

# 銲接程序及銲後處理對鋁合金 6061 銲件疲勞壽命之影響

## Effects of Welding Procedure and Post-Weld Treatments on Fatigue Life of Aluminum Alloy 6061 Weldments

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### Abstract

In this study, gas tungsten arc welding was conducted on aluminum alloy 6061 plates with different welding fillers. Experimentally developed welding filler with addition of Cu, Mg and Si was introduced to generate a more prominent precipitation hardening response. Fatigue testing was performed on weldments treated with various post-weld treatments. The use of high-strength filler results in significantly higher weld metal strength than the conventional welds after post weld heat treatment. The higher joint efficiency allows the weld reinforcement to be removed, which consequently, eliminates the stress concentration at the weld toe, results in largely improved fatigue life of the weldment. Shot peening and surface grinding are also proven to effectively increase the fatigue life by forming compressive stress and reduce surface roughness on the material surface, respectively. During fatigue testing, the surface compressive stress formed by shot peening will be gradually relaxed. The rate and degree of stress relaxation was affected by the stress amplitude.

Keywords: Aluminum alloy 6061, fatigue, welding filler, shot peening, residual stress relaxation.

### 1. Introduction

Aluminum-based alloys are one of the most commonly used metallic materials in industrial applications, especially in transportation industries, high-end automotive, bicycles and fitness products. In the aforementioned applications, 6XXX series aluminum alloys are often chosen as structural components thanks of their low cost, high strength-to-weight ratio, heat-treatable nature and relatively good weldability compared with other heat-treatable aluminum alloys[1-4].

Among 6XXX series aluminum alloy, aluminum alloy 6061 (6061 alloy) is the most popular thanks to its superior mechanical strength [5]. The heat treatment procedures, mechanical properties and welding characteristics of 6061 alloy have been comprehensively studied for decades[6-11]. The highest mechanical property of 6061 alloy can be achieved by T6 temper, which involves quenching the material from a high temperature followed by low temperature peak aging for maximum precipitation hardening effect[12, 13]. However, the intense and abrupt energy input of the welding process often upsets the mechanical strength of 6061 alloy. Over-aging and dissolution of the strengthening precipitates in the heat-affected zone (HAZ) leads to significant drop in mechanical strength[7, 14, 15]. Therefore, the post-weld heat treatment (PWHT) is usually necessary for 6061 alloy weldments to regain its designed mechanical properties[16].

On the other hand, 6061 alloy also suffers from

solidification cracking in the fusion zone (FZ) during autogenous welding[17]. With the combination of low Si and Mg contents, the amount of liquid during the final stage of solidification is relatively low, leading to the formation of solidification cracks along the grain boundaries. Commercial welding fillers ER4043 and ER4047 were developed to prevent such problem by increasing the Si content and the amount of eutectic liquid[17]. However, the weld metals produced by ER4043 and ER4047 are lacking in elements with precipitation hardening potential, which makes the weld metal unable to regain T6 peak strength after PWHT[18]. To overcome this situation, weld metal reinforcement is often necessary in actual industrial practice. Thicker weld metal provides extra strength for the weld joint to meet the desired mechanical specifications.

Fatigue failure is another major problem in the application of aluminum alloys, which is hard to detect and can often cause sudden and catastrophic failure. Hence, the factors affecting the fatigue property of 6061 alloy have also been widely investigated[19-21]. It has been reported that the introduction of welding process also deteriorates the fatigue strength of 6061 alloy from many aspects. Firstly, the decreased mechanical strength of the HAZ significantly reduces the fatigue strength of the weldment when PWHT is not feasible. Secondly, even though in many cases the mechanical properties of the HAZ can be restored by PWHT, weakness still exists in the FZ. The existence of weld reinforcement is unavoidable due to the use of under-matching welding filler. However, while the

thicker weld metal provides extra mechanical strength to match the base metal (BM), the geometry of the crown also creates stress concentration sites at the weld toe, which is harmful to the fatigue strength of the weldment [22]. Other factors affecting the fatigue life of 6061 alloy such as residual stress and surface roughness also applies to weldments. It is widely agreed that tensile residual stress has a detrimental effect on fatigue life, while compressive residual stress produced by shot peening, laser shock peening and other surface treatments are beneficial [19-21, 23-25].

