Failure Analysis for the Economizer Tube of the Waste Heat Boiler

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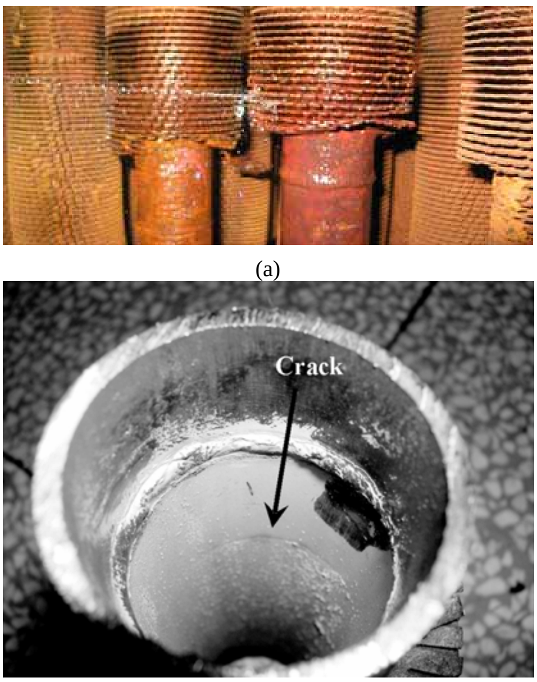
The failure analysis of the leakage of the economizer tube of the waste heat boiler in the energy factory is investigated in this study. The experimental methods included metallurgical and mechanical properties examination, XRD analyses of the corrosion products, and fractural observation of the failed tube. The results show that although the material and mechanical properties of the failed tube, were inferior to those of the new one, most of them were still satisfactory to the criterion requirement. From SEM observation, it is clear that the crack initiated in the outer surface and propagated toward the inner surface of the tube. The fracture, through the entire thickness of the tube, was identified to be intergranular. The crack formation is not dominated by overall degradation in the tube, but might result from a combination with the decrease in the toughness. The toughness degradation in the grain boundary of the economizer tube must have taken place during the fin welding process.

1. INTRODUCTION

In boilers, economizers are heat exchange equipments that heat water to a temperature close to boiling point. Economizers make use of the enthalpy in the hot streams. Because the streams are usually still not hot enough to be used in a boiler, economizers recover the more useful enthalpy and improve the boiler's efficiency. Therefore, the operating temperature of the economizer is much lower than the main heating device of the boiler. The economizer tubes are fitted to a boiler which saves energy by using the exhaust gases from the boiler to preheat the cold feed water. In this case, leakage was found in the vicinity of the welding between the fin and the outer surface of the economizer tube, as depicted in Figure 1(a). The fin was welded circularly on the tube surface to enhance the heat exchange efficiency. The crack of the failed tube could be easily observed with visual inspection (Fig. 1(b)). The equipment had been operated for only 4 years and 3 months with daily start-stop cycle. Because the failure of the economizer tube happened in such a short period, it was necessary to explore the cause. Therefore, the failure analysis for the economizer tube of the waste heat boiler is performed in this study.



(a)

(b)

Fig. 1. Appearances of the failed tube: (a) leakage location; (b)internal evidence of crack.

2. EXPERIMENTAL METHOD

In order to compare the difference in the material properties of the normal and failed economizer tubes, another unused economizer tube was also analyzed in this study. Several analyses, including chemical composition and mechanical property examinations of the above two economizer tubes were performed. In addition, the fracture surface of the failed tube was also inspected to explore the fracture type. The detailed experimental process is described in below.

2.1 Chemical Composition Confirmation

The materials of the economizer tube were claimed to be in accordance with the ASME SA 178-A standard. The chemical composition of the failed economizer tubes was confirmed by Spark-OES analysis. One unused economizer tube was also analyzed for comparison.

2.2 Metallurgical Examination

The new and failed tubes were cut into specimens with suitable dimensions and ground with silicon carbide paper to a 1,000 grit finish and polished with 1 μm alumina particles. 3% Nital etching solution was applied next to reveal the microstructure. The cross section morphology of the economizer tube was then examined using a scanning electron microscope (SEM).

