EFFECTS OF AGING TREATMENT ON MICROSTRUCTURE AND STRENGTH OF WELD HEAT AFFECTED ZONE OF 6N01-T5 ALUMINUM ALLOY

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ABSTRUCT

Effects of the aging treatments on the microstructure and strength of heat affected zone(HAZ) in the welds of a age-hardened Al-Mg-Si alloy, 6N01-T5, were investigated. The base metal aging treatments before MIG welding were conducted at 423K to 473K for 28.8ks.Post weld heat treatment (PWHT) to recover the HAZ strength was performed at 448K for 28.8ks. Microstructure observations, hardness measurements and tensile tests were conducted to study properties of the MIG weld joints. The position of the softest region in HAZ where the hardness insufficiently recovered after natural aging and PWHT was at a distance of approximately 15mm from the center of the fusion zone. Hardness of the softest regions after natural aging and PWHT decreased with increase in the base metal aging temperature. TEM observation clarified that strengthening β” (Mg_2Si) precipitates and coarse β’ precipitates affected the hardness of HAZ. Incomplete recover of hardness in HAZ after PWHT was caused by the precipitation of non-hardening β’ phase during the weld thermal cycle. In order to examine the effects of weld heat input and welding speed, the laser weld joints were also investigated and compared with the MIG weld ones. Laser welding had the narrower width of the softened regions in HAZ compared with MIG welding. The hardness of the softest regions of the laser welds after PWHT was higher than that of the MIG welds. Quantitative relations between hardness of the softest region and base metal aging temperature were obtained for both welding processes. Accordingly, the equations to estimate the strength of the weld joints after PWHT with varying base metal aging temperatures were proposed for MIG welding and laser welding.

KEYWORDS
Al-Mg-Si alloy, MIG welding, laser welding, aging treatment, heat affected zone

1. Introduction

Aluminum alloys are lightweight, corrosive resistant, and easy to process[1],[2]. Because of these characteristics, aluminum alloys are available for many fields including automobile and airline industries. For saving energy and environmental protection, the use of aluminum alloys is expected furthermore. In aluminum alloys, 5000series and 6000series are popularly utilized. In particular, 6000series are expected for automobile, because they are age-hardened[3],[4], corrosive resistant, and easier to recycle. 6N01-T5 aluminum alloy is expected to automobile industry for its good extrusion.

Al-Mg-Si age-hardened aluminum alloys are strengthened by β” (Mg_2Si) precipitates, and welding of these alloys have a problem of softened in heat affected zone (HAZ), which results in loss of the strength of the weld. To recover HAZ hardness, aging treatment after solution treatment has a beneficial effect. However, solutionizing whole weld joint is technically difficult, therefore, only aging treatment without solution annealing after welding is desirable. In this case, the precipitation of non-hardening β’ phase during the weld thermal cycle causes the decrease in β” precipitates after PWHT because the amount of free Mg or Si to form β” precipitates decreases. This causes an insufficient recovery of the HAZ hardness after PWHT. To obtain higher strength of the weld joint, it is necessary to reduce the softened of HAZ. The factors that affect the reversion of the softened regions are the morphology of the precipitates in base metal, the weld thermal cycle, and PWHT conditions. In order to optimize the strength of the weld joints, it is essential to control those three conditions.

This work focused on the effects of the aging treatments on the microstructure and the strength of the HAZ in the welds of 6N01-T5 aluminum alloy. To this end, the base metal aging treatments before MIG welding were conducted with varying aging treatment of 423K to 473K for a constant holding time of 28.8ks. PWHT to recover the HAZ strength was performed at 448K for 28.8ks. Microstructure observation, hardness measurement and tensile test were conducted to study the properties of the MIG weld joints. In order to examine the effects of weld heat input and welding speed, the laser weld joints were also investigated and compared with the MIG weld ones.

2. Experimental procedures

An age-hardened Al-Mg-Si alloy, 6N01-T5 was used in this experiment. Its thickness was 3.0mm and chemical compositions are given in Table 1. MIG welding procedure was automatic welding and made perpendicular to the extrusive direction. Filler metal was A5356-WY (□1.2mm ˜ . Its power level was 3.45kW, traverse speed was 750mm/min, and shielding gas was Ar. CO_2 laser. welding was also performed with a power level of 3.75kW and a traverse speed of 750mm/min. The base metal aging treatments before welding were conducted with varying temperatures of 423K to 473K for 28.8ks. PWHT to recover the HAZ strength was performed at 448K for 28.8ks. The position of measuring hardness was the center of the thickness and conducted at intervals of 500μm with a load of 1.96N and holding. TEM microstructure of the HAZ was observed at each position of 5, 10, 15, and 20mm from the center of the weld metal. Tensile tests were conducted to examine the tensile strength of the weld joints. Dimensions of the tensile test specimens were given Fg.1 and the front and back surfaces of the weld bead were not finished.

