DEVELOPMENT OF FILLER METAL FOR WELDING OF NICKEL-BASE SUPERALLOY IN738LC BY MATHEMATICAL PROGRAMMING METHOD

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ABSTRACT

There is a great demand for filler metals for high-performance IN738LC Ni-base superalloy, which is widely used for blades in recent advanced gas turbines. These fillers are required to have compatible high temperature properties and hot cracking resistance. This paper reports on investigations made on the weld metal of alloys with a composition similar to that of IN783LC but varying Al, Ti and C contents. Their hot cracking susceptibility was examined by transverse Varestraint tests. The mathematical programming method was used to determine the optimum Al, Ti and C contents in the weld metal with a good balance of hot cracking resistance and mechanical properties at elevated temperatures. The method adopted was a satisficing trade-off method with a neural network model, which enabled to efficiently determine the optimum Al, Ti and C contents in the weld metal: 3%, 2% and 0.26%, respectively. The Varestraint tests indicated that the hot cracking susceptibility in the weld metal with the optimized Al, Ti and C contents was remarkably reduced. Hot tensile tests revealed that the creep rupture strength of the weld metal with that composition was also at a satisfactory level as slightly lower than that in the IN738LC base metal.

IIW-Thesaurus keywords: *Nickel alloys; Inconel; Weld metal; Consumables; Solid filler wire; Composition; Al additions; Ti additions; Carbon; Computation; Weldability tests; Elevated temperature strength; Hot cracking; Microstructure; Eutectics; Practical investigations.*

1 INTRODUCTION

Nickel-base superalloy IN738LC is widely used for high temperature applications, especially for blades in recent advanced gas turbines, due to its good mechanical properties at elevated temperatures [1-4]. As these blades are exposed to extremely high temperatures, they tend to suffer from significant material degradation during service [4-6]. For instance, serious damages like cracks and erosion may occur owing to the long-term exposure to high temperatures and severe loading conditions, even though they are made of the superalloy of excellent high temperature performance. Therefore, there are a lot of demands for the repair technique for damaged turbine blades in order to reduce the life cycle cost of gas turbines. From the viewpoint of convenience and cost performance most feasible methods are overlay and repair by arc welding techniques. However, Ni-base superalloys of high performance exhibit high hot cracking susceptibility in welding [7,8] because these alloys are remarkably hardened by the precipitation of γ′ phase during welding due to high contents of Al and Ti. Although hot cracking susceptibility of these alloys is known to be prevented by reducing the Al and Ti contents, it adversely degrades mechanical properties at elevated temperatures. Therefore, it is demanded to develop for this type of alloys filler metal being a compromise between excellent mechanical properties at elevated temperatures and hot cracking resistance in the weld metal.

In order to develop such filler metal for IN738LC, the optimum composition of Al, Ti and C in the weld metal which provide a good balance of hot cracking resistance and mechanical properties at elevated temperatures was investigated in this study. The mathematical programming method was used to determine efficiently and rationally the optimum contents of Al, Ti and C in the weld metal.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

The materials used were laboratory-melted alloy 738, which with various Al, Ti and C contents in order to evidence the effect of these elements on strengthening at elevated temperatures and the hot cracking susceptibility in weld metals. Commercial Inconel 738 and Inconel 600 were also used for comparison. The chemical compositions of these alloys are indicated in Table 1.

The transverse Varestraint test was used for evaluating the hot cracking susceptibility in the weld metal of these

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Table 1. Chemical compositions of materials used (mass%).

Mark	C	Cr	Mo	Al	Ti	Fe	Ni
Alloy LC1	0.095	15.89	1.82	1.73	1.75	0.02	Bal.
Alloy LC2	0.090	15.97	1.81	1.75	3.59	0.02	Bal.
Alloy LC3	0.095	15.92	1.82	3.48	1.76	0.01	Bal.
Alloy LC4	0.097	15.96	1.83	3.49	3.57	0.03	Bal.
Alloy LC5	0.29	16.09	1.83	1.73	1.74	0.01	Bal.
Alloy LC6	0.30	15.97	1.83	1.74	3.55	0.01	Bal.
Alloy LC7	0.030	15.97	1.82	3.55	1.75	0.01	Bal.
Alloy LC8	0.29	15.90	1.81	3.65	3.57	0.03	Bal.
Alloy LC9	0.20	15.99	1.81	2.59	2.60	0.02	Bal.
Alloy LC10	0.19	16.01	1.82	1.75	2.60	0.02	Bal.
Alloy LC11	0.20	16.02	1.83	2.64	1.81	0.02	Bal.
Alloy LC12	0.19	15.96	1.81	3.59	2.67	0.01	Bal.
Alloy LC13	0.19	15.91	1.81	2.56	3.55	0.03	Bal.
Inconel 738	0.11	15.93	1.75	3.40	3.47	0.30	Bal.
Inconel 600	0.01	21.7	8.83	0.26	0.16	4.24	Bal.

alloys. The welding current, voltage and velocity were 150A, 13V and 1.67mm/s, respectively. The augmented strain in the Varestraint test was varied to 0.4%, 0.8% and 1.6%. Schematic illustrations of the transverse Varestraint test apparatus and specimens for this test are shown in Fig. 1. Mechanical properties at elevated temperatures were examined by the hot tensile test at 1123K.

3 THEORETICAL ANALYSIS METHODS FOR OPTIMIZING

The mathematical programming method was used to search efficiently the optimum contents of Al, Ti and C in the weld metal, which provide a good balance between high temperature properties and hot cracking resistance in welding. The method is composed of the neural network model for formulating the evaluating factors and the satisficing trade-off method with the genetic algorithm for searching the ideal point of evaluating factors. For optimizing the Al, Ti and C contents in the weld metal, the hot cracking susceptibility determined by the Varestraint test and the mechanical properties at elevated temperatures were used as evaluating factors.

In order to formulate these evaluating factors with limited experimental data, the neural network model was adopted for interpolation. The neural network is constituted by three layers as shown in Fig. 2. The input layer corresponds to the Al, Ti and C contents in the alloys. The output layer provides formulations of evaluating factors as functions of the element contents.