In this study, various attempts were introduced individually and combined to improve the fatigue life of 6061 alloy weldment. A lab produced high-strength welding filler was introduced into the GTA welding of 6061 alloy plates. Precipitation hardening behavior during PWHT was detected to understand the effects of filler metal composition on mechanical properties. Tensile fatigue testing was conducted under various weld reinforcement conditions. The interactive relationship between weld metal strength and weld reinforcement angle is carefully discussed. Additional surface treatments including shot peening and surface polishing were introduced to further improve the fatigue life of 6061 alloy weldments. An optimal combination of the aforementioned factors is proposed by the end of this article.

## 2. Experimental procedure

### 2.1 Specimen preparation

Commercially available 6061 alloy plates (200 × 100 × 5 mm) and bars (diameter = 12 mm) were received in T6 condition for tensile and rotary fatigue specimens, respectively. The nominal composition of 6061 alloy is listed in Table 1.

Table 1. Nominal composition of 6061 alloy (wt %)

Element	Mg	Si	Cu	Cr	Fe	Mn	Ti	Sn
6061 alloy	0.8-1.2	0.4-0.8	0.15-0.4	0.04-0.35	<0.7	<0.15	<0.15	<0.25

### 2.2 Welding parameters and PWHT

Gas tungsten arc welding (GTAW) was performed on 6061 alloy plates with parameters listed in Table 2. The plates were partially grooved as shown in Fig. 1 to avoid warping. Compositions of filler metals ER4047 and lab produced experimental ERX01 are listed in Table 3. The composition of ERX01 was developed in an unpublished research to provide better weld metal strength while maintaining good weldability by raising Si, Mg and Cu contents. PWHT equivalent to T6 temper was conducted on all welded specimens to regain the mechanical properties of both the FZ and HAZ of the as-welded 6061 alloy weldments, which includes solution treatment at 530 °C for 1 h followed by water quenching and aging treatment at 180 °C for 8 h.

Table 2. GTA welding parameters

Welding process	GTAW
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Filler rod diameter	2.4 mm
Current polarity	AC
Welding current	130 A
Welding speed	1~1.3 mm/sec
Shielding gas	Argon
Shielding gas flow rate	15 L/min

Table 3. Chemical compositions of welding fillers (wt%)

Element	Al	Mg	Si	Cu	Mn	Fe	Zn	Cr	Be
ER4047	Bal.	<0.05	11.0-13.0	<0.3	<0.05	<0.8	<0.2	--	<0.01
ERX01	Bal.	1.0	11.0	3.0	<0.1	<0.1	<0.1	<0.1	--

Note: Chemical composition of ERX01 was acquired by EDS analysis in SEM microscopy.

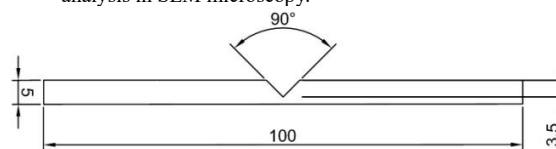


Fig 1. Dimension of the partially grooved 6061 alloy plates for GTAW (mm).

### 2.3 Mechanical testing and tensile fatigue testing

Specimens for tensile testing and tensile fatigue testing were machined from GTA-welded plate. The welded plates were milled from the bottom surface to remove the un-welded portion until the thickness is reduced to 3 mm. The 3-mm-thick plates were then CNC machined into the dimensions as shown in Fig. 2 before receiving PWHT. Tensile testing was performed on MTS 810 material testing platform according to ASTM E8M on both 6061 alloy BM and welded specimens. Displacement control was used with displacement rate of 1 mm/min. The weld reinforcement angles were kept at 0° for all tensile specimens to understand the joint efficiency of the 6061 alloy weldments produced with different fillers. Vickers microhardness traverses of the weldments from the FZ toward the BM were measured prior and after PWHT with 300 g loading force. Microhardness measurement helps reveal the amount of hardness recovered during PWHT.

