Effect of Burr Grinding on Fatigue Strength of Steel Butt-Welded Connections

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Received: 6 January 2018, Revised: 2 February 2018, Accepted: 8 April 2018

Abstract: Among assembling methods, welding is most widely used in various industries. During the welding operation, material is heated to a temperature above the melting point and melted material forms a weld pool. This leads to the formation of tensile residual stresses in the weld toe. In this paper, effect of burr grinding technique on fatigue strength of butt-welded joint has been evaluated. Burr grinding is one of the weld geometry modification methods that with removing small crack-like defects at the weld toe and increasing weld toe radius leads to reduction of stress concentration factor (SCF) and improvement of fatigue strength of weld. Also, the finite element simulation was performed by using ABAQUS software and stress concentration factor was chosen as a criterion. This factor was calculated using analytical and numerical methods for samples before and after grinding. Burr grinding procedure on welded samples was done using an electric grinder and different conical burrs. Burrs with different radii have been selected in order to provide a better comparison. Fatigue life of samples before and after grinding was determined by fatigue tests under constant amplitude loading. The results show 43.72 percent improvement in stress concentration factor and 50.61 percent improvement in fatigue life of samples. In experimental study, the best result belongs to grinding with a 3 mm tapered burr leading to an improvement of 50.61% in fatigue life while grinding with 1 mm tapered gives the worst result of 8.88% improvement in fatigue life.

Keywords: Burr grinding, Fatigue strength, Stress concentration factor butt weld

Reference: Abbas Fadaei and Annette Betkhoodu, “Effect of Burr Grinding on Fatigue Strength of Steel Butt-Welded Connections”, Int J of Advanced Design and Manufacturing Technology, Vol. 11/No. 2, 2018, pp. 15-25.

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1 INTRODUCTION

Welding is a critical technique in the field of connecting parts in the industry and is one of the production methods. Its purpose is permanent connection of engineering materials such as metals, ceramics, polymers and composites to each other. Welding defects, welding geometry such as toe radius and the pattern of tensile residual stresses, have a significant impact on fatigue strength of welded connections and weld failures. During the welding operation, welding zone experiences high temperature differences compared to the surrounding area. Under thermal loads, the material expands and the environment is an elderly inhibition and this leads to excitement of stresses. Since the yield strength decreases with increasing temperature, these stresses often exceed yield stress which results in development of tensile residual stresses in weld toe. As a result, welded connections have less fatigue strength in relative to base metal. Weld toe is the main source of fatigue cracks due to stress concentration. In this zone, impact of stress concentration increases because of the presence of defects; hence, fatigue cracks are ready to initiate and develop.

Recently, improving the fatigue strength of welded connections using different methods has attracted much attention. Most of these methods have been developed in years between 1960 until early 1970. In general, weld fatigue improvement methods can be divided into two main groups [1]: weld geometry modification methods and residual stress methods. The former removes weld toe defects and/or reduces the stress concentration. The latter introduces a compressive stress field in the area where cracks are likely to initiate. Many parameters influence on the performance of different weld fatigue improvement methods such as material of the weldments, loading conditions, type of welding process, welding configuration, and the skill and ability of operator. To improve the repeatability of the methods and to increase the degree of the efficiency of the methods in the operating conditions, an inter-laboratory test program was investigated by Haagensen [2] for International Institute of Welding (IIW) in 1995. Thirteen labs in ten countries took part in this program preoccupied the three universally methods including burr grinding, tungsten insert gas (TIG) dressing and hammer peening.

Clegg et al. [3] studied the impact of seven toe improvements on the fatigue resistance in structural steel plate weldments to appoint which one of the methods possesses the better effect in modifying the fatigue life. For each of the improvement method, S-N curves were obtained by testing the specimens in the bending condition. Based on the test results, the treatments including weld toe grinding, hammer peening and ultrasonic impact produced the better fatigue resistance. Pedersen et al. [4] compared three post weld treatments for improving the fatigue life in the welded joints. They studied burr grinding, TIG dressing and ultrasonic impact (UI) treatments for medium cycle area, i.e. 10000-500000 cycles, and very high stress ranges. This study shows that the fatigue resistance of the specimens from the three improvement treatments was nearly similar, so that the fatigue strength was increased 31% by burr grinding, 33% by UI treatment and 38% by TIG dressing.

Tai et al. [5] considered the fatigue strength improvement of out-of-plane gusset plate specimens by burr grinding and hammer peening treatments. The specimens were tested in high-cycle fatigue condition with constant and variable amplitude loading. They concluded that the fatigue life can be increased by the reduction of stress concentration using the burr grinding treatment. Baptista et al. [6] presented the fatigue behavior of Duplex S31803 and Austenitic 304L in air and 3% NaCl solution as welded and toe grinding treatment. The results were indicated that the fatigue strength of the toe grinding specimens was greater than the as welded specimens. Knight [7] used burr grinding and disc grinding methods for improving the fatigue strength of the weldment. He found out that in high cycle, fatigue strength improvement using burr grinding of weld toe is about 100% and for disc grinding is about 40%.