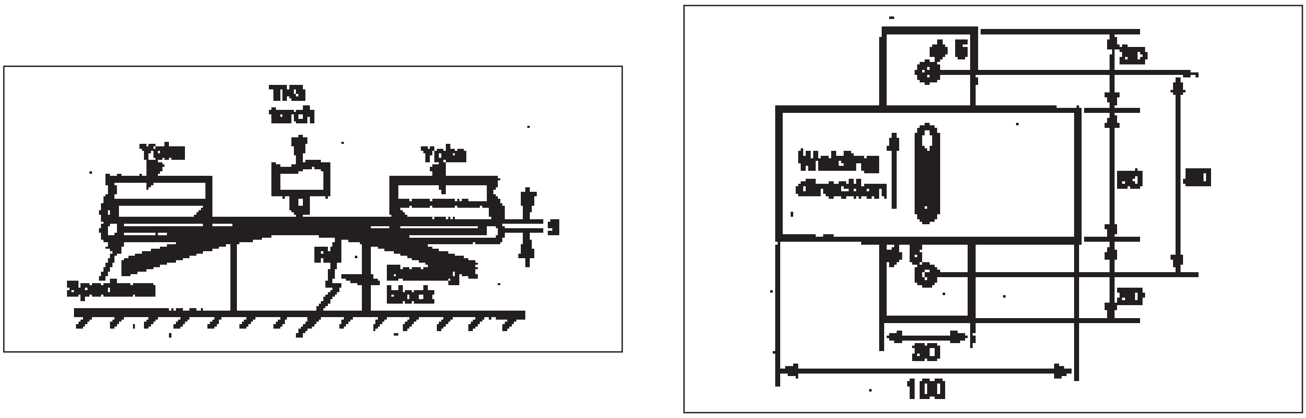
The genetic algorithm is a progressive idea to search an optimum condition on the basis of a concept of an evolutional selection. The algorithm is composed of processes as follows: (a) Primary generation, (b) Pairing, (c) Cross-over, (d) Calculation of fitness function, (e) Selection, (f) New generation, as shown in Fig. 3. The optimum condition was determined by calculation repeating these processes.

The satisficing trade-off method is one mathematical technique for searching optimum point satisfying all aspiration levels determined according to objective performances of evaluating factors, as demonstrated in Fig. 4. In this model, the ideal points and nadir points, which correspond to the maximum and/or minimum values of experimental data in evaluating factors, respectively, were set prior to the calculation. The optimum point was calculated by minimizing the following function:

$$g^k(x) = \max\{W_i^k (f_i(x) - f_i^k)\} \quad (1)$$

$$W_i^k = 1 / (f_i^k - f_i^*) \quad (2)$$

where f_i^k is the aspiration levels, f_i^* is the ideal points and $f_i(x)$ is the data points in the formulation of evaluating factors.



(a) Transverse Varestraint test **(b) Specimen**

Fig. 1. Schematic illustration of transverse Varestraint test and specimen for the test.

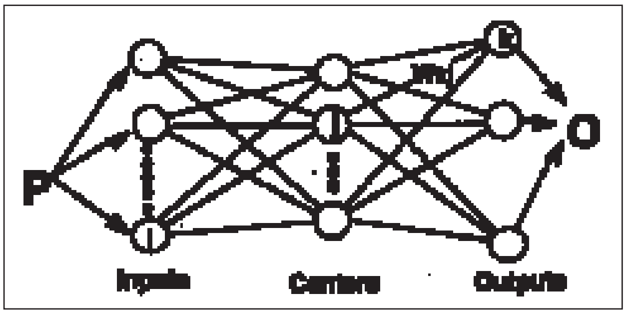


Fig. 2. Neural network model.

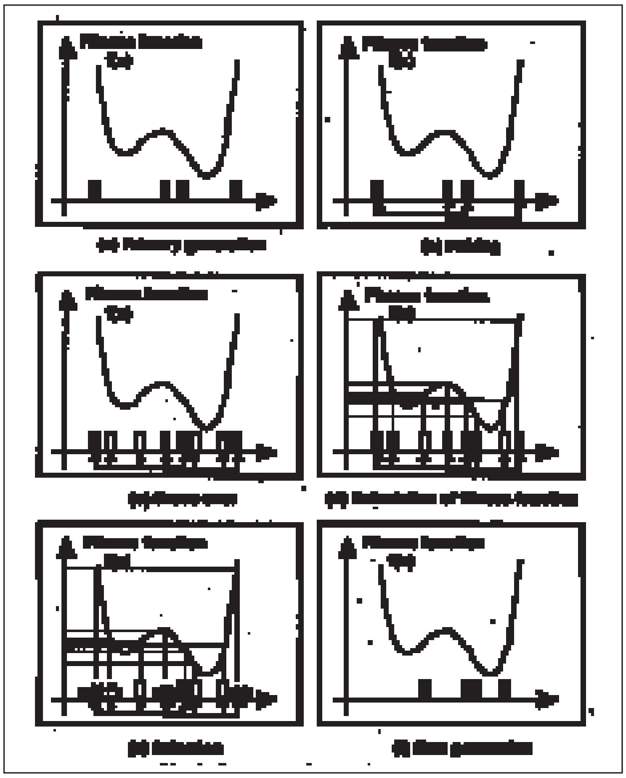


Fig. 3. Concept of genetic algorithm.

On the basis of the above-mentioned series of mathematical process, the optimum Al, Ti and C contents in the weld metal were calculated by using a computer.

4 RESULTS

4.1 Hot cracking susceptibility and mechanical properties in elevated temperatures

Hot cracking susceptibility in the weld metal of materials was examined by transverse Varestraint tests. Figure 5 shows the appearance of the weld metal of alloy LC10 after the Varestraint test. When an augmented strain of 0.8% was applied, small cracks occurred adjacent to the edge of the molten pools. Microscopic observation of the fractured surface revealed that the specimens were cracked by dendrite boundary fractures, as shown in Fig. 6. The feature that the dendrite surface was smooth is the evidence of liquid films existing at dendrite boundaries when the crack

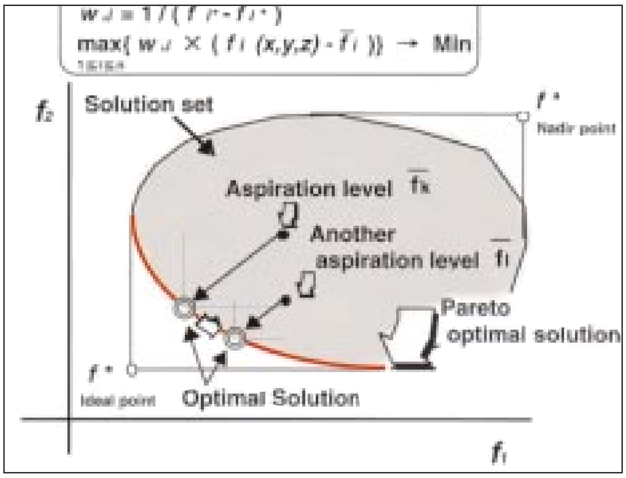
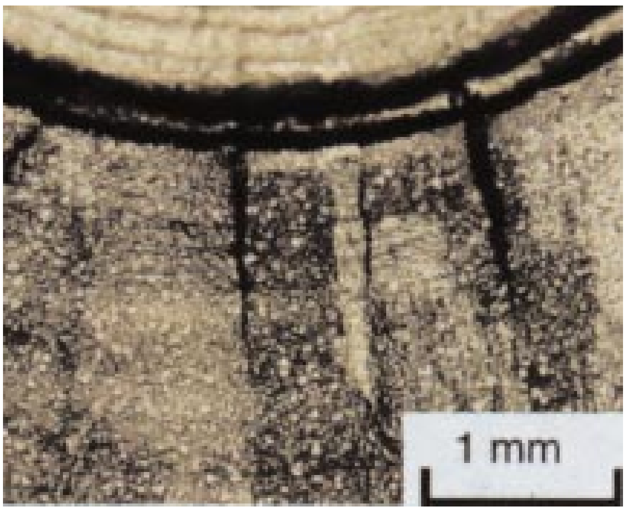


Fig. 4. Concept of satisficing trade-off method.

occurred. From these microscopic observations, cracks in the weld metal caused by the Varestraint test were considered to be solidification cracks.