2.3 Mechanical Property Measurement

In this study, the mechanical properties of the economizer tubes were evaluated by employing the Vickers hardness and tensile tests. The hardness of the tubes was recorded through the entire thickness with the same spacing. The average value of the measured hardness of the individual tubes was also calculated for each respective tube. The preparation of the specimen and the testing procedure of the tensile test was in accordance with ASTM E8 standard. The magnitude of the ultimate tensile stress (UTS), yield stress (YS) and elongation obtained from the tensile test was collected.

2.4 Corrosion Product Analysis

The surroundings of the outer and inner surfaces of the economizer tubes were quite different in the operating environment. The corrosion product was necessarily analyzed to determine whether the aggressive corrosives existed. EDS and XRD analyses were performed in this study.

2.5 Fracture Observation

The economizer tubes, including the failed part, were cut into specimens. The specimens were immersed in liquid nitrogen for a certain period. Below the ductile-brittle transformation temperature, the materials would become brittle. The specimens were punched at transformation temperature to obtain completely fractured surfaces. The morphology of the fracture surfaces was examined by SEM. Prior to the examination, the oxide formed on the surfaces was descaled.

3. RESULTS

3.1 Chemical Composition Confirmation

The chemical compositions of the new and failed tubes are shown in Table 1. It reveals obvious differences in C, Si, Mn and S between these two specimens. In general, the materials properties are greatly affected by the contents of C and S. A decrease in mechanical strength always corresponds to a decrease in C content. However, the toughness is generally related to the quantity of S. For the failed tube, the S content increased to 560 ppm which was almost twice the standard value (350 ppm). The degradation in toughness for the failed tube due to the higher S content is expectable.(1)

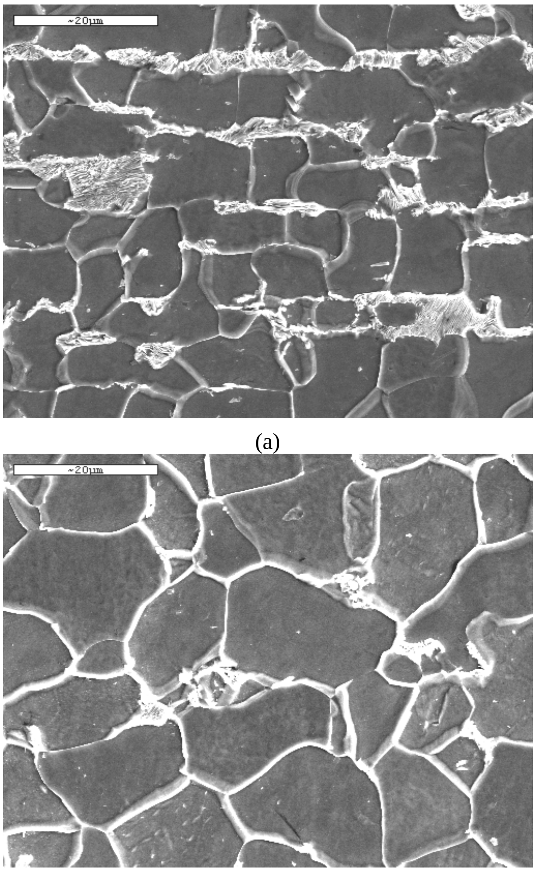
3.2 Metallurgical Examination

The microstructures of these two tubes were observed by using SEM examination. Figure 2 shows the cross-sectional SEM micrographs of the new tube and the failed tube after proper etching. Both micrographs reveal the band structure composed of alternate white ferrite and black pearlite phases. However, there was still slight discrepancy between these two tubes. The proportion of black pearlite in the new tube seemed higher than that in the failed one. The failed tube did not exactly display the band structure, but showed a partially equi-axied grain (Fig. 2(b)). Besides, the failed tube exhibited a grain size slightly larger than the new one. Overall, the above result implies that the failed tube was affected by the high temperature.

Table 1 Chemical compositions of different tubes

specimens \ element	C	Si	Mn	P	S	Fe
ASME SA178A criterion	0.06~0.18	--	0.27~0.63	0.035 max.	0.035 max.	Bal
New tube	0.175	0.185	0.698	0.016	0.038	Bal
Failed tube	0.075	0.086	0.485	0.014	0.056	Bal

Unit: wt%



(a)

(b)

Fig. 2. Cross-sectional SEM micrographs of the economizer tubes: (a) new tube; and (b) failed tube.