Mohr et al. [8] published the results of applying different improvement techniques on cross welded samples. They have proved that fatigue improvement of samples due to grinding is a factor of 2.2. Data have been collected from researches in United States of America, Canada, England and Norway. Kirkhope et al. [1], [9] used fatigue life improvement methods in ship structures. The results had been provided in two different papers; in the first one, published data for improving the fatigue life and applications of fatigue life improvement methods to ship structure were identified. In the second paper, suitable techniques for ship structures were considered. It has been shown that burr grinding, TIG dressing and hammer peening treatments for ship structure applications comprise more potential and the fatigue life was increased approximately 120% for all specimens treated by the toe grinding. Pang [10] analysed the stress in as-welded and weld toe ground fillet weldments. The weld toe radii were selected 0.5, 1.0, 2.5 and 5.0 mm. The stress distributions through the plate thickness and the stress concentration factor were assessed and the results of finite element analysis indicated that the toe grinding leads to increase in the crack propagation cycles by up to 53%.

Huther et al. [11] studied more than 300 sets of data for burr grinding and TIG dressing treatments applied to butt joints, T-shape joints and longitudinal joints in a non-corrosive environment. Nguyen and Wahab [12] presented an analytic model to describe the effect of the weld geometry parameters and residual stresses on the fatigue resistance of butt weldments for tensile and bending loading. They deduced that the fatigue resistance can be increased considerably by reducing the radius of weld toe.

In this paper, effect of burr grinding technique on fatigue strength of steel butt-welded connections is investigated. This technique is based on removing surface material from the weld toe, increasing the weld toe radii and reducing the severity of this detail. St 37 is selected as the material for the welding plates due to its numerous applications in manufacturing various structures such as bridges, steel structures and industrial machine components. This paper presents the fatigue results obtained from experimental study for two different conditions (as-welded and weld toe grinded). In order to investigate the geometry effect of burrs on fatigue life, three different burrs are selected. Eventually, SCF results obtained from simulations (numerical method) are compared with results of analytical method.

2 BURR GRINDING

The intensity of the stress concentration in weld toe leads to cracking in weldment. The existence of little crack-like flaws increases the stress concentration effect and as a result, flaws extend to depths to a few tenths of a millimetre. Fatigue cracks easily initiate at these flaws and slowly propagate. These flaws can be eliminated or decreased by size using the fatigue life improvement methods and results in delaying the crack initiation or extending the fatigue life. In addition, local stress concentration can be reduced to produce smooth edge across the plate and the weld face [2].

Today, grinding is the most important way to create a smooth surface which can be used in various industries such as aerospace, automotive, transportation, medical devices and electronics which needs high-level quality. The primary aim of the grinding is to remove or reduce size of the weld toe flaws from which fatigue cracks propagate. At the same time, it aims to reduce the local stress concentration effect of the weld profile by smoothly blending the transition between the plate and the weld face. This process is implemented by mounting tool bits in grinding devices. The tool bits are normally burrs which are classified on the basis of materials, hardness grades, tool shapes and grit sizes. The burr grinding treatment is demonstrated in "Fig. 1". As it is shown, burr is positioned on the weld toe and the angle between the tool axis and the horizon should be considered 45-60°. Besides, the angle of tool axis relative to the direction of movement is selected 30-45° and the tool is squeezed or dragged along the weld toe. The treatment should be conducted so that the tool can produce a straightforward-symmetric groove. Generally, the burr grinding should reach to minimum depth of 0.5 mm below any evident undercut [2].

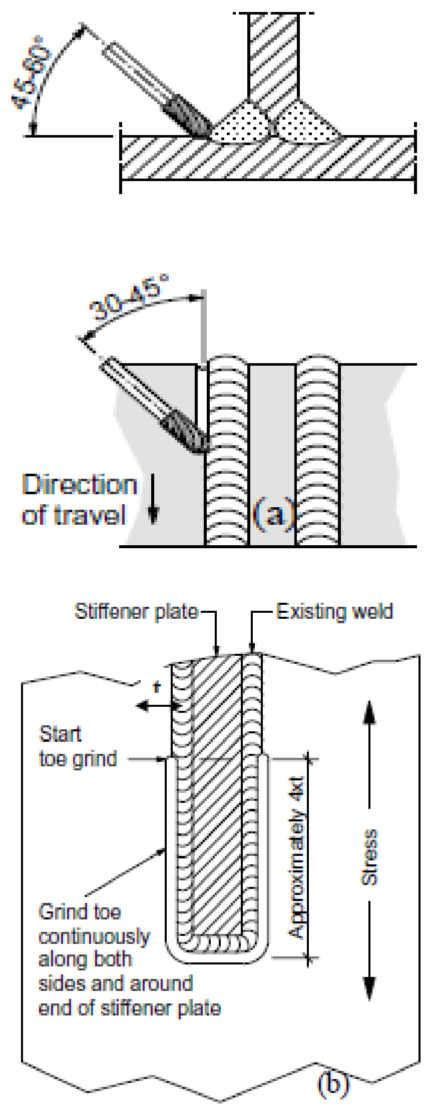


Fig. 1 The burr grinding technique: (a): Side view and (b): Top view [2]

3 EXPERIMENTS

3.1. Welding Specimens

Two St-37 plates with dimension of 300 mm in length, 125 mm in width and 8 mm in thickness were butt welded by the Gas Metal Arc Welding (GMAW) method using CO_2 as protective gas and E7018 electrodes. The cross section of weld was selected according to AWS D1.1 [13]. The test and Standard: BS EN 10025-2 (2004) Grade S235 JR (RSt37-2)-1.0038 chemical composition and mechanical properties of the material are given in Table 1 and Table 2, respectively.

