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Experimental Study on Improving Fatigue Behaviour of Weldment by Grinding Treatment

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Abstract: Fatigue strength of ship hulls has been received increasing attention due to the use of high tensile steels and the increase of stress levels of hulls.The fatigue life of ship structures is mostly dependent on the fatigue life of their weldments.It is important to know the effect of weld geometry parameters on fatigue life and know how to improve the fatigue behaviour of ship structures by practicable and economic methods.In this paper,the influence of weld geometry parameters on fatigue strength of welded structures were analysed firstly,the experiments on simple tension and fatigue specimens that made of steel ABS-A and steel 945 respectively with grinding and as-welded weldments have been performed.The experimental results show that the fatigue life of steel welded joints can be improved by grinding the weld bead,especially for the higher strength steel.The experimental results also show the great difference between manual grinding and machine grinding on improving the fatigue life of butt-welded joints and the scatters of the experimental fatigue lives are very large.The fatigue life improving processes should be studied in more detail.

Key words: butt welded joint; stress concentration; fatigue life; weld grinding

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1 Introduction

Ship and ocean engineering structures today are fabricated by welding. These welded structures are often subjected to dynamic service loads ranging from cyclic fluctuations to completely random loads.The fatigue behaviour of these welded structures is affected by many factors intrinsic to the nature of welded joints and is also greatly affected by the geometry of welded joints.Considerable research on the fatigue of welded joints has been carried out and reported in the literature(e.g.Nguyen and Wahab,1995,1996,1998;Taylor et al,2002)[1-4].However, there are few experimental researches on the fatigue behaviour of welded joints,especially on improving the fatigue behaviour of the welded joints.Grinding techniques are used as a method of improving the fatigue performance of welded components and structure in the offshore, shipbuilding and steel construction industries.The benefit is derived from reducing the stress concentration by producing a favourable weld shape and by removing harmful surface defects and undercuts at the weld toe (Kirkhope et al, 1999; Knight, 1978)[5-7]. Therefore, this experimental study aims to give a quantitative effect of improving the fatigue behaviour of the

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welded joints by grinding techniques.

Because the fatigue failure of butt-welded joints are always initiated at the weld toe, the SCF of weld toe plays a very important role in fatigue failure of welded structures.In this paper,the SCF and its main influence factors of butt welded joints are analysed.The experiments on simple tension and fatigue specimens that made of steel ABS-A and steel 945 respectively with grinding and as-welded joints were carried out.

2 Analysis of weld geometry parameters on fatigue strength of butt-welded joints

Fatigue cracks in fabricated steel structure often occur at welded joints where stress concentrations due to the joint geometry are relatively high. Because the SCF of weld toe plays a very important role in fatigue failure of welded structures,the SCF and its main influence factors of welded joints should be analysed firstly. Nguyen and Wahab (1995) has analysed the effect of weld geometry parameters on fatigue crack propagation life,and pointed out that the degree of influence of various weld geometry parameters on fatigue behaviour of butt welded joints is of the following order:flank angle,weld toe radius,plate thickness,tip radius of undercut and edge preparation angle.The geometry parameters of butt-welded joint are shown in Fig.1.

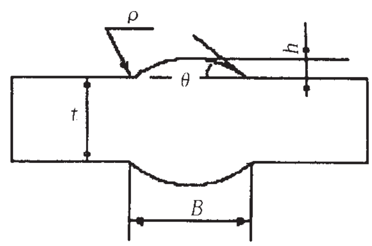

Fig.1 Geometry parameters of a butt-weld joint

The geometric parameters will play a vital role in butt-welded joint fatigue when the stress perpendicular to the weld bead.The flank angles θ are changing along the weld bead,the θ is changing in the range of 20°~35° for joints that were made by manual metal arc welding, and θ is about 30° for joints that were made by automatic welding.The SCF K_t at weld toe of butt-welded joints can be simply expressed as the function of flank angle θ. K_t=1.4~1.6 for θ=20°~35°(CHEN XY,1990)[8].