Figure 7 shows the maximum and total lengths of cracks occurring in the weld metal in the Varestraint test. The maximum crack length increases with increasing Al and Ti contents in the case of the C content being constant. When the Al + Ti contents were constant, the maximum crack lengths decrease with increasing C content. A similar tendency can be seen for the total crack length. The mechanical properties of the weld metal at elevated temperatures were examined by hot tensile tests at

(a) Appearance of bead



(b) Hot cracking observed in weld metal
Fig. 5. Appearance of weld bead after transverse Varestraint test (Alloy LC10, Augmented strain: 0.8%).

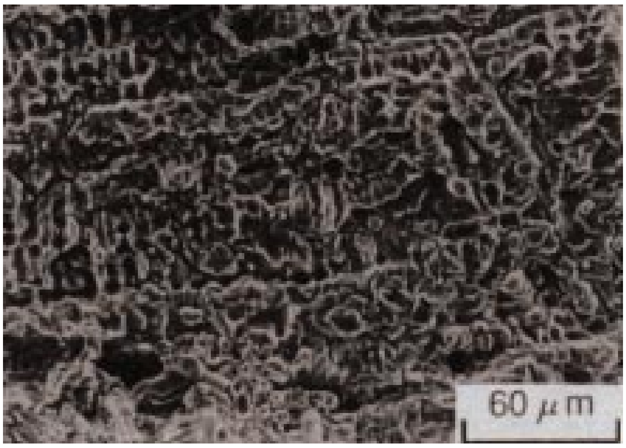
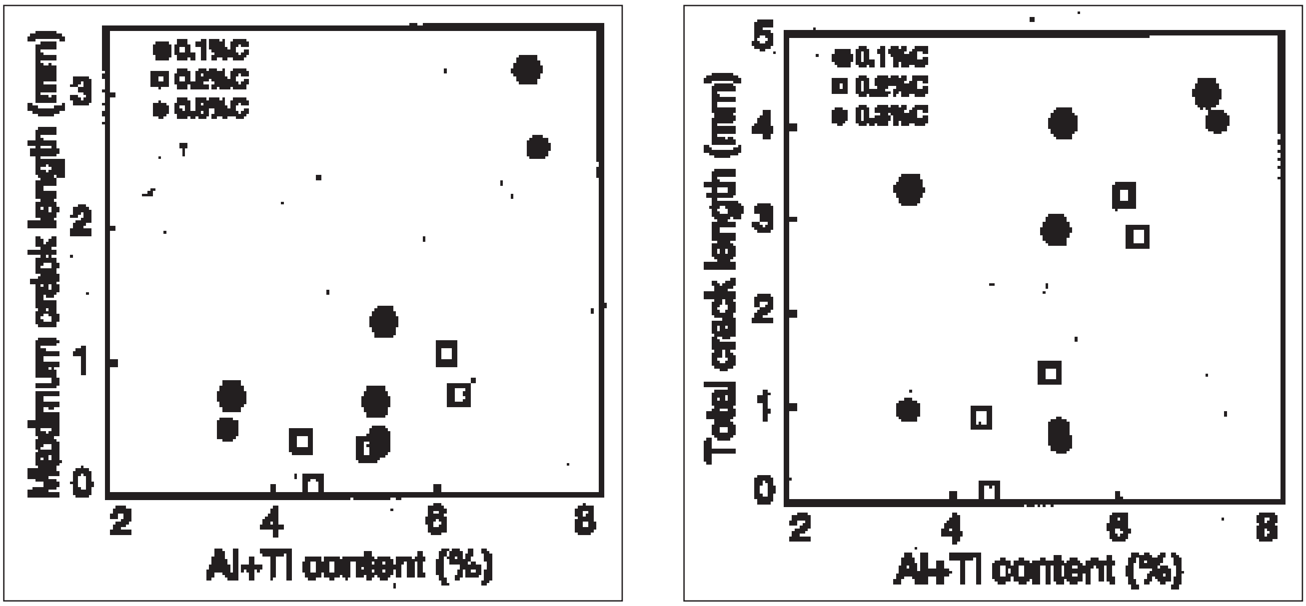


Fig. 6. Fractograph of hot crack occurred in weld metal after transverse Varestraint test (Alloy LC4).

1123K. Figure 8 indicates the effects of the Al, Ti and C contents on the tensile strength and elongation of the weld metal. The tensile strength decreases with increasing Al and Ti contents when the C content is constant. In contrast, the elongation decreases with increasing Al and Ti contents in the case of the C content being at the same level.

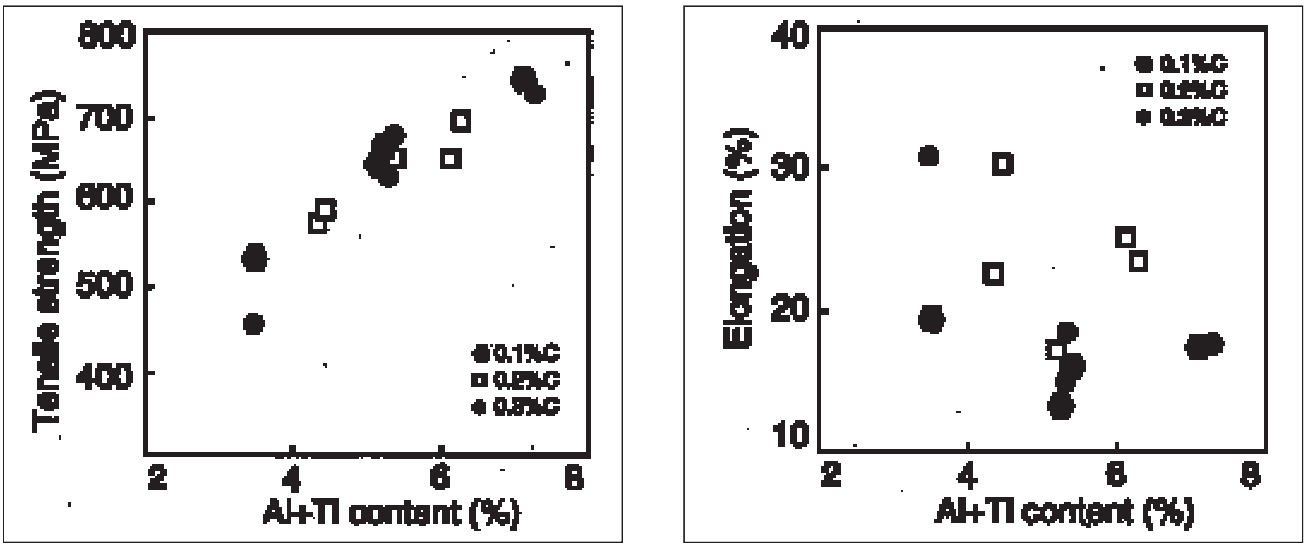
4.2 Determination of the optimum Al, Ti and C contents in the weld metal