Table 1 The chemical composition of St37 steel

Element	Test, %	Standard, %
C	0.050	Max. 0.190
Mn	0.380	Max. 1.500
P	0.013	Max. 0.045
S	0.008	Max. 0.045
Cu	0.070	Max. 0.600

Table 2 The mechanical properties of St37 steel

	Ultimate strength, MPa	Yield strength,Mpa	Elongation %
Test 1	373	286	41.0
Test 2	375	284	42.5
Standard	360-510	>235	>26

3.2. Fatigue Testing

Fatigue testing was performed under constant amplitude loading by using a 200 KN fatigue testing machine at room temperature and no heating of the specimens occurred. Low cycle fatigue tests using the equipment shown in Fig. 2, were implemented. The stress ratio (R) and frequency were kept at 0.125 and 3Hz, respectively. The final specimen geometry is shown in Fig. 3.

Fig. 2 Fatigue testing machine

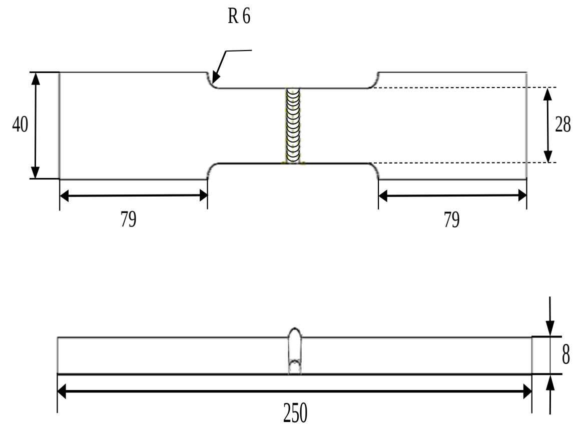


Fig. 3 Test specimen designed for fatigue test (dimensions in mm)

3.3. Weld Toe Burr Grinding

Burr grinding process was performed by an electric grinder with rotational speed 27000 rpm and power of 500 watts. To investigate the effect of burr grinding on fatigue life of welded joints, Tapered burrs in hardness grade M with three different radii were selected. This grade of burrs is manufactured from a mix of dark red and white aluminium oxide in a vitrified bond. This grit combination leads to a good balance between stock removal rate and tool life. The hardness grade M is the most universally used bond for steel and cast steel. Fig. 4 gives an overview of the tapered burrs [14].

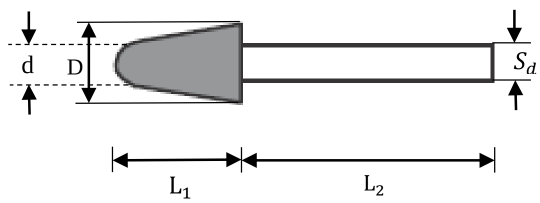
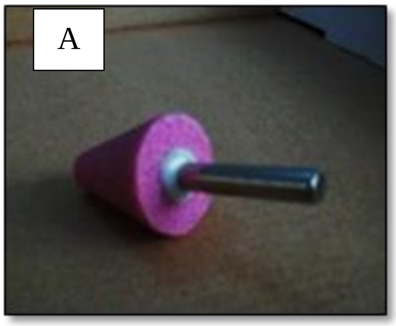


Fig. 4 Dimensions of Tapered burr [14]

Grinding process was conducted by using three different sizes of burrs in order to allow a better comparison. In weld toe burr grinding only the weld toe is machined to remove weld toe defects and reduce the weld toe angle which results in a decrease in the weld toe stress concentration. Therefore, material is removed to a depth of 1mm with respect to the thickness of specimen. Details of burrs used in burr grinding are listed in Table 3 and in Fig. 5, a view of them is shown. In Fig. 6, a grinded specimen is represented.