Li and Cao (1997)[9] studied the influence of weld toe angle (flank angle) and weld toe transition radius on SCF by finite element analysis.The result shows that it is possible to ease the stress concentration of butt-welded joint effective by decreasing the weld toe angle or/and increase the weld toe transition radius.An empirical formula for calculating the SCFs of butt-welded joints has been expressed in the following form (Li and Cao,1997):

$$K_t=1+1.107\rho^{-0.54}(\sin\theta)^{0.193} \quad (1)$$

Hu et al (1994)[10] analysed the statistical distribution of weld toe angle,weld toe transition radius,weld width.An empirical formula for calculating the SCFs of butt-welded joints has been expressed as equation (2).Based on the statistical value of the geometry parameters and equation (2),the SCFs at weld toe of butt-welded joints is varying between 1.2~3.2.

$$K_t=1+0.27(\mathrm{tg}\theta)^{0.25}(t/\rho)^{0.5} \quad (2)$$

Based on equations (1) and (2),the SCFs at weld toe of butt welded joints vary with the flank angle θ and the weld toe transition radius ρ and they can be illustrated in Fig.2 (ρ=0.5,1.0,1.5,2.5 mm, respectively).

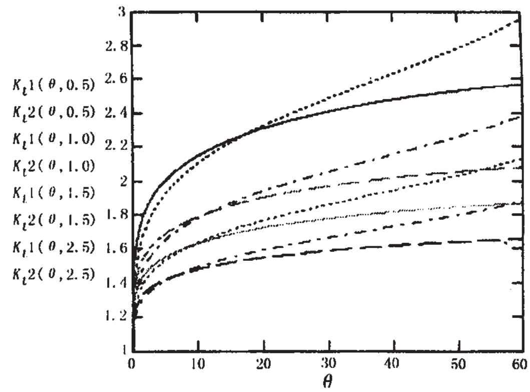

Fig.2 SCFs at weld toe of butt-welded joint varying with θ and ρ

Fig.2 shows the effect of flank angle and transition radius on the SCF of weld toe. It is obvious that the SCF increases as the value of θ increases,and the SCF decreases as the value of ρ increases.It means that the SCF of the butt-welded joint can decrease by increasing the value of transition radius ρ and decreasing the value of flank angle θ.It also shows that the SCF is greatly affected by flank angle in the range of θ=0°~10° and the SCF greatly affected by transition radius in the range of ρ<2.5mm.The SCFs are varying slowly with the flank angle in the range of θ=30°~90°.

The effect of weld flank angle θ on fatigue strength reported by Nguyen and Wahab (1995) was shown in Fig.3. It shows that the S-N curve tends to move from left to right as the value of flank angle decreases.Comparing Fig.2 and Fig.3,it can be found that the effect of weld flank angle θ on fatigue strength is the same as the effect of weld flank angle θ on SCF.So the weld geometry parameters on fatigue strength can be simply treated as the weld geometry parameters on SCF.

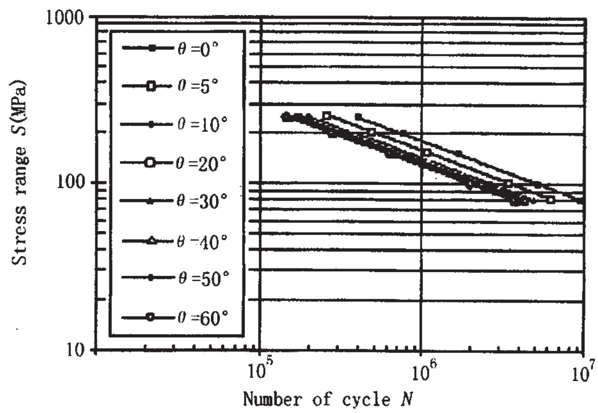

Fig.3 The effect of weld flank angle θ on fatigue strength (Nguyen and Wahab,1995)

It means that the fatigue strength and fatigue life of butt-welded joints can be improved with respect to smaller flank angle or/and larger weld toe transition radius, i.e.to smoother weld bead.The flush ground welded plate will have the highest fatigue strength and this is equal to the fatigue strength of the parent plate (Maddox,1991)[11].

The effect of the height of reinforcement of weld on fatigue strength of butt-welded joint was shown in Fig.4 (Fuchs and Stephens,1980)[12].It shows that the fatigue strength can be greatly improved by removing the height of reinforcement of the weld.

Based on the above analysis,if we want to improve the fatigue strength of butt welded structures by decreasing the flank angle or/and increasing the weld toe transition radius,the value of flank angle should be less than 10° and the weld toe transition radius should be greater than 2.5mm. In this way, improving the fatigue strength of butt-welded structures by removing the height of reinforcement of weld using flush grinding is a practical method.