For determining the optimum Al, Ti and C contents in the weld metal, the maximum and total crack lengths, tensile strength and elongation of weld metal were formulated using the neural network model as functions of the contents of these elements. Figure 9 shows formulated



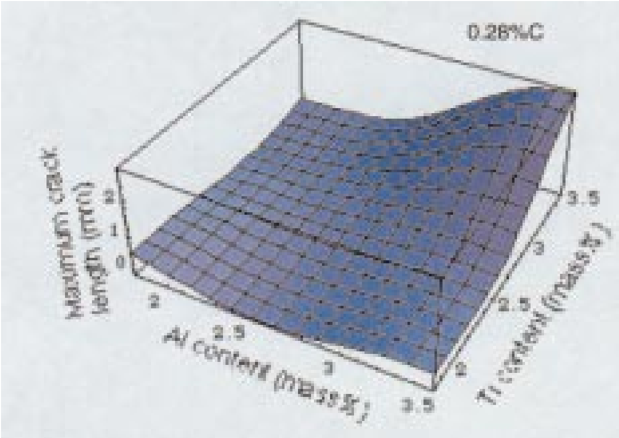
(a) Maximum crack length **(b) Total crack length**

Fig. 7. Maximum and total length of cracks occurred in weld metals after transverse Varestraint test (Augmented strain: 0.4%).

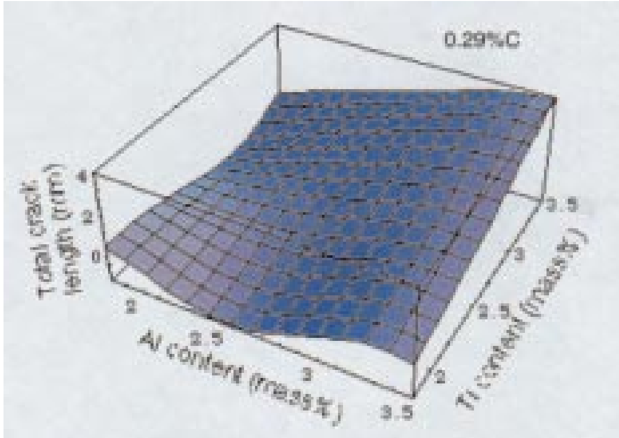


(a) Tensile strength **(b) Elongation**

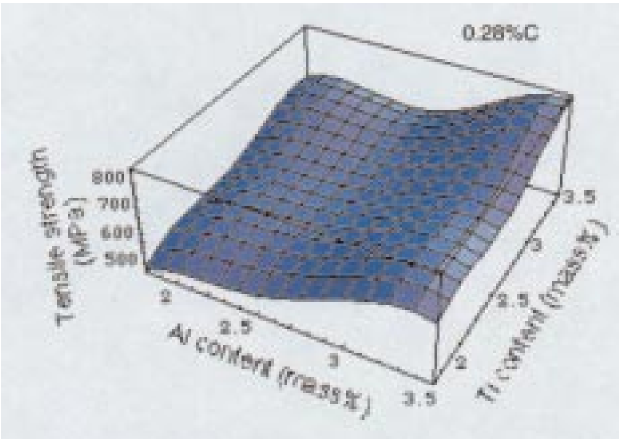
Fig. 8. Effect of Al + Ti content on tensile strength and elongation at 1123K.



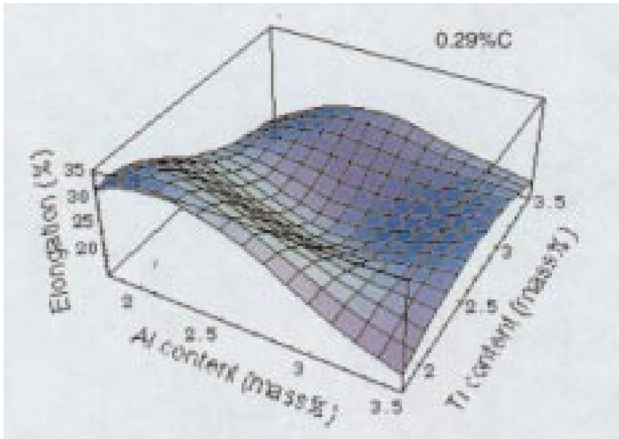
(a) Maximum crack length



(b) Total crack length



(c) Tensile strength



(d) Elongation

Fig. 9. Contour maps of maximum crack length, total crack length, tensile strength and elongation.

results of these evaluating factors represented as 3-dimensional contour maps. The curved surfaces of these contour maps were smooth and had no plural polarizations. The optimum Al, Ti and C contents in the alloy were calculated by the satisficing trade-off method with the genetic algorithm, using previously formulated results as evaluating factors. The aspiration levels of the tensile strength and elongation at elevated temperatures were determined at 604MPa, which is 80% of that in Inconel 738, and 15%, which is equal to that of Inconel 738, respectively. The aspiration levels of maximum and total crack lengths were set at 0.35mm and 0.6mm, respectively. These values are the respective minimum values determined by the Varestraint test. Figure 10 indicates a thus calculated contour map for the evaluating function. The optimum contents, which were calculated by the satisficing trade-off method, were also plotted on this map. In calculation, the value of the evaluating function was determined as each evaluating factor to be satisfied with the respective aspiration level. As the results, the optimum Al, Ti and C contents in the alloy were obtained as 3%, 2% and 0.26%, respectively, as shown in Fig. 10.