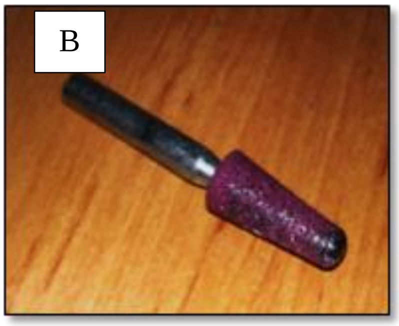


Fig. 5 Burrs used in the burr grinding

Table 3 Dimensions of burrs used for grinding sampling (dimensions mm)

Case	S_d	L_1	L_2	D	d
A	6	18	40	14	2
B	6	25	40	10	5
C	6	40	40	20	6

Fig. 6 Grinded specimen

4 FINITE ELEMENT ANALYSIS

4.1. Welding Simulation

Welding simulation is a thermo-mechanical analysis. In finite element method, there are two distinct approaches: direct method (coupled) and indirect (uncoupled). In this paper, the thermal and mechanical analyses are only sequentially coupled, so the heat effect of the plastic deformation in the mechanical field is neglected during the thermal analysis. As a result, first a thermal analysis is conducted to calculate the transient temperature field used as input data for the second step. The material properties are considered to be temperature dependent but microstructural phase transformation is not considered in order to simplify the analysis [15]. In both temperature dependent thermal and mechanical analyses, the thermo-physical and mechanical properties of the base metal were used in the computations. The material properties of St 37-2 as the function of temperature, including thermal conductivity, specific heat, yield stress, elastic modulus, Poisson's ratio and thermal expansion coefficient were extracted from [16]. The density is considered 7870 Kg/m^3 and temperature independent.

In this research, The Goldak double-ellipsoid heat source model was adopted to calculate the volumetric heat flux distribution as the input heat into the welding pool. The heat source distribution as shown in Fig. 7, combines two different ellipses, i.e. one in the front quadrant of the heat source and the other in the rear quadrant of it. The heat input is modelled by the user subroutine DFLUX which is written as FORTRAN code.

The power densities of the double-ellipsoid heat source, $q_f(x,y,z)$ and $q_r(x,y,z)$ describing the heat flux distribution inside the front and rear quadrant of the heat source, can be expressed as following [17]:

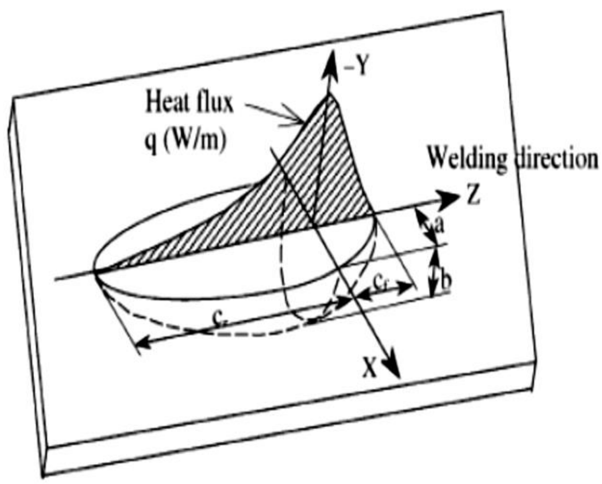


Fig. 7 The Goldak double-ellipsoid heat source model [17]

$$q_f = \left(6\sqrt{3}Qf_f/abc_f\pi\sqrt{\pi}\right)e^{-3\left(\frac{x^2}{a^2}\right)}e^{-3\left(\frac{y^2}{b^2}\right)}e^{-3(z^2/c_f{}^2)} \quad (1)$$

$$q_r = \left(6\sqrt{3}Qf_r/abc_r\pi\sqrt{\pi}\right)e^{-3\left(\frac{x^2}{a^2}\right)}e^{-3\left(\frac{y^2}{b^2}\right)}e^{-3(z^2/c_r{}^2)} \quad (2)$$

In mentioned equations, a is the weld width along the tangent direction x, b is the weld penetration depth along the arc direction y, c_f and c_r are the front and rear weld pool length in the weld path direction z, and f_f and f_r are some dimensionless factors. In order to calculate a and b, the cross section of weld was sanded using different grades of sandpapers in metallographic laboratory to observe its elliptical distribution. Two parameters c_f and c_r were determined using the following relationships [17]:

$$c_f \in (0.5a, a) \quad \& \quad c_r \in (2a, 4a) \quad (3)$$

Two dimensionless factors f_f and f_r were obtained from the following equations [17]:

$$f_f = 2c_f/(c_f + c_r) \quad \& \quad f_r = 2c_r/(c_f + c_r) \quad (4)$$

The calculated parameters of the heat flux distribution are listed in Table 4.

Table 4 The parameters of the heat flux distribution (dimensions include a, b, c_f and c_r are mm)

Parameter	a	b	c_f	c_r	f_f	f_r
Value	6	5	6	18	0.5	1.5

Two kinds of the boundary conditions including convection and radiation were considered in the thermal analysis [11]:

(a)- Heat transfer by convection: Heat transfer by convection occurs in liquids or gases caused by movement of molecules. The Newton's law describes convection with [17]:

$$Q_c = h_c(T_a - T_0) \quad (5)$$

Where T_a is the surface temperature of plate; T_0 is the ambience temperature; and h_c is the heat transfer coefficient due to convection. The heat transfer coefficient is dependent on the flow conditions, the surface and temperature differences between the material and the surroundings and was assumed 15 W/ (m^{2}K) [17].