3. Results and discussion

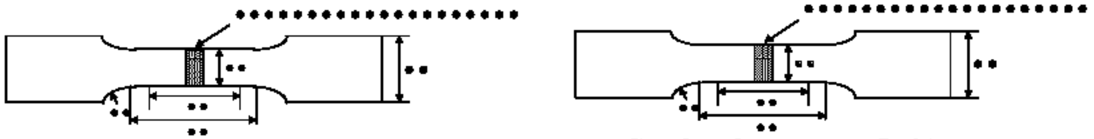
3.1 Relation between strength of the base metal and aging conditions

The hardness and tensile strengths of the base metals were plotted against aging temperatures in Fig.2. The aging temperature providing the maximum strength was 448K to 453K. It is clarified that below 448K aging states were insufficient, and above 453K over-aging occurred. The change in the hardness with aging temperature is similar to the change in the strength excepting a higher aging temperature for providing the maximum hardness. TEM microstructures were shown in Fig.3. At 423K, β" could not be confirmed clearly because the lower aging temperature causes small size and small amount of β" precipitates. Needle-shaped β" precipitates formed at the aging temperature of 448K, and larger amount of precipitates causes higher hardness and strength. Compared with the aging temperature of 448K, rod-shaped precipitates were observed at the aging temperature of 473K, and they were non-hardening β' precipitates causing the degradation of the strength. Therefore, The hardness and tensile strength of the base metals depend on the amount of strengthening β" precipitates.

Table 1 Chemical composition of aluminum alloy used.

Chemical composition (mass%)											
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Bi	Pb	Sn	Zr
0.50	0.18	0.06	0.03	0.63	0.01	0.01	0.02	<0.001	0.002	0.002	0.015

Mn+Cr=0.046 Mn/Si=1.249(mass%)



Gage length	L=50
Length of smooth part	P=60
Width	W=25
Radius	R=15
Thickness	T=3.0
	B=30 (unit:mm)

(a) MIG weld joint

Gage length	L=31
Length of smooth part	P=37
Width	W=20
Radius	R=15
Thickness	T=3.0
	B=30 (unit:mm)

(b) Laser weld joint

Fig.1 Dimension of tensile test specimen.

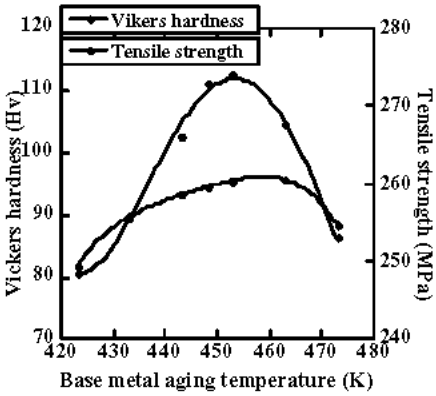
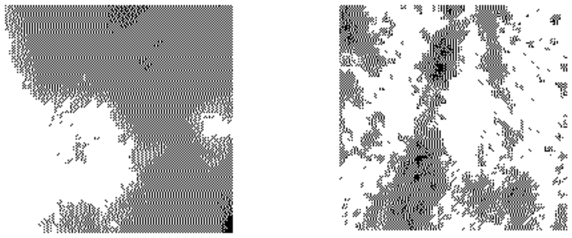
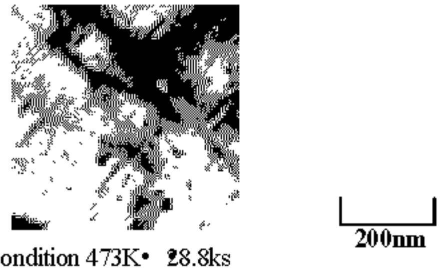