In order to ensure the validity of this calculation, the hot cracking susceptibility and mechanical properties at elevated temperatures in the weld metal of the alloy, with thus determined optimum Al, Ti and C contents (alloy OP), were examined and compared with those of commercial Ni-base superalloys Inconel 738 and Inconel 600. Figure 11 shows the appearance of the specimens after the Varestraint test, which indicates that many cracks occurred adjacent to the edge of the molten pools in the weld metals of commercial Inconel 738 and Inconel 600. In contrast, a number of cracks occurred in the weld metal of alloy OP where the optimum Al, Ti and C contents were remarkably less than those in the commercial alloys. Figure 12 compares the maximum and total crack lengths for the commercial Ni-base superalloys and alloy OP. Not only the maximum crack lengths but the total crack lengths in the weld metal of

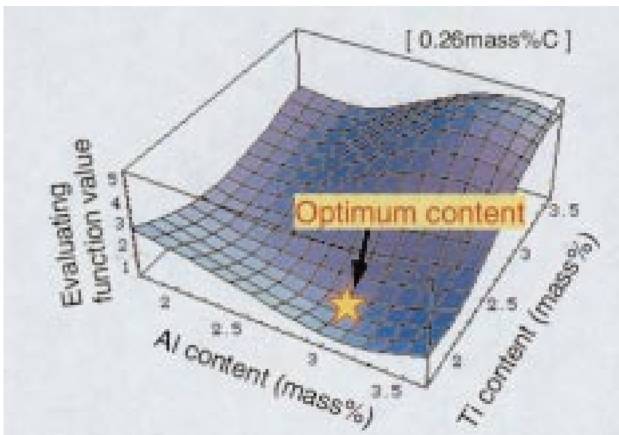


Fig. 10. Contour map of evaluating function.

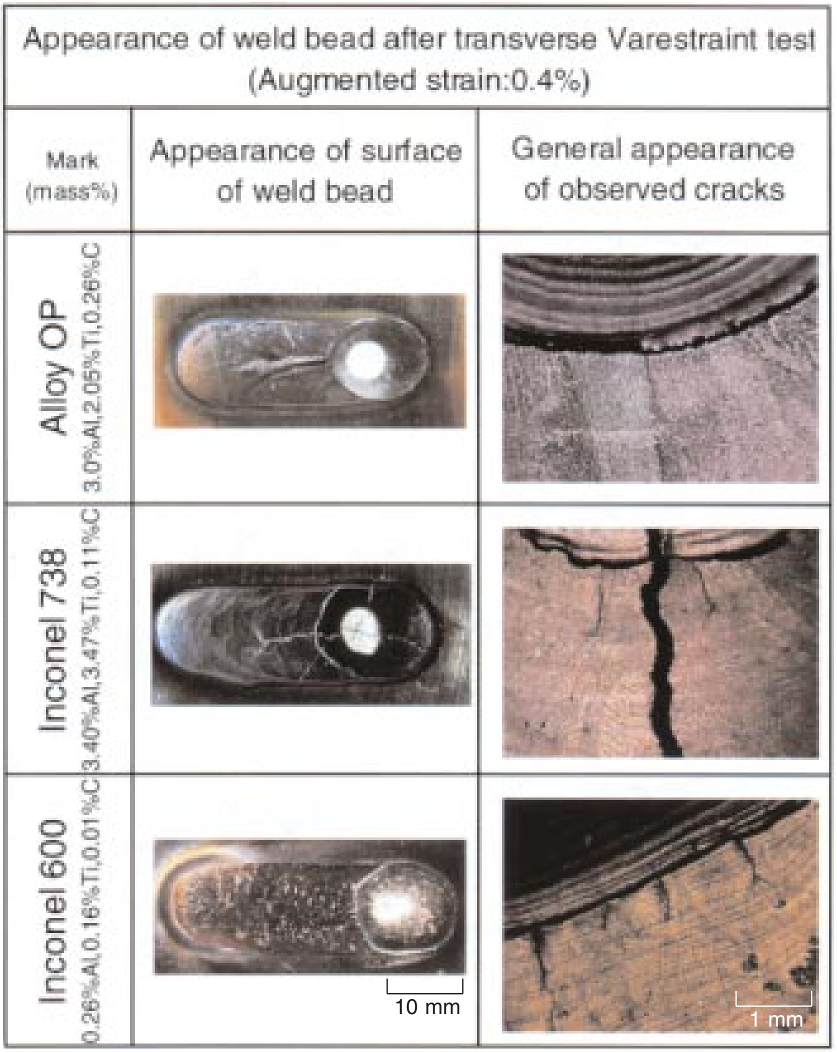
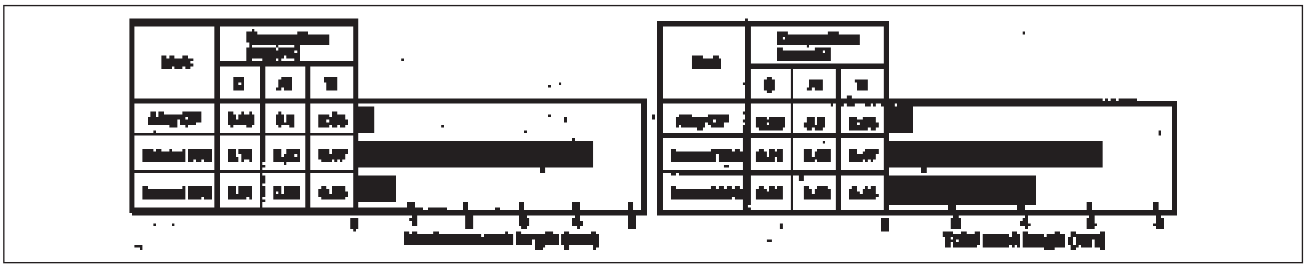
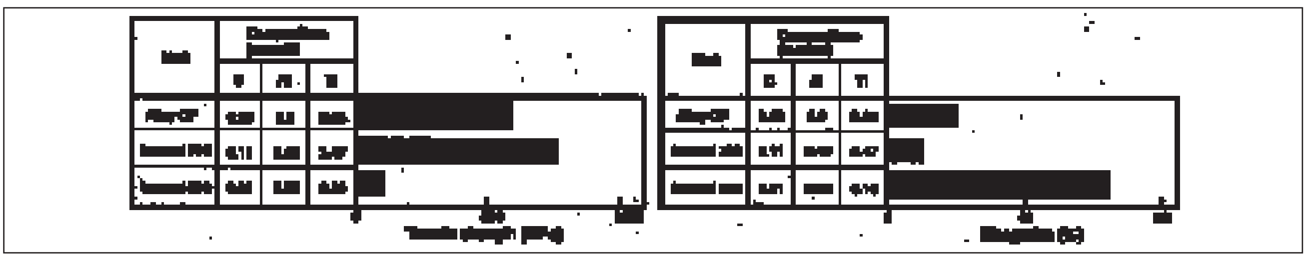


Fig. 11. Appearance of weld bead after transverse Varestraint test (Augmented strain: 0.4%).



(a) Maximum crack length (b) Total crack length

Fig. 12. Comparison of solidification cracking susceptibility measured by transverse Varestraint test in alloy OP, Inconel 738 and Inconel 600.