Tensile fatigue testing was conducted on the same platform shown above. Specimen dimensions of the fatigue specimens were identical to that of the tensile specimens. Additional weld reinforcement with angles of 0°, 10° and 30° were introduced into the fatigue specimens, as shown in Fig. 2(c). Tensile fatigue testing was operated at 8 Hz with displacement control. Stress cycle between -150 MPa and +150 MPa was applied to all specimens, which is approximately 50% of the yield stress of 6061 alloy BM under T6 temper. Addition to the fatigue life of the specimens, the fracture locations were also recorded.

### 2.4 Shot peening and surface polishing

Shot peening and surface polishing was additionally conducted on some specimens with the attempt to further increase the fatigue life span. Shot peening was conducted using pressurized bainitic steel balls with diameter between 0.30 and 0.60 mm, and a

surface coverage of 200%. Surface polishing was conducted with 1200 grid abrasive sandpaper, and the resulting surface roughness Ra was maintained below 0.5 μm for un-peened specimens. As for the shot-peened specimens, Ra value was kept below 1.0 μm to avoid excessive removal of the plastically deformed layer.

### 2.5 Rotary fatigue and residual stress measurement

In order to understand the stress relaxation phenomenon of the shot-peened specimen during fatigue testing with different stress amplitude, rotary fatigue testing was used to test the shot-peened 6061 alloy bars. No welding was introduced into this part of the study. Dimensions of the bar form specimens are shown in Fig. 3. Non-destructive X-ray diffraction residual stress measurement was employed with Pulstec μ-360. The relaxation of residual stress of the shot-peened specimens during the fatigue testing before specimen failure was recorded by measuring the surface residual stress periodically.

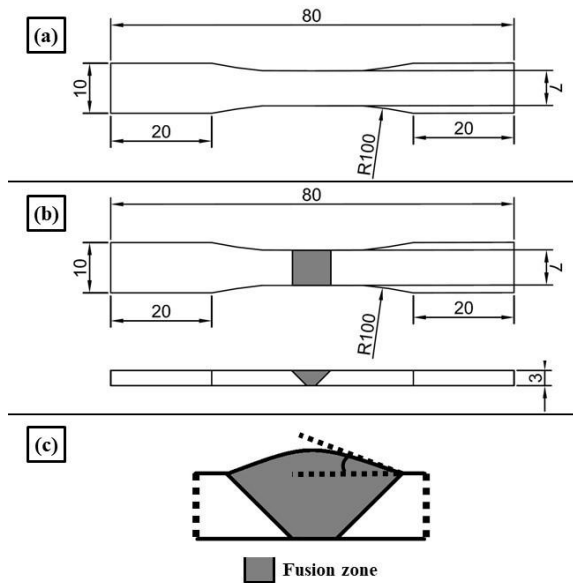


Fig 2. Dimensions of 6061 alloy tensile fatigue specimens (a) BM, (b) welded specimen, and (c) demonstration of weld reinforcement angle (mm).

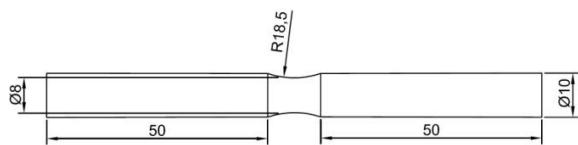


Fig 3. Dimensions of 6061 alloy BM rotary fatigue specimens (mm).