3.3 Mechanical Property Measurement

Table 2 shows the experimental results of the micro-hardness tests for these two tubes. It is clear that the average value of the failed tube (HV: 116.1) is much lower than that of the new one (HV: 167.5). Both the lower ratio of pearlite phase and the lower value in hardness for the failed tube are considered to reflect the lower carbon content in comparison with the new one.

The mechanical property of the two tubes was also examined by using tensile tests. The experimental results, including yield stress, ultimate tension stress and elongation are listed in Table 3. The mechanical properties, including YS, TS, and elongation, of the failed tube are less than those of the new one. On other hand, the mechanical properties of the failed tube still satisfactory met the criterion requirement, even though the properties were affected by the high temperature.

3.4 Corrosion Product Analysis

Figures 3 and 4 demonstrate the EDS and XRD analysis results of the corrosion products obtained from the outer and the inner surfaces of the failed tube, respectively. It is clear that, no matter whether found on the outer or the inner surfaces, the corrosion products are mainly composed of Fe and O which was identified as Fe_2O_3 from XRD analysis. Additionally, the slightly larger content of S found on the outer surface should come from the surrounding waste-heat atmosphere. In addition to Fe_2O_3, α-Fe was also detected in XRD signal of the corrosion product on the inner surface, indicating the thinner oxide layer formation. It is realized that the thinner oxide film on the inner surface resulted from the lower temperature due to the cooling of the flowing fluid. The above result reveals that, on both the inner and the outer sides of the economizer tube, there were no obvious aggressive corrosives from the environment.

3.5 Fracture Observation

With visual inspection, the fracture part of crack propagation appeared dark. The lower left fracture surface, showing metallic brightness, resulted from artificial impact after immersion in liquid nitrogen

Table 2 Micro-hardness (HV) of different tubes

Position / Specimens	*Cross section of the tube*						***Ave.***
	Outer side ←				→ Inner side		
New tube	176.8	176.0	164.3	159.6	161.9	166.4	***167.5***
Failed tube	113.1	124.4	110.8	113.1	109.3	126.0	***116.1***

Loading weight: 200g

Table 3 Results of the tensile tests for different tubes

Specimens		Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
ASME SA178A criterion		180	325	35
New tube	#N1	309.9	495.1	40.1
	#N2	350.8	497.3	41.8
Failed tube	#F1	307.0	394.0	37.4
	#F2	301.7	395.8	39.3

Gage length: 25 mm

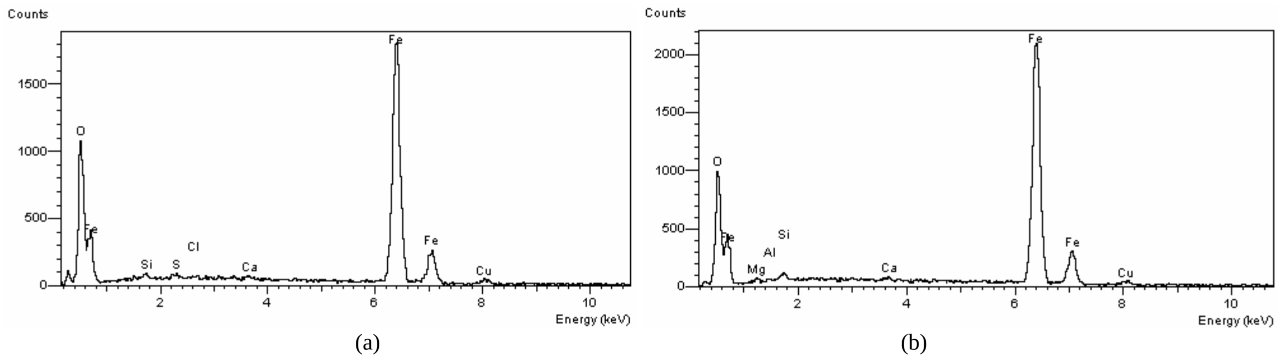


Fig. 3. EDS analyses of corrosion products obtained from different locations of the failed tube: (a) outer surface; and (b) inner surface.