(a) Tensile strength (b) Elongation

Fig. 13. Comparison of tensile strength and elongation measured by hot tensile test in alloy OP, Inconel 738 and Inconel 600.

alloy OP were much less than those of the other commercial alloys. The hot tensile properties at 1123K for the welded joints in alloy OP, Inconel 738 and Inconel 600 are shown in Fig. 13. The test results indicate that the tensile strength in the alloy OP joint is about 80% of that in commercial Inconel 738 as shown in Fig. 13 (a). Moreover the elongation in the alloy OP joint was about twice that in the weld metal of commercial Inconel 738, as shown in Fig. 13 (b).

These experimental results have shown that the weld metal with the newly determined Al, Ti and C contents provide a good balance in mechanical properties at elevated temperatures and hot cracking resistance.

5 DISCUSSION

In order to clarify the cause of improvement of hot cracking susceptibility in the weld metal of alloy OP with the newly determined Al, Ti and C contents, the effect of the C content on the microstructure in the weld metal was investigated.

Figure 14 shows weld metal microstructures of the alloys containing an Al + Ti contents of about 6.5%, with a C content increased from 0.097% to 0.29%. A eutectic phase was observed at dendrite boundaries in the weld metal of these alloys. The eutectic phase increases with increasing C content. Figure 15 shows a SEM image

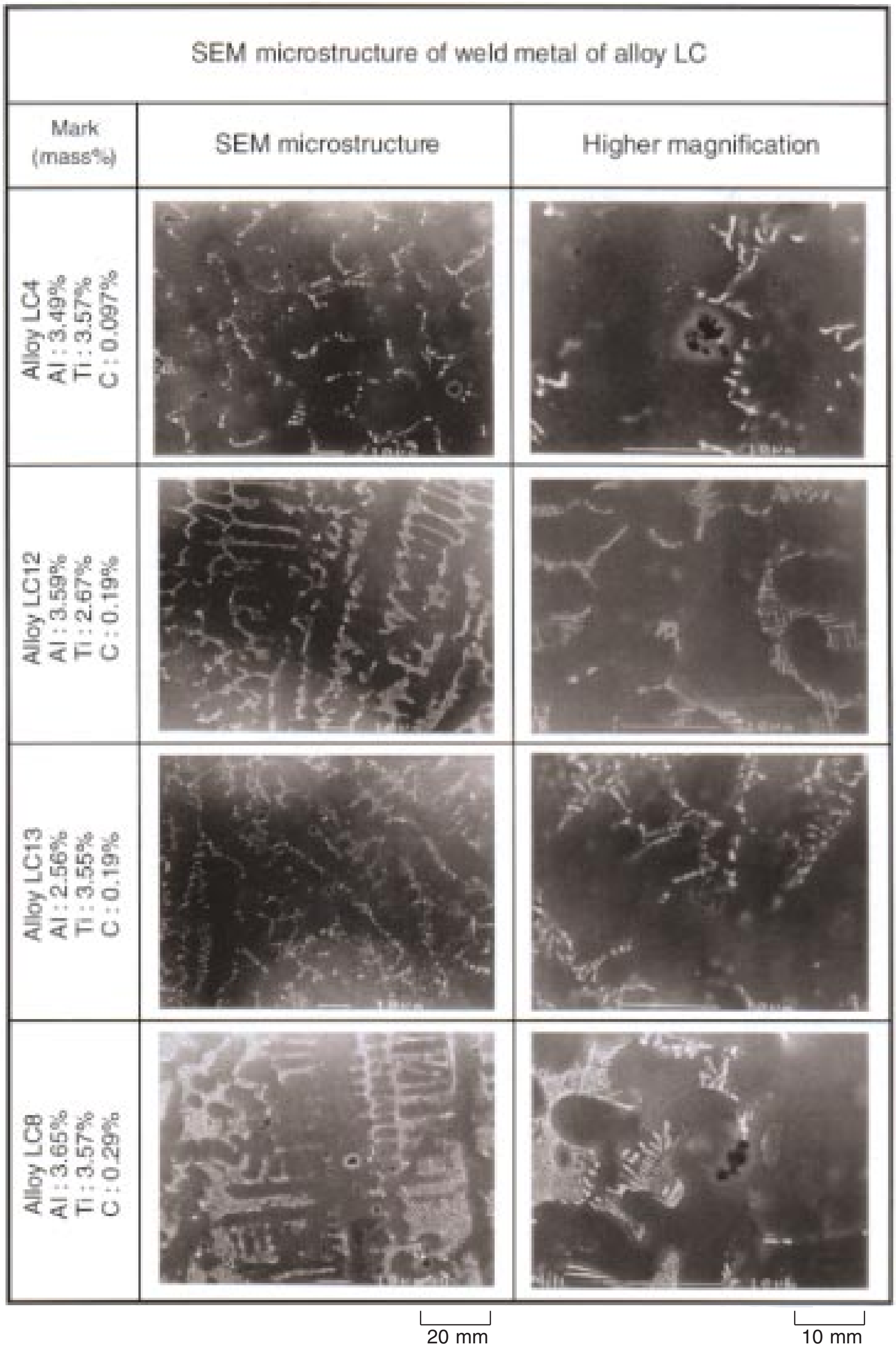


Fig. 14. SEM microstructure of weld metals.

and the result of EPMA analysis for the eutectic phase respectively. From the element mapping by EPMA analysis, it was apparent that this phase was enriched in Ti and C. Figure 16 shows a transmission microstructure, diffraction pattern and identified result for the eutectic phase. This result suggests that these eutectic phases were composed by TiC and the matrix. Other types of eutectic phase were also observed at the dendrite boundaries. These phases mainly exist at the triple point of the dendrite boundaries and are characterized as blocky shapes, as shown in Fig. 17. These eutectic phases were identified as γ-matrix/γ′ phase [$Ni_3(Ti,Al)$]. On the other hand, as shown in Fig. 18, the number of eutectic γ-matrix/γ′ phases at dendrite boundaries decreases with increasing C content in the weld metal. It was reported by Ikawa et al. that the eutectic γ-matrix/γ′