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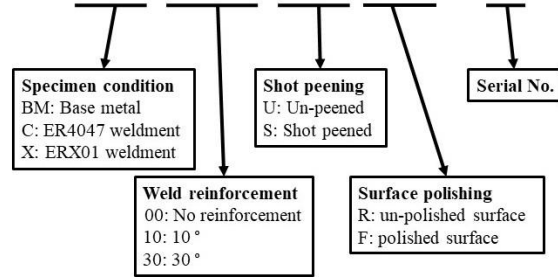


Fig 4. Nomenclature of 6061 alloy fatigue specimens.

## 3. Results and discussion

In this study, effects of filler metal composition, weld reinforcement angle, surface roughness, shot peening on the mechanical properties and fatigue life of 6061 alloy weldments were studied. The results were discussed in different aspects in the following sections. Fig. 4 shows the simplified nomenclature of the 6061 alloy fatigue specimens of multiple parameters employed in this study.

### 3.1 Effects of welding filler composition on mechanical properties and fatigue life

Figure 5 shows the microhardness variation of the 6061 alloy welded with ER4047 before and after T6 PWHT. The average microhardness value of the unaffected 6061 alloy BM is approximately 100 Hv. Due to the abrupt welding heat input, the hardness values of the BM gradually decrease through the HAZ toward the FZ. The softening found in the HAZ is caused by the over-aging of the precipitates in the low temp. HAZ and the complete dissolution of alloying elements in the high temp. HAZ. The area closer to the weld center was exposed to higher peak temperature and longer heat-affected time, hence sustains more loss in mechanical strength. Adjacent to the HAZ, the as-welded FZ produced by ER4047 filler rod vary between 50 and 70 Hv. The rapidly solidified and cooled FZ demonstrates similar mechanical strength as the as-quenched material after solution treatment, as both materials were rapidly cooled from elevated temperature, which provides no time for any precipitation hardening to take place. After T6 PWHT, recovery in microhardness values can be found in the specimen welded by ER4047 filler, as shown in Fig. 5. The hardness of the HAZ recovers to the same level as the BM. Thanks to the complete cycle of solution treatment, quenching and aging, the alloying elements in the HAZ were allowed to re-precipitate into peak aged condition. The microhardness of the FZ on the other hand, only increases slightly to 80 Hv, which is still 20% lower than that of the BM. The increased Si content in the FZ prevents the risk of solidification cracking, but at the meant time, the lack of precipitation encouraging elements limits the hardness recovery of the FZ during PWHT.

The microhardness values of weldments produced by ER4047 and ERX01 after T6 PWHT are shown in Fig. 6. The HAZ and BM of both weldments behave identically prior and after PWHT since the chemical compositions in these area cannot be altered during welding. The FZ of both weldments also behaves similarly prior to PWHT, since no precipitation has taken place in the newly solidified FZ. However, the precipitation hardening and microhardness recovery is significantly more prominent in the FZ produced by ERX01 filler due to the addition of Mg, Cu alloying elements, resulting in the final microhardness value up to 150 Hv in the FZ of ERX01 weldment, which is almost two times higher than that of the ER4047 weld metal. Sadly, the exact strengthening mechanism and the development process of the ERX01 filler are contained in an unpublished research and are yet confidential since further improvement and testing of this welding filler is still being studied.

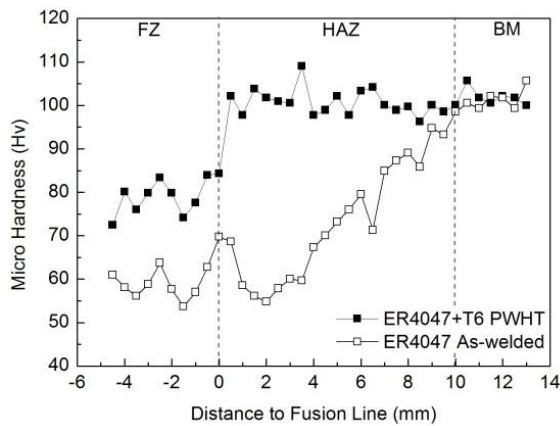


Fig 5. Microhardness traverses of 6061 alloy weldment produced by ER4047 filler before and after T6 PWHT.