Knight (1978) gave results for burr and heavy disc grinding as shown in Fig. 5.Results for mild steel and a high strength steel are shown in the figure.The fatigue strength improvement for the higher strength steel is more significant.At relatively high cycles (about 5×10^5 cycles) an improvement in fatigue strength for the toe grinding is almost 100% over the as-welded condition,in the case of heavy disc grinding the improvement is about 40% .The corresponding improvement for the mild steel is about 17% for both treatments.It means that the effect of fatigue improvement by some treatment method is different for different strength steels.The higher of the steel strength, the more dramatic improvement of its fatigue strength.

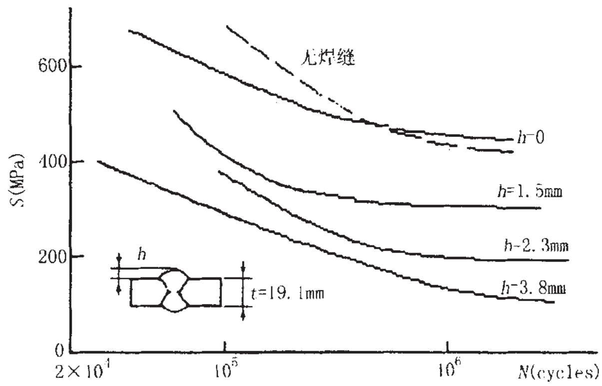

Fig.4 S–N curves of butt welds with different height of reinforcement of weld (S_u=785MPa,R=0)

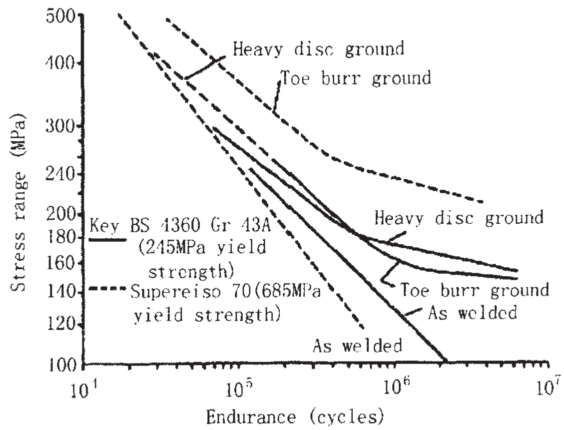

Fig.5 Fatigue strength improvements due to toe burr and disc grinding (Knight,1978)

3 Experimental details

Welded joints were made using automatic submerged arc welding. The materials used were low-carbon steel ABS-A and low alloy steel 945, their mechanical properties were listed in Tab.1. All fatigue tests were carried out at a frequency of 20Hz and stress ratio R=0.1.

Tab.1 Mechanical properties of two steels

Property / Material	σ_s [MPa]	σ_b [MPa]	δ_5 [%]
945	⩾440	550~685	⩾20
ABS-A	⩾235	400~490	⩾22

3.1 Plate specimens

Specimens were made of 6mm thick plate,which were used to determine the mechanical properties of the steel 945 and steel ABS-A by simple tensile testing.The test results were listed in Tab.2 and Tab.3.The mean yield strength and ultimate strength of steel ABS-A are 316.8MPa and 450MPa respectively.The mean yield strength and ultimate strength of steel 945 are 492.5MPa and 575.2MPa respectively.

Tab.2 Tensile test results of steel ABS-A

No.	σ_s [MPa]	σ_b [MPa]
1	320.7	463.1
2	315.3	458.3
3	331.6	464.8
4	315.7	453.8
5	311.5	438.3
6	323.1	451.0
7	308.4	425.4
8	309.2	448.2
9	315.4	450.7
10	317.3	446.7
mean	316.8	450.0

Tab.3 Tensile test results of steel 945

No.	σ_s [MPa]	σ_b [MPa]
1	518.3	578.6
2	471.7	543.0
3	490.0	558.7
4	481.7	571.3
5	500.2	608.3
6	461.2	569.8
7	508.3	583.7
8	483.2	555.0
9	506.7	591.4
10	477.5	552.3
11	507.2	598.3
12	503.4	591.5
mean	492.5	575.2

3.2 Butt-welds

Specimens of butt welds were made of 6mm thick plate,welded from both sides.The specimen size is detailed in Fig.6.The produced height of weld reinforcement is about 1.3mm above the plate surface.The fatigue life test results were listed in Tab.4 and Tab.5.Fatigue cracks initiated from the weld toe.