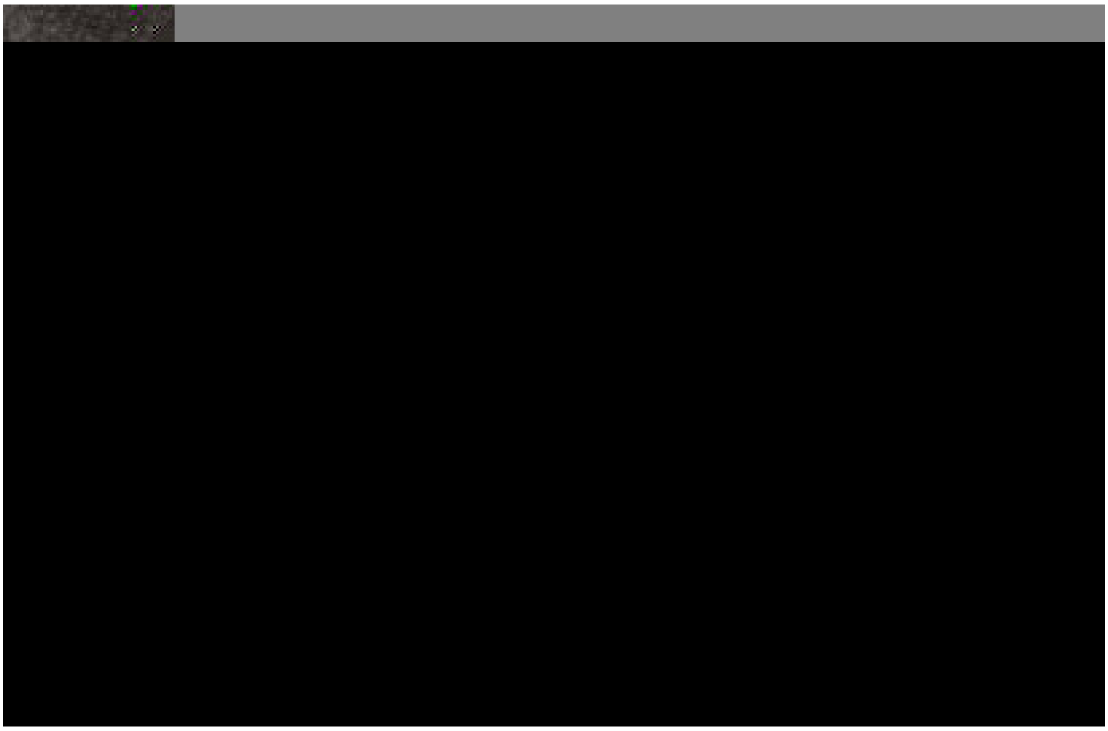


Fig. 15. SEM structure and elemental scanning images of precipitation in weld metal.

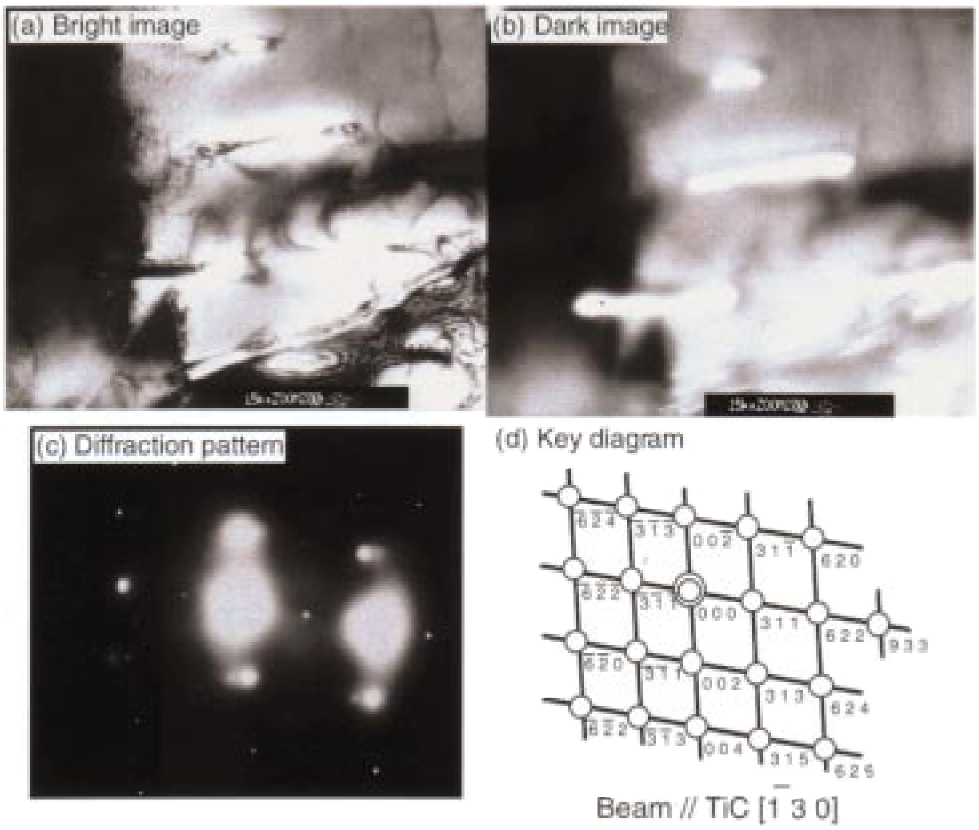


Fig. 16. TEM images, diffraction pattern and key diagram of eutectic phase at dendrite boudary.

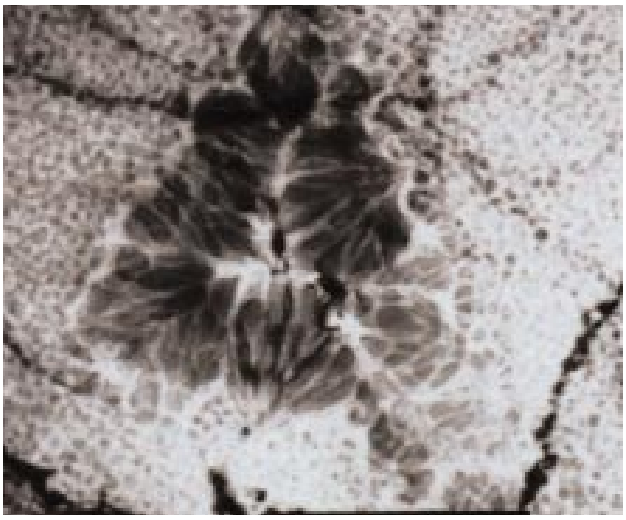


Fig. 17. TEM microstructure of eutectic phase in weld metal.

phases have a much lower melting point than the γ-matrix, which could be the main cause for solidification cracking in Ni-base super alloys [9]. Therefore, the decrease in γ-matrix/γ' eutectic phases at the dendrite boundaries in the weld metal of alloy OP with the newly determined Al, Ti and C contents seems responsible for the improvement of the hot crack susceptibility.