Fig.2 Relation between the strength of base metal and aging temperatures



(a) Aging condition 423K×28.8ks (b) Aging condition 448K×28.8ks



(c) Aging condition 473K×28.8ks

Fig.3 TEM microstructures of base metals

3.2 Effect of the aging treatments on the properties of HAZ in MIG weld joints

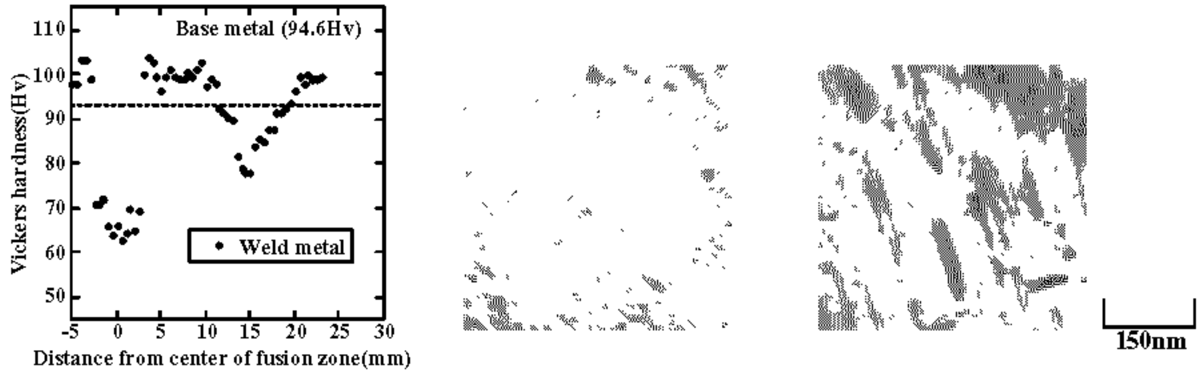
Some examples of the hardness measurements and TEM microstructures of MIG weld joints were given in Fig.4. Figures

4 (a-1)-(a-3) were those after natural aging, and Fig.4 (b-1)-(b-3) were those after PWHT at 448K for 28.8ks. The position of the softest region in the HAZ whose hardness did not recover after natural aging and PWHT was at a distance of approximately 15mm from the center of the weld metal. After welding, in the HAZ within approximately 10mm from the center of the weld metal, the β'' precipitates dissolved in the matrix during the weld thermal cycle beyond the solvus temperature. While after natural aging a certain amount of β'' precipitates can occur, the precipitates is not clearly seen in the TEM observation (Fig. 4 (a-2)) because of its small size and small fraction. Non-hardening β' precipitates were confirmed at a distance of approximately 15mm from the center of the weld metal (Fig.4 (a-3)). After PWHT, in the vicinity of the fusion boundary within 10mm from the center of the weld metal the hardness completely recovered. This is because solute dissolved in the matrix after welding recombined to form hardening β'' precipitates by PWHT. At the distance of approximately 15mm, β' precipitates after PWHT were coarser than those after natural aging. Accordingly significant softening was recognized at this point of the HAZ. This is caused by the precipitation of non-hardening β' consuming solute to form hardening β''. Figure 5 (a)-(c) shows the hardness profiles and TEM microstructures of MIG weld joints after PWHT using 473K• 28.8ks aged base metal. More serious softening occurred and accordingly more β' precipitates were observed in comparison with the weld joint using 448K• 28.8ks aged base metal.

Figure 6 shows the relation between the base metal aging temperature and the hardness of the softest regions in the HAZ after PWHT. The hardness of the softest regions after PWHT declined linearly with increasing the base metal aging temperature. Therefore, the hardness of the softest regions depends on the amount of non-hardening β' precipitates after PWHT, which reasonably increase with increasing base metal aging temperatures. Thus, the states of the precipitates in the base metals apparently affect the strength of the weld joints after welding and after PWHT.