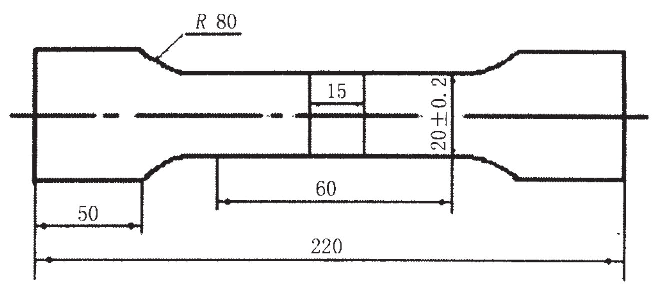

Fig.6 Geometry of test specimens

3.3 Ground butt welds

A series of tests were carried out using butt welds constructed as above which had the excess weld material removed by manual grinding and machine grinding respectively.It was found that cracks initiated rom close to the weld/HAZ boundaries,in similar locations to those observed in the as-welded welds.The fatigue test results were listed in Tab.6 and Tab.7.

Tab.4 Fatigue test results of butt-welded joints of steel ABS-A

No.	Test load [kN]		H[mm]	Fatigue life [cycles]
	P_{max}	P_{min}		
1	36.7	3.6	1.2	187954
2	36.7	3.6	1.2	67915
3	36.7	3.6	1.3	78073
4	36.7	3.6	1.2	87987
5	36.7	3.6	1.2	76641
6	36.7	3.6	1.3	74167
7	36.7	3.6	1.3	104719
8	36.7	3.6	1.2	139880
9	36.7	3.6	1.2	95089
10	36.7	3.6	1.2	156364

Tab.5 Fatigue test results of butt-welded joints of steel ABS-A

No.	Test load [kN]		H[mm]	Fatigue life [cycles]
	P_{max}	P_{min}		
1	47	4.7	1.2	28078
2	47	4.7	1.2	34931
3	47	4.7	1.3	18548
4	47	4.7	1.2	21806
5	47	4.7	1.2	21315
6	47	4.7	1.3	18491
7	47	4.7	1.3	19224

Tab.6 Fatigue test results of butt-welded joints of steel ABS-A

No.	Test load [kN]		H[mm]	Fatigue life [cycles]
	P_{max}	P_{min}		
1	36.7	3.6	0.25	187606
2	36.7	3.6	0.30	200000
3	36.7	3.6	0.32	105687
4	36.7	3.6	0.31	169348
5	36.7	3.6	0.35	95500
6	36.7	3.6	0.36	89466
7	36.7	3.6	0.32	219411
8	36.7	3.6	0.34	141008

Tab.7 Fatigue test results of butt-welded joints of steel ABS-A

No.	Test load [kN]		H[mm]	Fatigue life [cycles]
	P_{max}	P_{min}		
1	47	4.7	0.32	90489
2	47	4.7	0.21	106642
3	47	4.7	0.35	30521
4	47	4.7	0.35	46012
5	47	4.7	0.36	33919
6	47	4.7	0.0	149382
7	47	4.7	0.0	439855
8	47	4.7	0.0	430227
9	47	4.7	0.0	672841
10	47	4.7	0.0	806884

Rem: The specimens of H=0 are machine ground.

4 Results and discussions

For determining the fatigue life increasing degree of ground welded joints, the results of fatigue testing of the ground specimens and that of the as-welded specimens were compared in the way as follows:

Mean value is calculated by

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i$$

Standard deviation

$$S_d=\sqrt{\frac{\sum_{i=1}^{n}x_i^2-n\bar{x}^2}{n-1}}$$

Coefficient of variation

$$C_v=\frac{s}{\bar{x}}$$

Tab.8 Comparation of fatigue life of ground and as-welded butt welded joints

Item	Fatigue life [cycles]			Increase rate[%]
	Mean	S_d	C_v	
ABS-A	106900	38660	0.362	
(as-welded) (ground)	151000	47140	0.312	141.3
945	23200	5689	0.245	
(as-welded) (manual groung)	61520	31110	0.506	265.2
(machine ground	499800	226000	0.452	2154.3

The calculated results were listed in Tab.8. The results show that the fatigue life of butt-welded joints of steel ABS-A and steel 945 increase 41.3% and 165% over the as-welded condition respectively by manual grinding. The fatigue life of machine grinding butt-welded joints of steel 945 increases almost 21 times of that the as-welded joints.It indicates that the fatigue life of butt welded joints can increase significantly by manual grinding, especially for high strength steels. It also shows the great difference between manual grinding and machine grinding on improving the fatigue life of butt-welded joints.It means that the technique parameters of manual grinding should be studied detailed,so as to made it possible to reach the level of the machine grinding in improving the fatigue life of welded joints.