(b)- Heat transfer by radiation: According to the Stephan-Boltzmann's law the heat flow density of a gray body caused by radiation is proportional to the fourth power of the temperature differences to its surroundings [17]:

$$Q_r = \varepsilon\sigma_0(T_a{}^4 - T_0^4) \quad (6)$$

Where ε, emissivity coefficient, is assumed 0.77 and σ_0 is the Stefan-Boltzmann constant (=5.670 × 10^{-8} W/ (m^{2}K^4)) [8].

4.2. The Weld Joint Geometry and Welding Parameters

Two St-37 plates with dimension of 300 mm in length, 125 mm in width and 8 mm in thickness were butt welded. It was assumed that the base metal and the weld metal have the same thermal and mechanical properties. Fig. 8 illustrates the mesh configuration of the weld plate in the thermal and mechanical analyses. Due to high temperature and the stress gradient near the weld line, a relatively finer mesh was provided and the element size was increased progressively with distance from the weld line. The element birth and death technique was used to simulate the weld passes and the filler metal deposition into the weld pool. In thermal analysis, 5200 elements of DC3D8 (eight-node hexahedral elements) were used for 3D meshing and the same number of elements of C3D8R were employed in mechanical analysis. Welding parameters are given in Table 5.

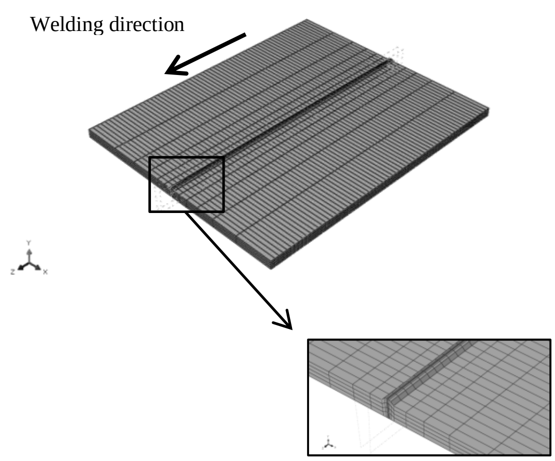


Fig. 8 The mesh configuration of the weld plate

Table 5 The parameters of welding

Parameter/ Pass	Current (A)	Voltage (V)	Speed (mm/s)	efficiency (%)
First	180	20	3.0	70
Second	180	20	1.5	70

4.3. Burr Grinding Simulation

Three different parameters including weld toe radius, grinding depth, and flank angle influence burr grinding analysis. In this paper, the effect of weld toe radius has been investigated and grinding depth and flank angle were assumed 1 mm and 45°, respectively. In burr grinding simulation, just a small fillet at the intersection of weld and base metal was developed resulting in reduction of stress concentration factor. Fig. 9 illustrates weld toe profile after burr grinding.

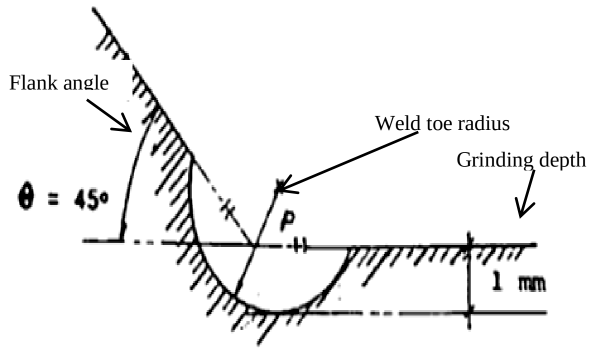


Fig. 9 Weld toe profile after burr grinding [10]

Since this process is carried out at a temperature slightly higher than ambient temperature and amount of material removal is also very low, creating a new model was not required and a new mechanical analysis was submitted by changing geometry of the same model. Therefore, residual stress field due to welding of plates was transferred to the grinding model which is the fatigue test sample and then geometrical changes were applied. Fig. 10 shows the grinding model. Simulation of burr grinding was carried out at three different weld toe radii and stress distribution of each was obtained. Different modes of grinding simulation are represented in Table 6.

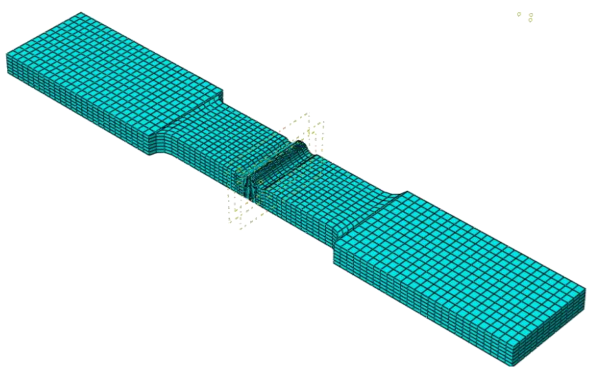


Fig. 10 Grinding model

Table 6 Different modes of grinding simulation

Case	Weld toe radius (mm)	Grinding depth (mm)	Flank Angle (degree)
A	1.0	1.0	45
B	2.5	1.0	45
C	3.0	1.0	45

4.4. Calculation of Stress Concentration Factor

In this paper, the purpose of simulations is finding stress concentration factor by which the effect of burr grinding is investigated. To find out stress concentration factor, both analytical and numerical methods have been employed. In numerical method, after finding stress distribution using finite element method, stress concentration factor is defined as a ratio between local maximum stress in the longitudinal direction and nominal stress [6]:

$$K_t = \sigma_{max}(longitudinal)/\sigma_{nominal} \tag{7}$$

Where K_t is the stress concentration factor.