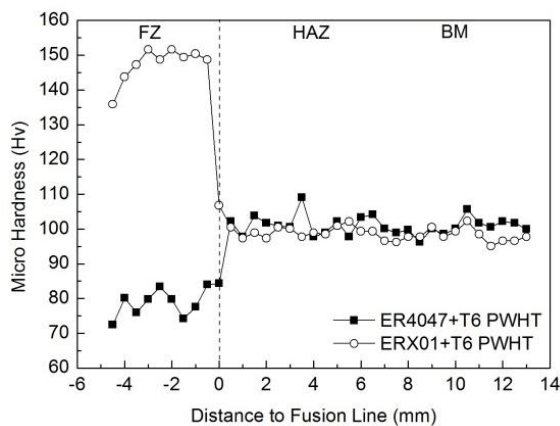


Fig 6. Microhardness traverses of 6061 alloy weldment produced by ER4047 and ERX01 filler after T6 PWHT.

The tensile properties of 6061 alloy BM, ER4047 weldment and ERX01 weldment are listed in Table 4. Ultimate tensile strength (UTS) and yield strength (YS) of the 6061 alloy BM were found to be 318.17 and 298.13 MPa, respectively. The UTS and YS of the ER4047 weldment are 258.92 and 221.14 MPa,

respectively, which are considerably lower than that of the 6061 alloy BM. The fracture site of the ER4047 weldment locates in the weakest FZ, which can be expected from the hardness testing results shown in Fig. 5. The ERX01 weldment on the other hand, performs almost the same as the 6061 alloy BM, with UTS of 338.24 MPa and YS of 301.72 MPa. Different from ER4047 weldment, the ERX01 weldment fractured in the HAZ, indicating that after T6 PWHT, the strength of the ERX01 weld metal is higher than that of 6061 alloy BM, which agrees with the results from the microhardness measurement. However, the elongation of the ERX01 weldment remains at the same level as the ER4047 weldment, and are slightly lower than the BM. The possible reason for this phenomenon may be caused by the grain coarsening in the FZ and HAZ during welding.

Results from the fatigue testing of 6061 alloy BM, ER4047 weldments and ERX01 weldments are summarized in Table 5. For all the results in Table 5, fatigue testing was conducted with displacement control which produced cyclic loading between +150 MPa and -150 MPa on the BM sample, which is approximately 50% of the YS of 6061-T6 BM.

Without weld reinforcement and shot peening, the fatigue life of the three ER4047 weldments (C00UF-X) are 11301, 4888 and 4401 cycles, respectively. The weaker FZ of the ER4047 weldment are unable match the strength of the BM, leading to poorer fatigue life performance, with the fracture sites locating in the FZ for all three tested specimens. Under the same specimen condition with no weld reinforcement and shot peening, the stronger FZ of ERX01 weldment (X00UF-X) significantly enhanced the fatigue life of the three tested weldments up to 58799, 53632 and 86168 cycles, respectively. And due to the stronger FZ, the fracture site of the ERX01 weldments (X00UF-X) is transferred from the FZ to the fusion line (FL) and BM. It can be concluded that the increase in weld metal strength in the FZ by using specific welding filler can significantly improve the fatigue strength of 6061 alloy weldments when weld reinforcement is not taken into account.

Table 4. Tensile properties of 6061 alloy specimens

Specimen	UTS (MPa)	YS (MPa)	Elongation (%)
6061 alloy BM	318.17	289.13	13.78
ER4047weldment	258.92	221.14	11.78
ERX01weldment	338.24	301.72	11.80

Table 5. Results of tensile fatigue test of 6061 alloy BM specimens and weldments.