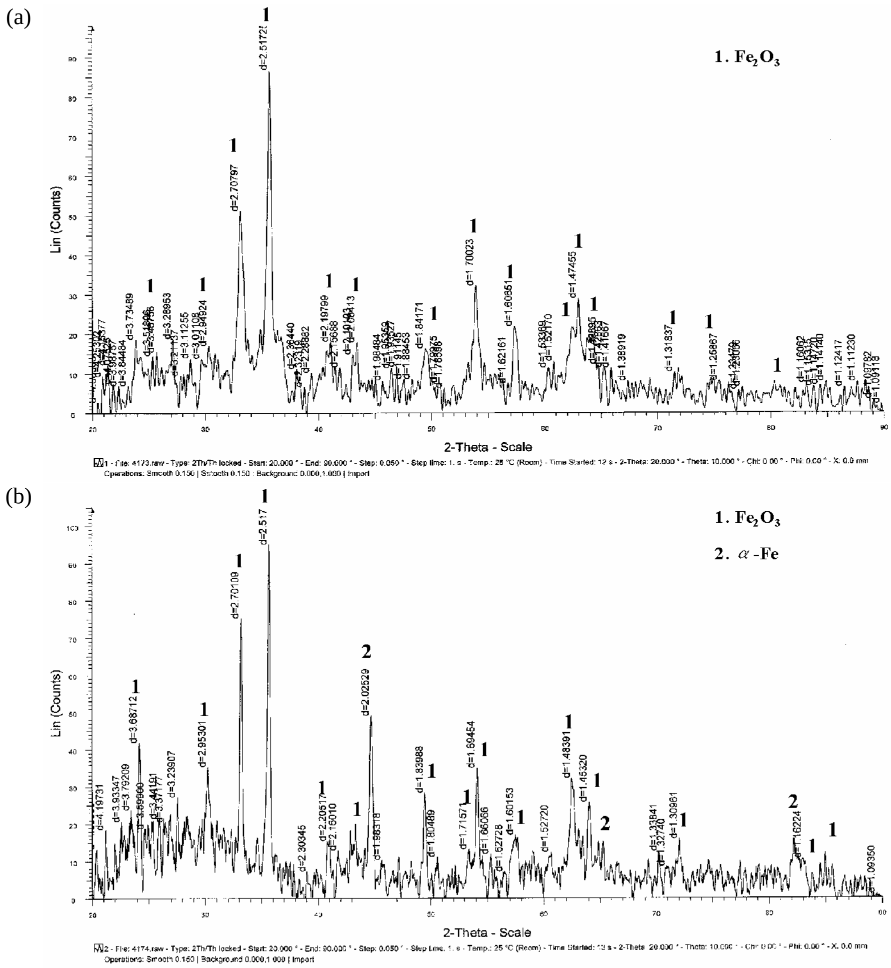


Fig. 4. XRD analyses of corrosion products obtained from different locations of the failed tube: (a) outer surface; and (b) inner surface.

(Figure 5(a)). SEM was also performed to examine the morphology of the fracture surface. However, due to the actual fracture surface being covered by oxide (the darker area), the fracture type could not be observed and identified. Therefore, the oxide was removed to explore the real morphology of the fracture surface.

Figure 5 (b) shows the fracture surface appearance of the failed tube after descaling. The region above the dotted line in the figure was the original darker region. SEM was also performed to observe the morphology of the fracture surface in detail. Fig. 6(a)~(c) are SEM micrographs at higher magnification for spot A~C, as designated in Fig. 5(b), respectively. Both spot A and B, located in the crack propagation region, revealed intergranular fracture (Figs. 6(a) and (b)). In other words, the fracture type through the whole region of the crack propagation surface was identified as intergranular. However, the fracture surface resulting from the artificial impact revealed a dimple morphology, as shown in Fig. 6(c).

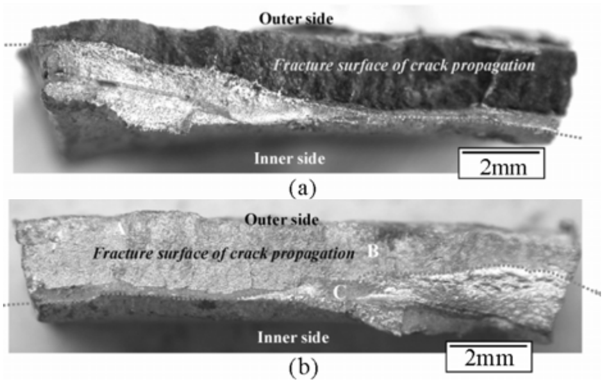


Fig. 5. The fracture surface appearance of the failed tube: (a) before descaling; and (b) after descaling.