In order to calculate K_t, the stress analysis including two steps was performed using finite element method. At the first step, stress field due to burr grinding was defined and then at the second step, axial loading was subjected to the end of one side, while displacement at the other side was considered zero. This analysis was carried out before and after burr grinding and for each case stress concentration factor was obtained.

In analytical method, formulae proposed by Gill et al. [18] for prediction of stress concentration factor of butt welded joints were used. As it can be seen, the stress concentration factor is obtained by multiplying the parameters of weld geometry:

$$F(H/T) = 1 - exp[-10.4 \times (H/T)^{0.7}] \tag{8}$$

$$F(W/T) = 1 - \exp[-4.92 \times (W/T)^{1.13}] \tag{9}$$

$$F(\theta) = \frac{\{1 - \exp[-4.10 \times (R/T)^{0.1} \times (\pi/180) \times \theta]\}}{\{1 - \exp[-4.10 \times (R/T)^{0.1} \times (\pi/2)]\}} \tag{10}$$

$$K_t = 1 + 0.322 \times F(H/T) \times F(W/T) \times F(\theta) \times (T/R)^{0.5} \tag{11}$$

Where H is height of weld bead, T is plate thickness, W is width of weld bead, R is weld toe radius, θ is flank angle, and K_t is stress concentration factor.

5 RESULTS AND DISCUSSION

5.1. Results of Welding Simulation

Fig. 11 shows the temperature field of welded plates after 100s from welding start in second pass, when the heat source (electrical arc) was in the middle of the plate at a distance of 150mm from the edge of plate. Elliptical distribution of Goldak heat source can be seen in Fig. 11.

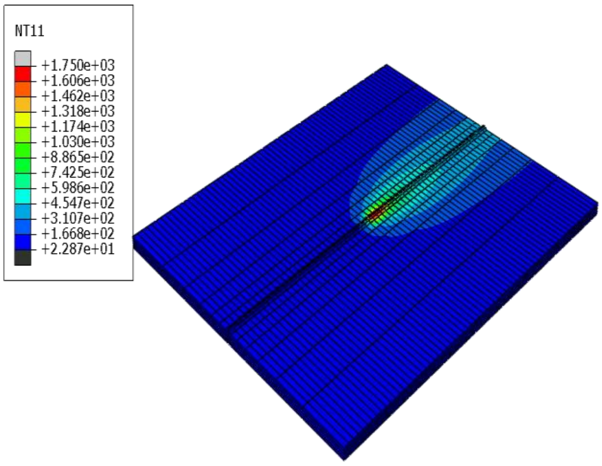


Fig. 11 Temperature field of 100s after the start of welding in second pass

Temperature history for a node in welding direction at a distance of 150mm from the edge of plate is shown in Fig. 12. It was evident from Fig. 11 that the temperature around the torch reached 1750°C. The thermal distribution attained via the Goldak thermal model, indicated that the highest temperature was achieved at the torch location. Then, the temperature gradually drops as the cooling starts and finally reaches the steady state.

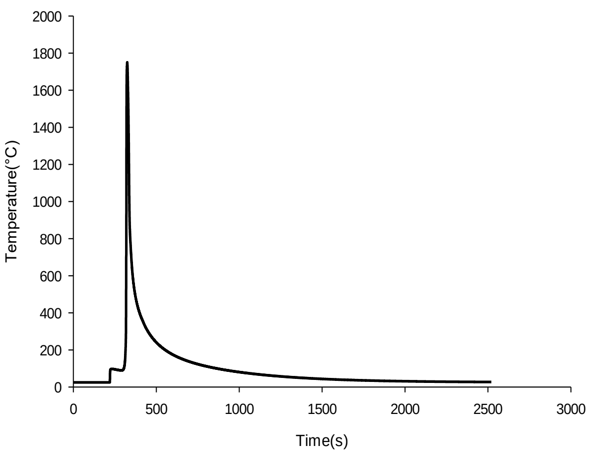


Fig. 12 Temperature history at *z*=150

Fig. 13 shows residual stress distribution along the transverse direction and welding direction. In transverse direction, residual stress around the weld line is tensile due to the thermal gradient of welding and as the distance from weld line to edge of the plate increases, it changes to compressive residual stress.