(a-1) Result of hardness measurement (a-2) 5mm from center of fusion zone (a-3) 15mm from center of fusion zone

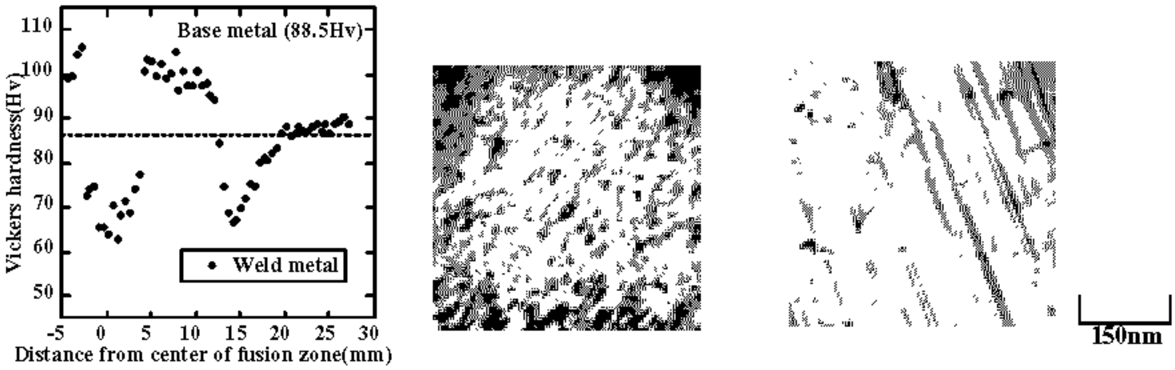
(a) After natural aging



(b-1) Result of hardness measurement (b-2) 5mm from center of fusion zone (b-3) 15mm from center of fusion zone

(b) After PWHT (448K• 28.8ks)

Fig. 4 The hardness measurements and TEM microstructures of MIG weld joints (Base metal aging condition 448K• 28.8ks)



(a) Result of hardness measurement (b) 5mm from center of fusion zone (c) 15mm from center of fusion zone

Fig. 5 The hardness measurements and TEM microstructures of MIG weld joints after PWHT (448K• 28.8ks) (base metal aging condition,473K• 28.8ks)

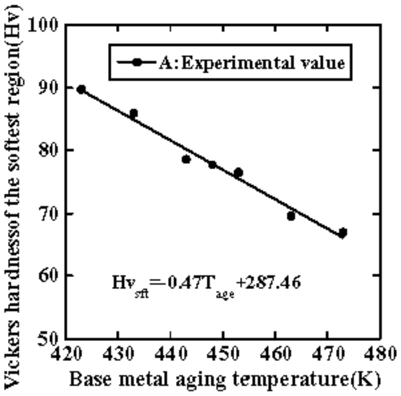


Fig.6 Relation between base metal aging temperature And hardness of the softest region in MIG weld joints

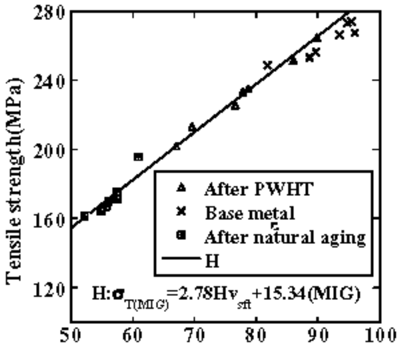


Fig.7 Relation between tensile strength and hardness of the softest region in MIG weld joints

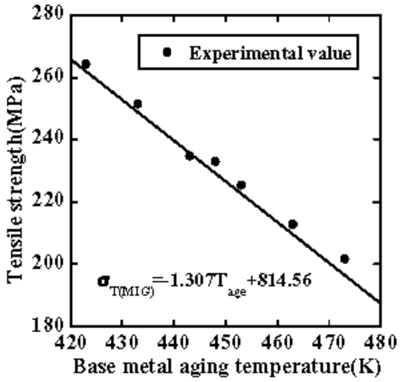


Fig.8 Prediction of tensile strength of MIG weld joints by eq(3).

As shown in Fig.6, relation between the base metal aging temperature (T_{age}) and the hardness of the softest region (Hv_{sft}) can be obtained and described as:

$Hv_{sft} = -0.47T_{age} + 287.46$ (1)

Figure 7 shows relation between the tensile strength and hardness of the softest region. In the tensile tests, the fracture occurred in the softest region in HAZ, because the weld metal with lower hardness had a reinforcement. Figure 7 includes the strength and hardness of the base metal. A linear relation between the hardness of the softest region (Hv_{sft}) and the tensile strength (σ□ □□G) can be described as the following equation by the method of least squares.

$\sigma_{T(MIG)} = 2.78Hv_{sft} + 15.34$ (2)

Thus, by using equation (2), the strength of the MIG weld joints can be derived from the hardness of the softest region. Finally, the relation between the base metal aging temperature and the tensile strength of the MIG weld joints was obtained by substituting eq(1) for eq(2).