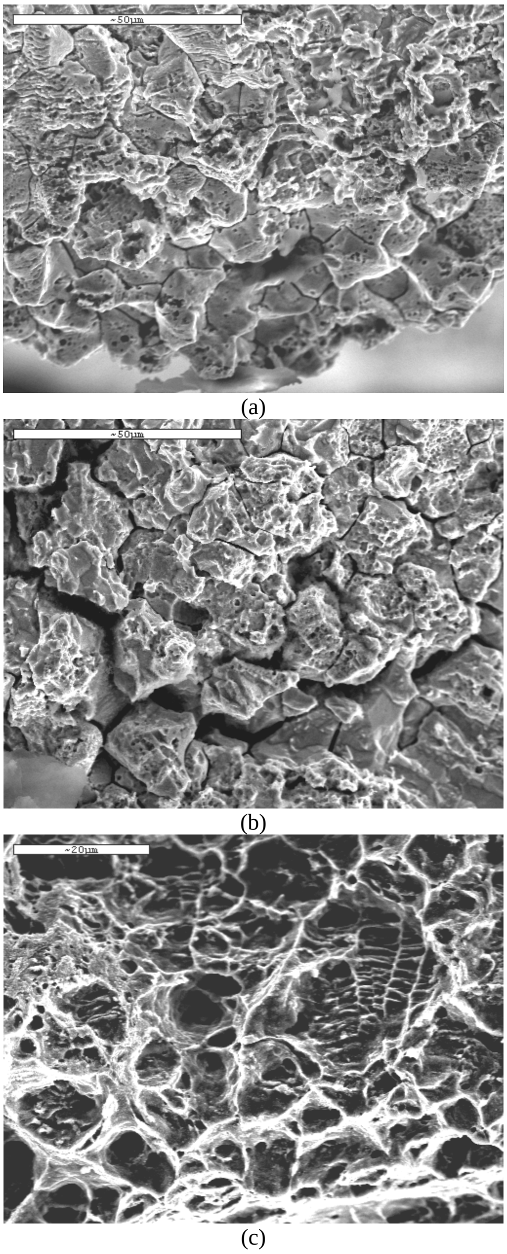


Fig. 6. SEM micrographs at higher magnification for: (a) spot A; (b) spot B; and (c) spot C, as designated in Fig. 5(b).

Generally, the formation of the intergranular fracture always corresponded to the metallurgical degradation or the elemental precipitation in the vicinity of the grain boundary. Therefore, in this study EPMA line scanning analysis was performed to evaluate some specific element distribution near the grain boundary of the failed tube. The result is shown in Figure 7. From Figs. 7(a) and (b), it is clear that two C signal peaks located in the grain boundaries showed carbide precipitation. Furthermore, a slightly higher intensity of S was also detected in the grain boundary. However, the content of P was independent of the locations along with the yellow dotted line in Fig. 7(a).

