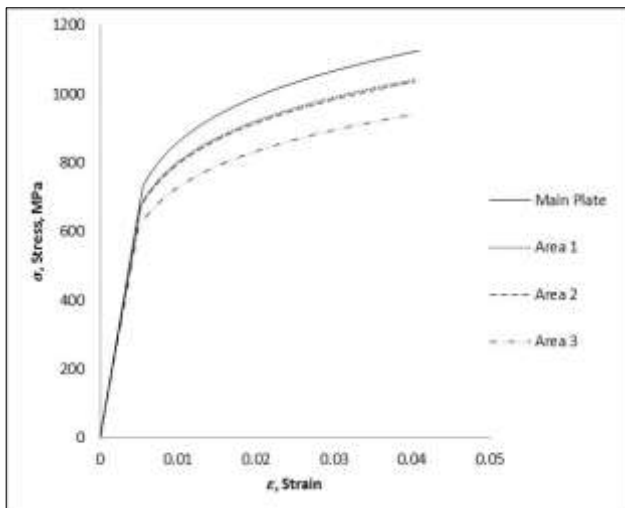| Area	1	2	3
Tensile strength (MPa) "Murakami equation"	1038	1030	936
Tensile strength (MPa) "ISO 18265"	1043	1036	940
Cyclic strength coefficient	1721	1709	1551

Fig. 7: Main plate and softened areas behavior curves

The load history, constraint conditions (symmetries), and mesh sizes and densities are the same as homogeneous case. The only difference is consideration of softened areas beneath the weld which have been shown in Fig. 8. Because of analyzing the weld toe on the main plate, no softened area on the attachment has been considered.

5. Results and comparison

In case of strain, the maximum values are near the free edge of the model which is because of free-side effect which has direct effect on the stress in this area. In order to obtain the cyclic stress-strain curve (CSSC), this matter should be taken into account, so the element with maximum stress and strain among the elements with
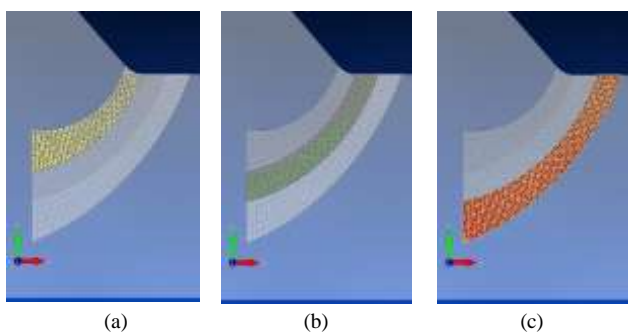

(a) (b) (c)

Fig. 8: Softened areas in FE model a) area1 b) area2 c) area3

distance of 2.5 to 3 mm from the free side should be found. The grouping has been used at weld toe area to find the exact element.

Plotting the results, gives us sixteen loops which 2 of them are in elastic area and from the third step, the model goes to plastic area and the loops have been formed. The overlapped hysteresis loops for homogeneous and inhomogeneous models have been shown in Fig. 9. In order to obtain the CSSC, the tips of hysteresis loops with maximum stress and strain values should be joined to each other (Figs. 10-11). It can be seen that because of reduction in hardness, the plastic deformation starts in earlier stages of loading and the inhomogeneous model reaches to tensile point earlier than homogeneous one. Since the main goal is analyzing the effect of softening on cyclic stress-strain behavior of weld toe, changing the element numbers, load history, and displacement are not allowed.
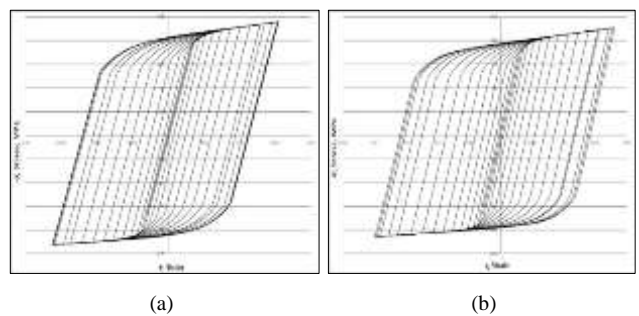

(a) (b)

Fig. 9: Cyclic stress-strain responses of (a) homogeneous and (b) inhomogeneous models at weld toe
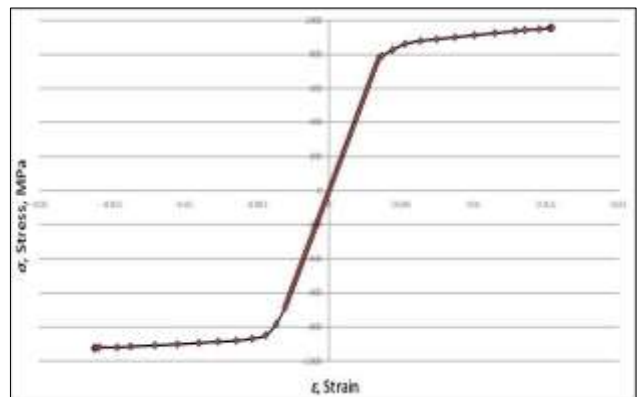