The scatters of the experimental fatigue lives are very large.

5 Conclusions

Fatigue failure of butt-welded joints initiated at the weld toe.The stress concentration and residual stress in weld toe play a very important role in fatigue failure of welded structures.The fatigue behavior of welded structures can improved by decreasing the stress concentration or/and producing compressive residual stress at the weld toe.

Decreasing the flank angle or/and increase the weld toe transition radius can reduce the stress concentration and improve the fatigue behavior of the weldments.

The experimental results on specimens with ground and as-welded welded joints showed that the fatigue life of butt-welded joints can increase significantly by manual grinding, especially for high strength steels.

The experimental results also show the great difference between manual grinding and machine grinding on improving the fatigue life of butt-welded joints.It means that the technique parameters of manual grinding should be studied detailed,so as to made it possible to reach the level of the machine grinding in improving the fatigue life of welded joints.

References

[1] Nguyen T N,Wahab M A. A theoretical study of the effect of weld geometry parameters on fatigue crack propagation life[J]. Engineering Fracture Mechanics,1995,51(1):1-18.

[2] Nguyen T N, Wahab M A. The effect of undercut and residual stesses on fatigue behaviour of misaligned butt joints [J]. Engineering Fracture Mechanics,1996,55(3):453-469.

[3] Nguyen T N,Wahab M A. The effect of weld geometry and residual stresses on the fatigue of welded joints under combined loading[J]. Journal of Materials Processing Technology, 1998,77:201-208.

[4] Taylor D,Niall Barrett N,Lucano G. Some new methods for predicting fatigue in welded joints [J]. International Journal of Fatigue, 2002,24:509-518.

[5] Kirkhope K J,Bell R,Caron L, Basu R I,Ma K-T.Weld detail fatigue life improvement techniques. Part 1: review[J]. Marine Structures, 1999,12:447-474.

[6] Kirkhope K J, Bell R, Caron L,Basu R I,Ma K-T.Weld detail fatigue life improvement techniques.Part 2:application to ship structures[J].Marine Structures,1999,12:477-496.

[7] Knight J W. Improving the fatigue strength of fillet welded joints by grinding and peening[J]. Welding Research International,1978,9(6):519-540.

[8] CHEN X Y. Low cycle fatigue of submarine and underwater vehicle[M]. Beijing: National Defence Industry Press,1990 (In Chinese).

[9] LI D C, CAO L J. Finite element analysis of stress concentration factor of butt welded joints, J.of Xian Petro.Inst.,1997, 12 (1):30-34(in Chinese).

[10] HU B, XUE J C, YANG Y G. Statical distribution of butt welded joints geometry parameters and calculation of Kt at the weld toe [J].ACTA aeronautic & astronautica sinica,1994,15(11):1408-1410(in Chinese).

[11] Maddox S J. Fatigue strength of welded structures[M]. Abington,1991.

[12] Fuchs H O, Stephens R I. Metal fatigue in engineering[M]. John Wiley & Sons,1980.

打磨处理改善焊缝疲劳性能的试验研究

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摘要：由于高强度钢的使用，船舶结构许用应力水平的提高，船舶结构的疲劳强度越来越受到关注。船舶结构的疲劳寿命取决于其焊接结构的疲劳寿命。因此，了解焊缝几何参数对焊件疲劳强度的影响以及采用经济实用的方法改善船舶结构的疲劳性能是十分重要的。本文首先对焊缝几何参数对焊件疲劳寿命的影响进行了分析，在此基础上用 ABS 钢和 945 钢两种钢板做试件，分别进行了简单拉伸实验及打磨和未打磨条件下对接接头的疲劳试验。试验结果表明焊件的疲劳寿命可以通过打磨焊缝得到改善，尤其对于高强度钢焊件。试验还说明手工打磨焊缝和机械磨削焊缝对焊件疲劳强度的改善效果差别很大，疲劳寿命的分散性也很大。因此，应当对改善焊件疲劳寿命的工艺进行更详细的研究。

关键词：对接焊缝；应力集中；疲劳寿命；焊缝打磨

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