Specimen	Angle (°)	Shot peening	Surface polishing	Fracture site	Fatigue life
BMUR-1	-	U	R	BM	52,908
BMUR-2	-	U	R	BM	49,872
BMUR-3	-	U	R	BM	62,011
BMSR-1	-	U	F	BM	123,337
BMSR-2	-	U	F	BM	103,256

BMSR-3	-	U	F	BM	96,160
BMUF-1	-	S	F	BM	210,043
BMUF-2	-	S	F	BM	152,022
BMUF-3	-	S	F	BM	157,249
C00UF-1	0	U	F	FZ	11,301
C00UF-2	0	U	F	FZ	4,888
C00UF-3	0	U	F	FZ	4,401
C10UF-1	10	U	F	FZ	8,748
C10UF-2	10	U	F	FZ	6,230
C10UF-3	10	U	F	FZ	6,710
C30UF-1	30	U	F	FL	10,031
C30UF-2	30	U	F	FL	17,678
C30UF-3	30	U	F	FL	16,710
X00UF-1	0	U	F	BM	58,799
X00UF-2	0	U	F	FL	53,632
X00UF-3	0	U	F	BM	86,168
X10UF-1	10	U	F	FL	44,281
X10UF-2	10	U	F	FL	36,320
X10UF-3	10	U	F	FL	38,104
X30UF-1	30	U	F	FL	33,320
X30UF-2	30	U	F	FL	35,021
X30UF-3	30	U	F	FL	37,311
X00SF-1	0	S	F	BM	510,021

### 3.2 Effects of weld reinforcement on fatigue life

Comparing the results shown in Table 5, the introduction of weld reinforcement affects the fatigue life of ER4047 and ERX01 weldments very differently. The fatigue testing results of the non-peened ER4047 and ERX01 weldments with different weld reinforcement angles are further summarized in Table 6. The average fatigue life of ER4047 weldments without weld reinforcement is 6,863 cycles. With increasing reinforcement angle and the increase in thickness and strength of the weld metal, the fatigue life of the ER4047 weldment increases accordingly. While the reinforcement angle reaches 30°, the fatigue life has increased up to an average of 14,806 cycles. However, with a higher weld reinforcement angle of 30°, the stress concentration effect at the weld toe begins to take over and becomes the main cause of the fatigue fracture, causing the fracture site to shift from the FZ toward the FL. On the other hand, the average fatigue life of ERX01 weldment without weld reinforcement is 66,200 cycles, which is approximately 10 times higher than that of the ER4047 weldment under the same condition. In contrary to ER4047 weldment, the fatigue life of the ERX01 weldment decreases largely with the appearance of weld reinforcement, and the fracture site quickly shifts from BM to the FL whether the weld reinforcement angle is at 10° or 30°. This indicates that the ERX01 weld metal provides enough mechanical strength without the requirement for reinforcement, and the stress concentration at the weld toe hinders the benefit introduced by weld reinforcement. Hence, the choice of welding filler can dramatically affect both mechanical and fatigue life performance of the 6061 alloy weldments. It can be concluded that the weld reinforcement can provide extra strength for the weaker weld metal when the weld metal of the FZ under matches the BM, but it will also cause stress concentration at the weld toe, which counteracts with the strengthened weld metal. On the other hand, when the weld metal strength of the FZ matches or over matches the BM in mechanical strength, the weld reinforcement is unable to provide positive effect on

the fatigue life of the weldments, and may even cause harm by introducing stress concentration. In the end, the fatigue life of the ERX01 weldments without weld reinforcement is still approx. 4.5 times higher than that of the 30° reinforced ER4047 weldment. Results shown in this paragraph once again indicates the importance of improving the weld metal strength in the FZ.

Table 6. Summarized results of tensile fatigue testing of un-peened 6061 alloy weldments with different reinforcement angles.