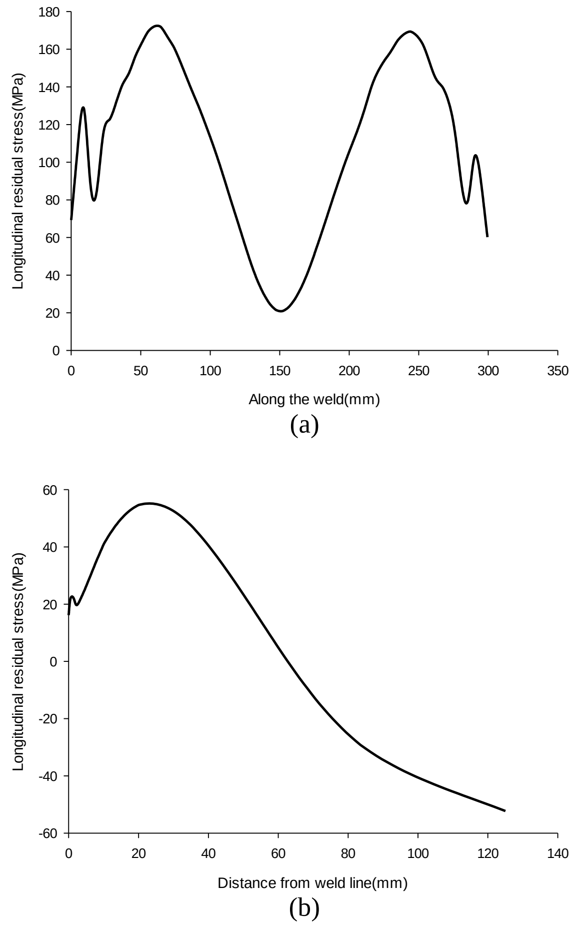


Fig. 13 Longitudinal residual stress distribution along the: (a): welding direction and (b): transverse direction

5.2. Results of Weld Toe Burr Grinding Simulation

Burr grinding method was simulated in ABAQUS by applying geometrical changes at weld toe region. For this purpose, three different cases of burr grinding with three different weld toe radius were analysed. The major aim of simulations is calculating stress concentration factor before and after burr grinding. Stress concentration factor for longitudinal stress and in transverse direction was selected as a criterion for comparison. Longitudinal residual stress before and after grinding has been shown in Fig. 14.

Fig. 14 also indicates that distance between weld line and peak of each graph in which maximum longitudinal residual stress occurs, increases by applying burr grinding. Thus, it is possible to conclude that weld toe grinding which increases the weld toe radii, decreases the local stress levels leading to reduction of stress concentration factor and an improved fatigue life. Stress concentration factors before and after grinding are shown in Fig. 15.

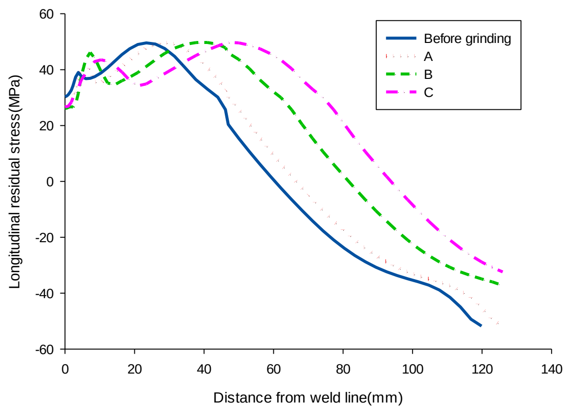


Fig. 14 Longitudinal residual stress in transverse direction before and after grinding

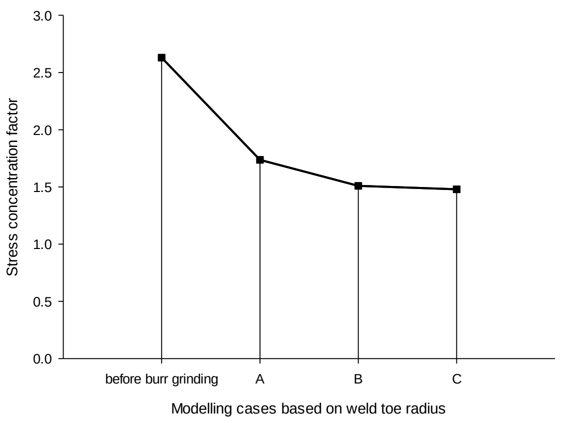


Fig. 15 Stress concentration factors before and after grinding

After modelling weld toe burr grinding with different weld toe radii, a significant reduction of stress concentration factor was observed. This suggests that increasing weld toe radius and smoothing the transition area between weld bead and base plate leads to reduction of stress concentration factor.

5.3. Analytical Results of Stress Concentration Factor

In this section, analytical method has been applied in order to obtain stress concentration factor. Therefore, equation (11) has been used to calculate stress concentration factor before and after grinding and Table 7 shows weld bead geometry and stress concentration factor with respect to weld parameters for all modelling cases in which dimensions are H=2 mm, T=8 mm, W=6.7 mm, R=0.22 mm and θ=61.4º. In order to provide a better comparison between analytical and numerical results, Table 8 has been prepared based on stress concentration factors obtained from both methods before and after burr grinding and the difference percentage between two methods was calculated.