$\sigma_{T(MIG)} = -1.307T_{age} + 814.56$ (3)

The strength of the MIG weld joints after PWHT can be calculated from the base metal aging temperature by using equation (3).

The relation between the values calculated from eq (3) and the experimental values is shown in Fig.7. Thus, quantitative relation between the strength of the MIG weld joints after PWHT and the base metal aging temperature was confirmed.

3.3 Effect of the aging treatments on the properties of HAZ in laser weld joints

Figure 9 shows a typical example of the hardness measurements of the laser weld joints. Compared with MIG welding, the width of the softened region in laser welding is less than a half of that in MIG welding, and the softest region of which hardness incompletely recovered after natural aging hardly exists. As shown in Fig.8 (b), the softened region after PWHT is extremely narrower in its width and its hardness drop is significantly smaller in comparison with that in MIG welding. This is caused by the rapid heating and cooling thermal cycle of laser welding. Namely, in the laser welds , the amount of β' precipitates during the weld thermal cycle become less and thereby the population of β" precipitates after PWHT increases.

Figure 10 shows a relation between the tensile strength and the hardness of the softest region in the laser weld joints. The estimated line for MIG welding using eq. (2) is also plotted in Fig.9. Similar to MIG welding, the tensile strength of the laser weld joints increased linearly with increase in hardness of the softest region. As shown in Fig.9, the relation between the tensile strength of the laser weld joints ($\sigma_{T(LB)}$) and the hardness of the softest region (Hv_{sft}) can be described as:

$$\sigma_{T(LB)} = 2.61Hv_{sft} + 33.83 \qquad (4)$$

Although the tensile strength of the laser weld joints is nearly equal to that of the MIG weld joints in higher hardness region, in lower hardness region, the former is somewhat higher than the latter. This may be caused by the narrower softened regions in laser welding being constrained by neighboring higher hardness regions.

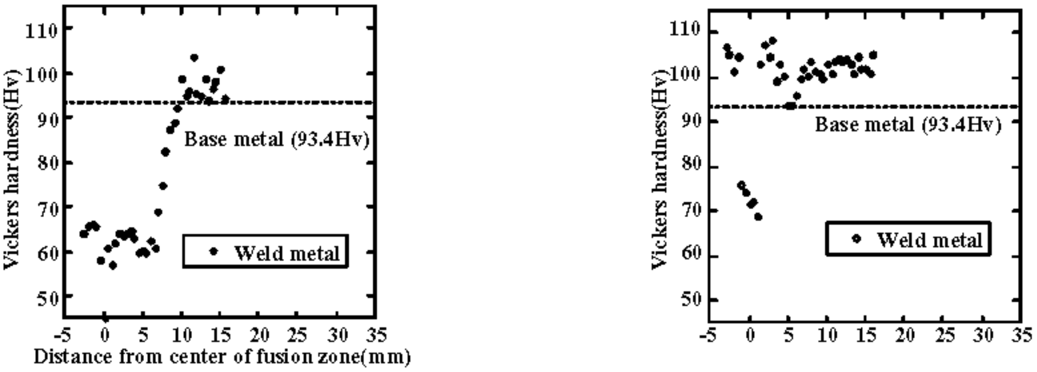
Figure 11 indicates the relation between the base metal aging temperature and hardness of the softest region in the laser weld joints after PWHT. As shown in Fig.5, the relation between the base metal aging temperature (T_{age}) and the hardness of the softest region (Hv_{sft}) can be described as:

$$Hv_{sft} = -0.105T_{age}^2 + 8.986T_{age} - 1828.2 \qquad (5)$$

The relation between the base metal aging temperature and the tensile strength of the laser weld joints is obtained by substituting eq (5) for eq (4).

$$\sigma_{T(LB)} = -0.027T_{age}^2 + 23.45T_{age} - 4737.78 \qquad (6)$$

Figure 12 shows the relation between the tensile strength and the base metal aging temperatures for laser welding together with that for MIG welding. Accordingly, the prediction equations to calculate the strength of the weld joints after PWHT with varying base metal aging temperatures were proposed for MIG welding and laser welding. In Fig. 12 the tensile strength of the base metals is also plotted compared to that of the weld joints. Although the strength of the weld joints increases with aging temperature, that of the base metal decreases at aging temperatures below approximately 453K. If PWHT is practically applied to only HAZ locally, the strength of welded structures will be equal to the lowest strength of the strengths of the HAZ and the base metal. In this case the strength of the HAZ should match that of the base metal. As shown in Fig.12, the strength of the HAZ is equal to that of the base metal at the aging temperature of 430K in MIG welding. On the other hand, in laser welding, at the aging temperature of 448K, which is higher than that in MIG welding, the matched strength is approximately 20MPa higher than that of MIG welding. As a result, laser welding is the advantageous process for welding age-hardened Al-Mg-Si alloy, 6N01-T5, compared with MIG welding.