Specimen	Sample 1	Sample 2	Sample 3	Avg.	St. Dev
C00UF	11,301	4,888	4,401	<b>6,863</b>	3,851
C10UF	8,748	6,230	6,710	<b>7,229</b>	1,337
C30UF	10,031	17,678	16,710	<b>14,806</b>	4,164
X00UF	58,799	53,632	86,168	<b>66,200</b>	17,485
X10UF	44,281	36,320	38,104	<b>39,568</b>	4,178
X30UF	33,320	35,021	37,311	<b>35,217</b>	2,008

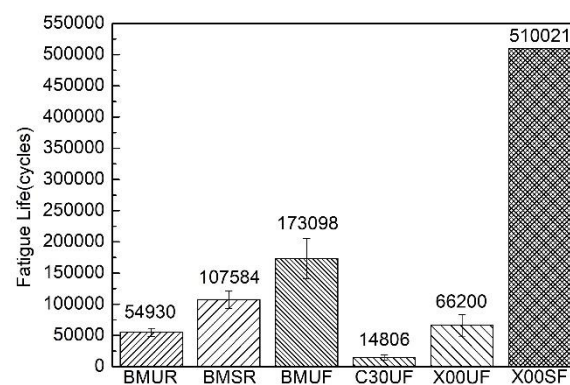


Fig 7. Summarized results of tensile fatigue testing of 6061 alloy specimens with different experimental parameters.

### 3.3 Effects of shot peening and surface polishing

Three groups of 6061 alloy BM specimens were subjected to tensile fatigue testing with untreated as-received surface, shot-peened surface and abrasive paper polished surface, with a specimen group name of BMUR, BMSR and BMUF, respectively, as shown in table 5. The results show that significant increase in fatigue life can be found when the specimens received either shot peening or surface polishing. However, due to the increase in surface roughness caused by severe surface plastic deformation, the amount improvement in fatigue life of the shot-peened specimens cannot reach the same level as the surface-polished specimens.

Taking the previously discussed parameters into consideration and averaging the fatigue testing results, the fatigue life of 6061 alloy BM and weldments with different surface conditions is shown in Fig. 7. The introduction of welding significantly deteriorates the fatigue life of 6061 alloy. Even with the aid of high strength welding filler ERX01, the average fatigue life of specimens X00UF is still only 38.2% of the BMUF BM specimens under the same surface condition. Thankfully, when the two surface treatment is combined in the proper sequence, the fatigue life of ERX01 weldment X00SF is increased dramatically up to 510,021 cycles. Hence, an optimal combination of

welding procedure and surface treatment to improve the fatigue life of 6061 alloy weldment is proposed. Firstly, the use of high strength weld filler generates stronger weld metal after PWHT, which allows the elimination of weld reinforcement. Secondly, shot peening employed after T6 PWHT creates compressive residual stress at the material surface, and thirdly, the defects and rough surface caused by shot peening is then removed by surface polishing. Theoretically, the addition of these three general steps will be able to fully compensate the significant setback in fatigue life caused by the welding process.

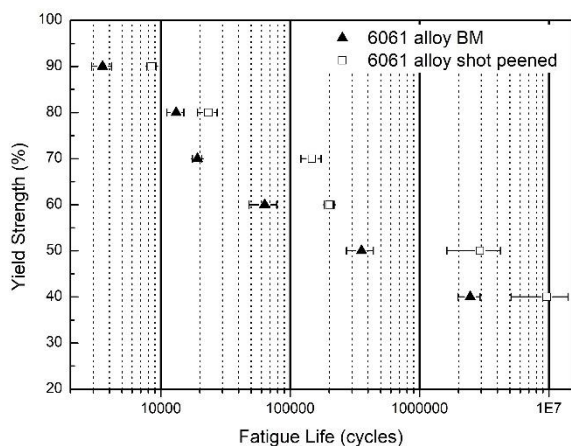


Fig 8. Rotary fatigue testing results of 6061 alloy BM and shot-peened specimens under various stress amplitudes.