Table 7 Weld bead geometry and stress concentration factor with respect to weld parameters

Parameter/ Case	F(H/T)	F(W/T)	F(θ)	K_t
Before grinding	0.980	0.980	0.964	2.790
A	0.980	0.980	0.977	1.850
B	0.980	0.980	0.983	1.540
C	0.980	0.980	0.984	1.490

Table 8 Comparison between results of analytical and numerical methods

Case	K_t Finite element method	K_t Analytical method	Difference percentage
Before grinding	2.63	2.79	5.73
A	1.73	1.85	6.48
B	1.51	1.54	1.94
C	1.48	1.49	0.67

As it can be observed from Table 8, stress concentration factor results of both methods are in good agreement with each other and the difference between them is acceptable. Moreover, it can be noticed that in both methods increasing of weld toe radius results in reduction of stress concentration factor.

5.4. Experimental Results

The fatigue cycles of samples were obtained according to fatigue tests results. Overall, two samples before and five samples after burr grinding were tested. After burr grinding, fatigue test was repeated for each radius once. Table 9 shows the results of fatigue tests.

Table 9 Fatigue tests results

Before or after grinding	Case	Fatigue life (cycles)
Before grinding	Test	28357
Before grinding	Re- test	30159
After grinding	A	30875
After grinding	B	34356
After grinding	Re-B	36544
After grinding	C	39076
After grinding	Re-C	42710

As it is noticed from Table 9, burr grinding with different radii leads to improvement of fatigue life of welded samples which is due to weld geometry improvement by burr grinding. In burr grinding for cases A, B and C, radius of 1, 2.5 and 3mm was selected, respectively. It is evident that by increasing radius of burr grinding, a better improvement in fatigue life is obtained. This indicates that by increasing the weld toe radii and consequently reducing the severity of the detail, stress concentration factor decreases. For a better comparison, the experimental results are plotted in Fig. 16. Table 10 shows percentage of fatigue life improvement for specimens after burr grinding compared to the test and the re-test results of as-welded specimens.

Fig. 16 Number of failure cycles versus different cases of burr grinding

Table 10 Fatigue improvement percentage of specimens due to burr grinding relative to the test and the re-test results of as-welded specimens

Relative to	Case	Fatigue improvement percentage
The test	A	8.9
The test	B	21.2
The test	Re-B	28.9
The test	C	37.8
The test	Re-C	50.6
The re-test	A	2.4
The re-test	B	13.9
The re-test	Re-B	21.2
The re-test	C	29.6
The re-test	Re-C	41.6

6 CONCLUSIONS

Burr grinding treatment has been investigated as fatigue strength improvement method. In order to validate the improvement effect on fatigue strength, fatigue tests were carried out. The fatigue and finite element analyses results suggested that weld toe treatment by burr grinding can improve the fatigue life. The main findings are summarized as follows:

- By comparing the simulated weld toe grinding specimens with the simulated as-welded specimens, it is clear that weld toe grinding treatment is very successful and leads to reduction of stress concentration factor.
- It is possible to conclude that weld toe grinding which increases the weld toe radii, decreases the local stress levels leading to reduction of stress concentration factor and an improved fatigue life.
- By comparing numerical and analytical methods, it is observed that stress concentration factor results of both methods are in good agreement with each other and the difference between them is acceptable.
- In numerical method, the best result is obtained for a weld toe radius of 3 mm which leads to a decrease of 43.72% in stress concentration factor compared to before grinding.
- In analytical method, the best result is obtained for a weld toe radius of 3 mm which leads to a decrease of 46.59% in stress concentration factor compared to before grinding.
- Experimental results have proved that weld toe burr grinding treatment increases significantly the fatigue life of welded specimens.
- A better improvement in fatigue life of welded specimens is observed by increasing the radius of burrs.
- In experimental study, the best result belongs to grinding with a 3 mm tapered burr (Case C) leading to an improvement of 50.61% in fatigue life while grinding with 1 mm tapered burr (Case A) gives the worst result of 8.88% improvement in fatigue life.

7 NOMENCLATURE

Q	Total heat input rate (W)
A	Weld width (mm)
B	Weld penetration depth (mm)
H	Height of weld bead (mm)
T	Plate thickness (mm)
W	Width of weld bead (mm)
R	Weld toe radius (mm)
q_f	Heat flux distribution inside the front quadrant of the heat source (W⁄m)
q_r	Heat flux distribution inside the rear quadrant of the heat source (W⁄m)
f_f	Fraction of heat in the front quadrant
f_r	Fraction of heat in the rear quadrant
c_f	Front weld pool length (mm)
c_r	Rear weld pool length (mm)
Q_c	Heat transfer by convection (W⁄m^2)
h_c	Convection coefficient (W⁄(m^{2}K)
T_a	Surface temperature of plate (K)
T_0	Ambient temperature (K)
Q_r	Heat transfer by Radiation (W⁄m^2)
K_t	Stress concentration factor
E	Emissivity coefficient
σ_0	Stefan-Boltzmann constant (W⁄(m^{2}K^4)
θ	Flank angle (degree)

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