(a) After natural aging (b) After PWHT(448K• 28.8ks)

Fig.9 The hardness measurements of laser weld joints (base metal aging condition,443K• 28.8ks)

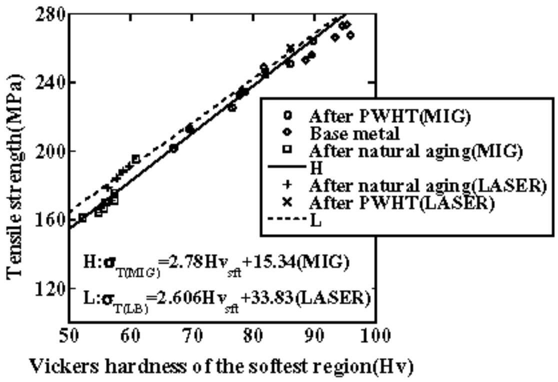


Fig.10 Relation between tensile strength and hardness of the softest region

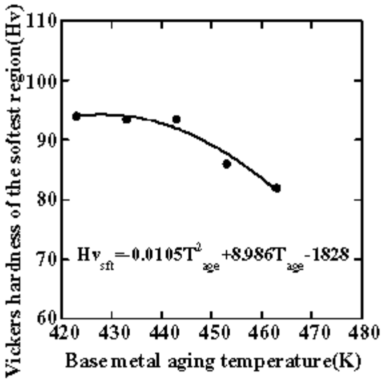


Fig.11 Relation between base metal aging temperature and hardness of the softest region in laser weld joints

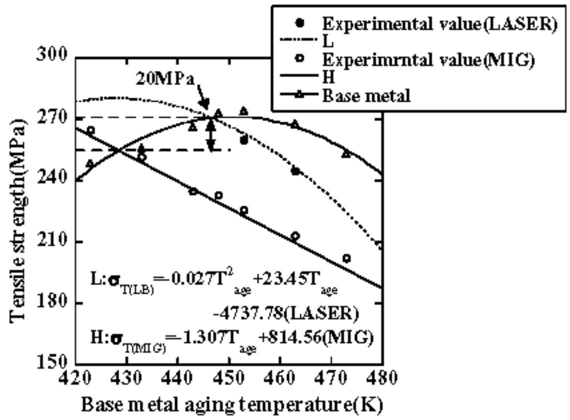


Fig.12 Relation between tensile strength and the base metal aging temperatures

4. Conclusions

In this study, the effects of base metal aging treatment on the microstructure and strength of HAZ in the 6N01-T5 alloy welds were investigated. The prediction methods to calculate the strength of the weld joints after PWHT were proposed for MIG welding and laser welding. The results obtained in this study are as follows.

1. In MIG welding, the position of the softest region of which hardness sufficiently recovered after natural aging and PWHT was at a distance of approximately 15mm from center of the fusion zone, and the hardness of the softest regions after PWHT decreased with the increasing the base metal aging temperature.
2. The states of the precipitates in the base metals affect the hardness and strength of the weld joints after welding and after PWHT. While in the vicinity of the fusion boundary, where the hardness sufficiently recovered, the strengthening β" precipitates were confirmed, in the softened regions, coarse β' precipitates are observed.
3. In laser welding, the width of the softened region is less than a half of that in MIG welding. The softened region after PWHT is narrower in its width and the hardness of the softest region is much higher in comparison with that of MIG welding.
4. The relations between base metal aging temperatures and the strength of the MIG and laser weld joints were formulated as $\sigma_{T(MIG)} = -1.307T_{age} + 814.56$ (MPa), $\sigma_{T(LB)} = -0.027T_{age}^2 + 23.45T_{age} - 4737.78$(MPa). .
5. In laser welding, the strength of the weld metal matched with the strength of the base metal was about 20MPa higher compared with MIG welding.

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