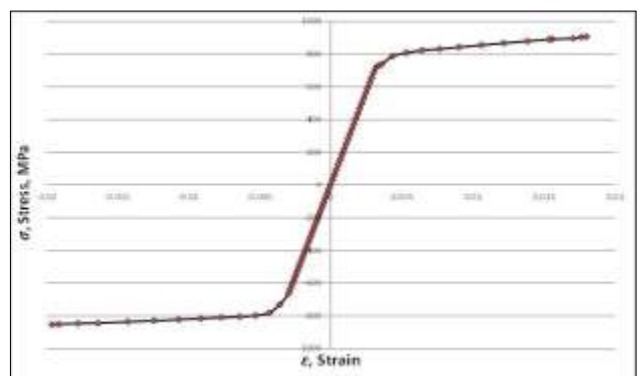Fig. 10: Connected tips of loops and CSSC of homogeneous model at weld toe

Fig. 11: Connected tips of loops and CSSC of inhomogeneous model at weld toe

33

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In order to compare the results and final CSSC for two different models, both curves have been illustrated in Fig. 12. It can be seen that softening and reduction in hardness especially in the areas close to weld toe can have a big effect on its cyclic behavior. The softening causes the earlier start of plastic strain in model. The relationship between hardness in softened areas and plastic strain has been illustrated in Fig. 13. The plastic strain, ε_p, has been started earlier in inhomogeneous model.

6.   Conclusion

The comparison of two FE models resulted in the following conclusions:

- Although the decrease in fatigue strength is influenced more significantly by the effect of the geometry of weld toe than by the softening effect based on previous studies [1,8], this study implies that softening can also have a big influence on the fatigue behavior of steel materials.

- The virtual material behavior has been used for main plate and softened areas in FE modeling. Having the exact values of material cyclic parameters from experiments can lead to more realistic results.

- Finite element modeling of cyclic loading should be conducted with a kinematic rather than isotropic hardening rule because of taking the Bauschinger effect into consideration. If more detailed data are available from cyclic material testing, modifications to both kinematic and isotropic hardening models can be made to increase the accuracy.

- Strain at weld toe is significantly influenced by mesh size, so double attention must be paid to element sizes in this area. In this study, the maximum number of elements has been calculated based on the available computer capability. Therefore, making a more condensed mesh especially at weld toe can lead to more realistic results.
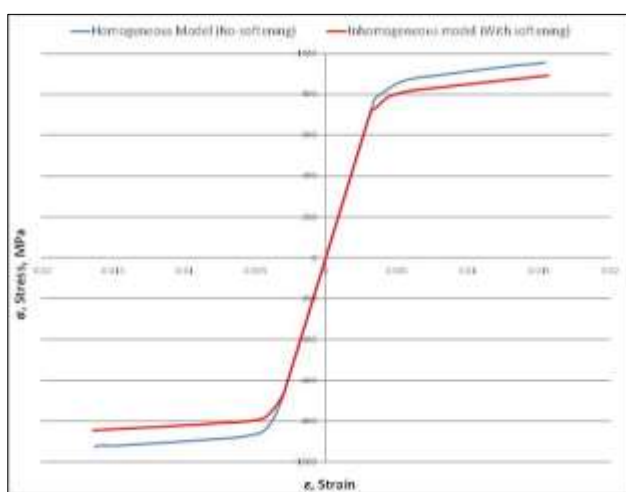

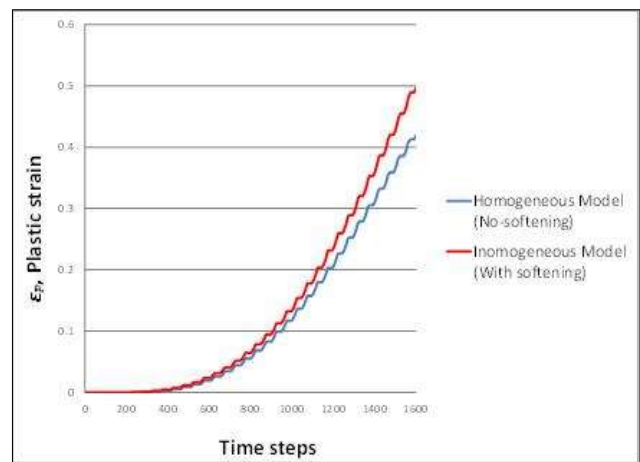Fig. 12: Comparison of CSSC at weld toe for two homogeneous and inhomogeneous models

Fig. 13: Plastic strain at weld toe

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The hardness reduction because of softening can lead to a big change in cyclic behavior of weld toe.