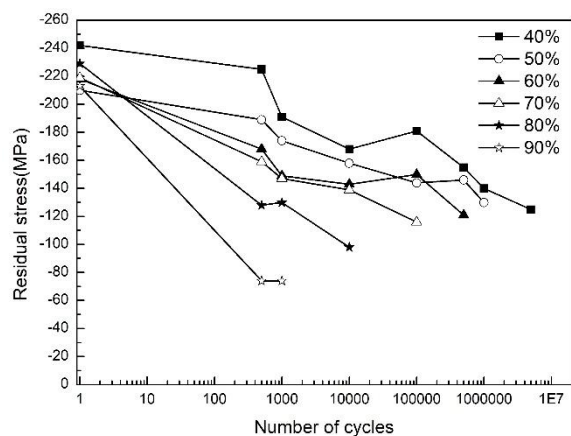


Fig 9. Residual stress relaxation of 6061 alloy shot-peened specimens during rotary fatigue testing under different stress amplitudes.

### 3.4 Residual stress relaxation during fatigue testing

The beneficial effects of shot peening on improving the fatigue life of 6061 alloy has been shown by many researches and this study as well. However, according to the additional rotary fatigue testing results performed in this study, as shown in Figs. 8 and 9, the amount of increase in fatigue life and the stress relaxation rate under different stress amplitude tend to vary significantly.

As shown in Fig. 9, the compressive residual stress relaxation rate increases with increasing stress amplitude, which corresponds to common belief.

Surprisingly, the final compressive residual stress value measured before specimen failure tends to decrease with increasing stress amplitude. In other words, the amount of residual stress relaxation decreases with decreasing stress amplitude. This result differs from the result proposed by Jong Cheon[26] with the fatigue test conducted with 304 stainless steel, which suggests that the degree of stress relaxation does not change with varying test stress amplitude. The residual stress relaxation behavior during fatigue loading may not be the same for different materials.

For future studies, the stress relaxation of various metallic materials under different fatigue loading conditions will be included. As for the development of ERX01 filler, several studies are still required before considering the possibility of commercialization. For example, the resistance against localized corrosion of the weld metal produced by ERX01 will need to be studied due to its complex alloying element

### 4. Conclusion

This research aims to determine the effects of welding filler composition, weld reinforcement angles and surface conditions on both mechanical properties and fatigue life of 6061 alloy weldments. The following conclusions can be drawn based on the experimental results.

- (1) The microhardness values of the as-welded and T6 postweld heat-treated weld metals produced by ER4047 welding filler are approximately 60 Hv and 80 Hv, respectively. The use of lab developed ERX01 welding filler significantly improves the weld metal microhardness up to 150 Hv after T6 PWHT, indicating that the alloying elements in ERX01 weld filler provide a more significant precipitation hardening effect than the ER4047 welding filler.
- (2) Without the weld reinforcement, the fatigue specimen of the ER4047 fails in the relatively weaker FZ. The fatigue life of ER4047 weld increases with the increasing weld reinforcement angle, thanks to the increase in the section thickness and total strength of the FZ. However, the increase in fatigue life is hindered by the stress concentration effect at the weld toe, resulting in an average fatigue life of 14,806 cycles with 30° reinforcement angle.
- (3) The weld metal produced by ERX01 after T6 PWHT is stronger than the as-received 6061 alloy T6 BM. Consequently, the presence of weld reinforcement is unable to provide positive effect on the fatigue life of the weldments, and may even cause harm by introducing stress concentration. Hence, the average fatigue life of the ERX01 weld with 0° reinforcement angle is 66,200 cycles, which will not improve with increasing reinforcement angle.
- (4) Both shot peening and surface polishing improve fatigue life of the 6061 alloy BM and weldments.

The optimal fatigue life result of 6061 alloy weldment is 510,021 cycles, which is achieved by using ERX01 welding filler followed by T6 PWHT, shot peening and surface polishing.

- (5) The residual stress relaxation of shot peened 6061 BM under different fatigue loading is studied additionally. Different degrees and rates of residual stress relaxation were found under different stress amplitudes. Higher stress amplitudes result in higher degrees of stress relaxation prior to fatigue crack initiation with faster relaxation rates.

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