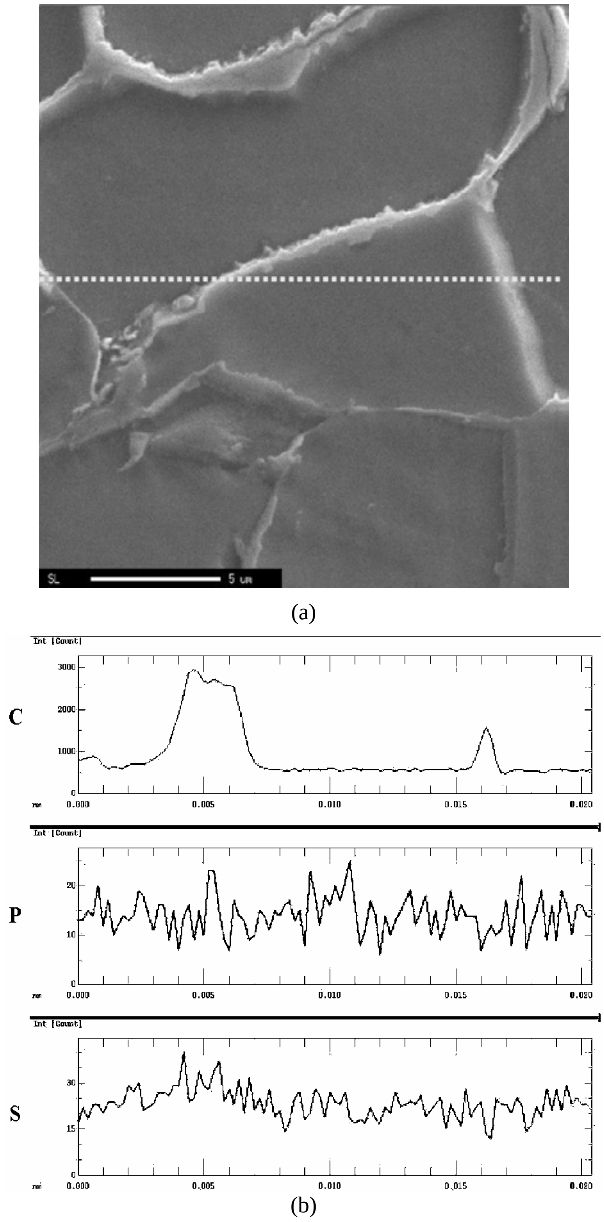


Fig. 7. EPMA line scanning analysis of failed tube: (a) SEM micrograph; and (b) C, P and S content distribution along the yellow dotted line in Fig. (a).

4. DISCUSSION

As mentioned above, although the material and mechanical properties of the failed tube, including chemical composition and metallurgical structure, were inferior to those of the new one, most of them still satisfactory met to the criterion requirement. Therefore, the crack formation did not result from the overall degradation in the particular tube. For the failed tube, the S content reached 560 ppm, which was almost twice the standard value (350 ppm). The degradation in toughness for the failed tube was due to the higher S content as expected. Besides, the type of crack propagation was identified to be intergranular, leading to the mechanical or metallurgical degradation in the grain boundary in a local region. The EMPA result demonstrated that the carbide precipitation and sulfur segregation took place in the grain boundary.

Carbides in steel can be precipitated in the grain boundary after thermal treatment in the range of 650~750℃. In addition, in the temperature range of 400~550℃, sulfur is more easily segregated in the grain boundary if its content is higher than the normal, such as in the failed tube of this study. Both intergranular carbide precipitation and sulfur segregation will lead to a decrease in toughness.

The crack formation might result from a combination of a decrease in the toughness, due to carbide precipitation and/or sulfur segregation in the grain boundary, and thermal fatigue due to the daily start-stop cycle. However, the actual operation temperature of the economizer tube was 140℃ which could not induce carbide precipitation and sulfur segregation. Therefore, the toughness degradation in the grain boundary must have taken place during the fin welding process. Toughness degradation due to an unsuitable welding process is generally called weld decay.(2,3)

The failure of the tube mainly resulted from the combination of an unsuitable welding process, unqualified materials, and fatigue due to the daily start-stop cycle. Therefore, the failure can be prevented by using qualified materials, applying post weld heat treatment (PWHT) on the welded tube, and reducing the frequency of the start-stop cycle, if possible.

5. CONCLUSIONS

In this paper, the failure cause of the economizer tube of the waste heat boiler has been investigated. Although the chemical composition indicated that the S content of the failed tube was much higher, even twice the standard value, its mechanical property still met the criterion of the standard requirement. It is concluded that the crack formation was not dominated by an overall degradation in a particular tube. From fractural observation, it was clearly evident that the crack propagated along the circumferential direction of the tube which was the same as the fin welding. The crack initiated from the outer surface, propagated through the whole thickness of the tube, and reached the inner surface. The fractural surface was identified as intergranular. Besides, the existence of the sulfur segregation and carbide precipitation in the grain boundary demonstrated the localized degradation of the failed economizer tube. Due to the lower operation temperature of the economizer tube, intergranular cracking resulting from the grain boundary segregation was not generated in the operation process. The localized toughness degradation took place in the unsuitable welding process generally called weld decay.

REFERENCES

1. Wen-Cheng Ho: “Study on the fatigue crack growth properties of A533 and A508 steels”, Master’s Thesis, Department of Mechanical Engineering, National Central University, 1997.
2. Kuang-Hung Tseng: Welding and Cutting, 9 (6), 1999, p. 17.
3. Chia-Ching Chiang and Hsin-Hao Wang: Welding and Cutting, 10 (2), 2000, p. 41. □