Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September–October
2006

Brittleness temperature range of Fe-Al alloy

J. Adamiec*, M. Kalka
Department of Materials Science, Silesian University of Technology,
ul. Krasińskiego 8b, Katowice 40-019, Poland
* Corresponding author: E-mail address: janusz.adamiec@polsl.pl

Received 15.03.2006; accepted in revised form 30.04.2006

Materials

ABSTRACT

Purpose: The purpose of this paper was to experimentally determine the brittleness temperature range of an alloy based on the intermetallic FeAl phase matrix. This was done in order to evaluate the applicability of the said alloy for bonding using welding methods, and specifically, whether the character of the brittleness temperature range of the material indicates susceptibility to hot cracking.
Design/methodology/approach: The research was executed using a Gleeble 3800 type simulating device. A simulation of the heating process at a set rate of 20ºC/s was conducted in order to determine the NST and then NDT temperatures during the heating stage, followed by the determination of DRT temperature during the cooling stage. This allowed to evaluate the brittleness temperature range.
Findings: The executed tests allowed to determine the brittleness temperature range for the examined FeAl alloy which was found to be situated between 1320°C and the liquidus temperature for the heating stage, and down to 1330 ºC for the cooling stage. The index of hot cracking resistance was found to be 0.05.
Research limitations/implications: The method of simulating the flow of a welding process using the Gleeble 3800 simulator allows to simply and effectively determine the characteristic temperatures of the process and the susceptibility of a given alloy to hot cracking.
Originality/value: Using a Gleeble 3800 type simulator for the examination of an FeAl alloy in a semi-solid state enables one to evaluate the material's suitability for permanent bonding, eg. welding. Such data is indispensable for a technologist or a constructor designing components made of an alloy based on the FeAl phase.
Keywords: Metallic alloys; FeAl intermetallics; Brittleness temperature range; Hot cracking

1. Introduction

Alloys based on the Fe-Al intermetallic phases matrix are becoming increasingly popular in terms of practical usage, due to their high resistance to oxidation, carbonization and sulfurization processes in high temperatures and their resistance to the effect of exposition to liquid salts [1]. Another important factor deciding about their application is the low cost of their main components, eg. iron and aluminium. A high content of aluminium also lowers the alloys intrinsic density (ρ = 5,6 g/cm^3), which, of course, lowers the weight of components made using the alloy [1-4].

The application of these alloys as construction materials should be preceded with a study of technological usefulness, in this case their suitability for welding [5]. The executed tests of weldability evaluation clearly indicate, that the alloys based on the matrix of intermetallic phases belong to the group of hard weldable materials, if weldable at all [6-9]. An important factor limiting their weldability is their susceptibility to hot cracking, both over the solidus temperature and below [9].

The welding of metals requires using high power concentrated heat sources, which besides having a favourable influence relying on melting the edges of the bonded materials, introduce irregularity in the temperature distribution in the material. This irregularity and a high gradient of temperature during welding are the cause of strain and stress in the welded material. The strains, to which the metal heated to high temperatures is exposed, can be the cause for forming of intercrystalline cracks, both in the weld

itself and in the heat affected zone. The low ductility of metal in high temperature ranges is also considered to be the main cause for the forming of hot cracks [10-11].

During the cooling of the liquid metal, eg. in the weld pool below the liquidus temperature, the primary crystals overgrow orthogonally to the direction of heat flow. These crystals bond with each other forming a coherent, but not entirely solidified mass [11, 12]. The metal gains a certain degree of mechanical strength, but it remains brittle until the ductility recovery temperature is reached (DRT). Further cooling of the bond causes a significant increase in the ductility of the material. The range between the nil-strength temperature (NST) and the ductility recovery temperature is considered to be the brittleness temperature range (BTR) (Fig. 1.) [13, 14].

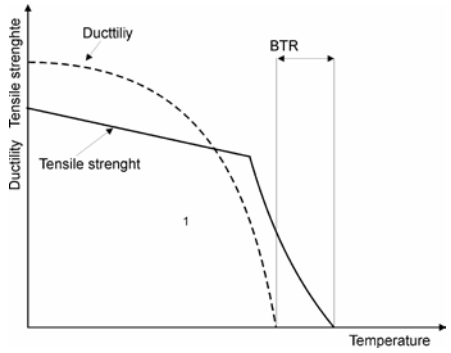

Fig. 1. Mechanical properties of an alloy prone to hot cracking in the vicinity of the solidus temperature

The temperature range during the solidification of the weld, in which the weld has only minimal plasticity, is referred to as the brittleness temperature range (BTR), and it determines whether the weld is susceptible to hot cracking.

The weld material in this range is subjected to strain resulting from shrinkage (Δe_{so}), and the influence of the thermal cycle of welding (Δe_k). The intensity of these strains buildup determines whether the solidifying weld will crack (Fig. 2) [13, 15].