To clarify the reason for the decrease of eutectic γ-matrix/γ' phases as the C content increases, the phase transformation during solidification was next investigated by thermodynamic analysis. This was done by using Thermo-Calc. Figure 19 shows the amount of liquid phase as a function of temperature in the pseudo-binary γ-C system, as calculated by using Thermo-Calc. The amount of liquid phase during solidification is remarkably depending on the C content in the alloys. That is, in the case of the alloy with 0.29mass%C (alloy LC8), as the temperature decreases, the liquid phase decreases more rapidly in the temperature range just above the

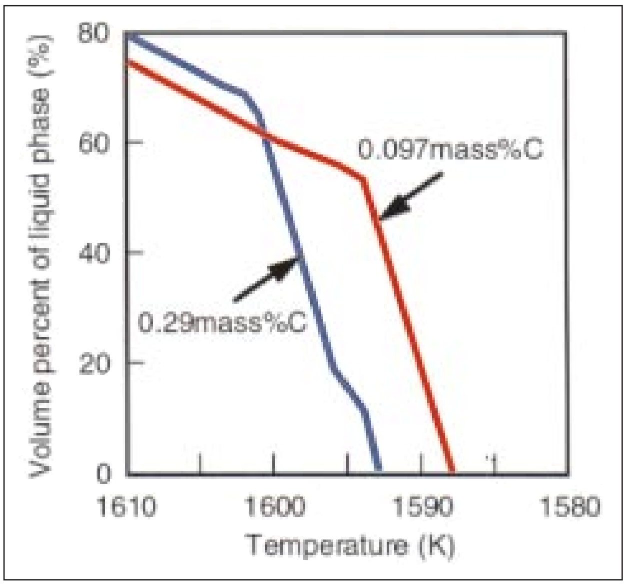


Fig. 19. Relationship between temperature and volume percent of liquid phase at dendrite boundary in the final stage of solidification calculated by Thermo-Calc.

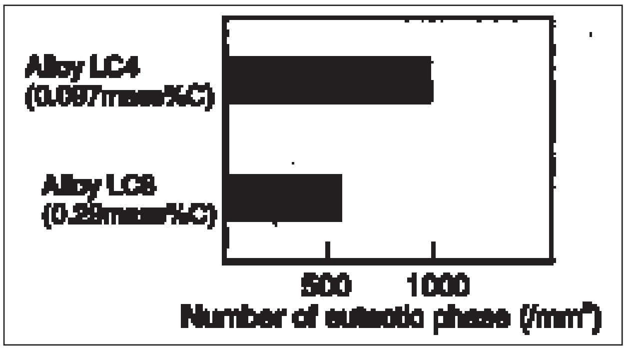


Fig. 18. Effect of C content on number of eutectic phase of γ/γ' in weld metal.

solidifying temperature than in the case of the alloy with 0.097mass%C (alloy LC4). Normally the alloy with a high C content is sequentially solidified as

$$L \rightarrow L + \gamma \rightarrow L + \gamma / TiC \rightarrow L + \gamma + TiC + \gamma' \rightarrow \gamma + TiC + \gamma'$$

as shown here. In this sequence, the eutectic reaction of γ-matrix/TiC starts at 1635K. As a result, the amount of the liquid phase is clearly reduced due to the formation of γ-matrix/TiC in the alloy with a higher C content. In addition, the precipitation of TiC also causes the amount of eutectic γ/γ' to decrease, because Ti is a compositional element of γ' [$Ni_3(Ti,Al)$], which has a lower melting point in the final stage of solidification.

From the above discussion it may be concluded that the prevention of hot cracking in weld metal with the newly determined composition with a higher C content is due to the abrupt decrease in the liquid phase at the dendrite boundaries in the final stage of solidification, due to the formation of the eutectic of γ-matrix/Ti carbide and decrease of the eutectic of γ/γ'.

6 CONCLUSIONS

The composition in the weld metal for Ni-base superalloy Inconel 738, which provides excellent mechanical properties at elevated temperatures and hot cracking resistance has been investigated in the present study. In order to realize a good balance of these properties in the welded joint, the optimum Al, Ti and C contents in the weld metal of the alloy were determined by using the mathematical programming method. Conclusions obtained in this study are summarized as follows:

1 According to the transverse Varestraint test results, the hot cracking susceptibility in the weld metal of Inconel 738 was remarkably improved with increasing C content in the alloys.

2 The optimum Al, Ti and C contents in the Inconel 738 weld metal, as determined by calculation using the mathematical programming method were 3%, 2% and 0.26%, respectively.

3 Experimental results revealed that the Inconel 738 weld metal with newly Al, Ti and C contents has an excellent balance in mechanical properties at elevated temperatures and hot cracking resistance.

4 Thermodynamic analyses revealed that the improved hot cracking susceptibility in the weld metal with the newly determined higher C content can be attributed to the decrease in the liquid phase at the dendrite boundaries in the final stage of solidification due to the formation of the eutectic of γ-matrix/Ti carbide.

REFERENCES

1. J.S. Zhang, Z.Q. Hu, Y. Murata, M. Morinaga and Y. Yukawa, “Design and Development of Hot Corrosion-Resistant Nickel-Base Single-Crystal Superalloys by the d-Electrons Alloy Design Theory: Part I. Characterization of the Phase Stability”, Metallurgical Transactions A, 24A (1993) 2443-2450.

2. J. Li and R.P. Wahi, “Investigation of γ/γ' Lattice Mismatch in the Polycrystalline Nickel-Base Superalloy IN738LC: Influence of Heat Treatment and Creep Deformation”, Acta Metall. Mater., 43-2 (1995) 507-517.

3. Y. Wang, D. Mukherji, W. Chen, T. Kuttner, R.P. Wahi and H. Wever, “The Cyclic Creep Behavior of Nickel-Base Superalloy IN738LC”, Z. Metalkd., 86-5 (1995) 365-370.

4. H. Chen, W. Chen, D. Mukherji, R.P. Wahi and H. Wever, “Cyclic Life of Superalloy IN738LC Under In-phase and Out-of-phase Thermo-mechanical Fatigue Loading”, Z. Metalkd., 86-6 (1995) 423-427.

5. D. Bettge, W. Österle and J. Ziebs, “Temperature Dependence of Yield Strength and Elongation of the Nickel-base Superalloy IN738LC and the Corresponding Microstructural Evolution”, Z. Metalkd., 86-3 (1995) 190-197.

6. S. Esmaeili, C.C. Engler-Pinto Jr., B. Ilschner and F. Rézaï-Aria, “Interaction Between Oxidation and Thermo-Mechanical Fatigue in IN738LC Superalloy-I”, Scripta Metallurgica et Materialia, 33-11 (1995) 1777-1781.

7. T.F. Berry and W.P. Hughes, “A Study of Strain-Age Cracking Characteristics in Welded René 41-Phase II”, Welding Research Supplement, (1969) 505s-513s.

8. N.L. Richards and M.C. Chaturvedi, “Effect of Minor Elements on Weldability of Nickel Base Superalloys”, International Materials Reviews, 45-3 (2000) 109-129.

9. H. Ikawa, S. Shin and Y. Nakao, “Study on Weld Cracking in Ni-Base Superalloy, Inconel 713C”, Transactions of Japan Welding Society, 2-2 (1971) 81-89.