According to N. Prochorow [1], if the sum of the strains ($\Delta e_{so} + \Delta e_k$) exceeds the minimal plasticity (P_{min}) cracking will occur in the weld (Fig. 2, line 2). In the case when this sum will remain lower than P_{min}, the material will show a certain reserve of plasticity (Δe_z) (Fig. 2, line 1) [6].

Also an exceedingly great rate and temperature of strain in the BTR range (Fig. 2, line 2) may cause hot cracking of the weld.

The literature lacks data in this area regarding the alloys based on the matrix of Fe-Al intermetallic phases. Thus, research was undertaken in order to determine the liquidus and solidus temperature, and the following:

- Nil-strength temperature (NST) - the temperature during heating at which the strength of the material tends to zero,
- Nil-ductility temperature (NDT) - the temperature during heating at which the ductility of the material tends to zero,
- Ductility recovery temperature (DRT) - the temperature during cooling at which the material starts to show an ability to become plasticly deformed,
- Brittleness temperature range (BRT) - the temperature range eg. during welding in which the material is susceptible to hot cracking,
- Cracking resistance index $R_f=(T_l\text{-NDT})/NDT$ [14].

The tests of high temperature brittleness of an FeAl alloy were executed using a Gleeble 3800 device.

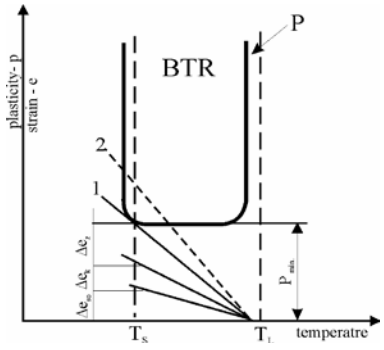

Fig. 2. A change in the plasticity of metal in crystallization temperatures range [6]

2. Materials for research and methodology

2.1. Material for research

An alloy based on the Fe-Al intermetallic phases matrix was used for the purposes of the described experiments. The alloy was smelted in the laboratory in a VSG-02 vacuum furnace mady by the Blazers company. Al_2O_3 crucibles were used for the melting. The process took place in a $5x10^{-2}$ torr vacuum. The superheating temperature of the alloy before casting was 30-50°C above the liquidus line. In order to homogenize the structure of the ingot, the alloy was remelted four times, and then cast into a graphite mould preheated to 400 °C giving a cylindrical casting measuring ø12 x 140. The chemical composition and the basic mechanical properties are shown in Table 1.

2.2. The determination of the liquidus and solidus temperatures

The method of differential thermal analysis (DTA) was used for the determination of the liquidus and solidus temperatures. The DTA tests were executed using a thermal analysis device SETSYS manufactured by Setaram company. A TG-DTA configuration was used in the test which allowed to measure the entalpy of the transformation related to the melting and solidification of the examined alloy. For the differential thermal analysis a „S" type Pt-Rh /Pt-Rh 10% thermocouple was used. The material was placed in a chemically inert argon atmosphere (Ar 99,999%). The maximal material heating temperature was set to 1460°C at a heating rate of 10°C/min.

Basing on the analysis of the DTA curves, the following temperatures were determined: liquid phase appearance temperature, eg. 1370 ^oC, the liquidus temperature, determined as the maximum on the endothermic peak, eg. 1436 ^oC, the temperature during cooling at which the first solid phase crystals appear, 1420 ^oC, and the solidus temperature determined as the maximum on the exothermic peak, 1411 ^oC (Fig. 3).

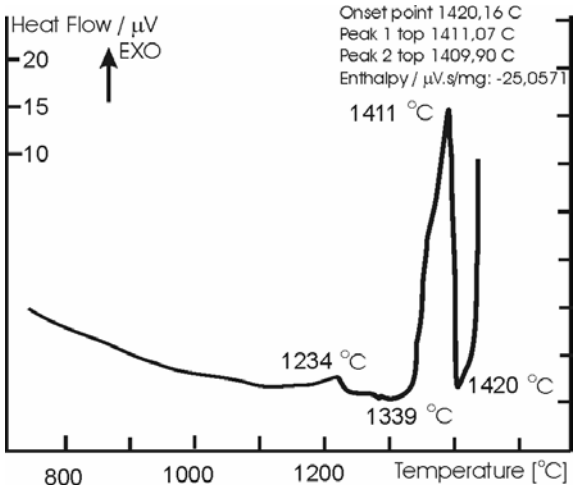

Fig. 3. Cooling stage DTA curve used in the research

2.3. Nil-strength temperature (NST)

The tests were executed on a Gleeble 3800 simulator. The tests were conducted with cylindical test samples measuring ø6 x 90 mm, to which S type thermocouples were bonded. The samples were securely placed in a chamber filled with argon, in copper heating fixtures, assuring a constant distance of 52,4 mm between them. A minimal preload of 0,6-0,7 kN was applied, which was maintained through the whole test. Next, the test samples were heated to 1300 ^{o}C at the rate of 20 ^{o}C/s, and then at the rate of 1 ^{o}C/s. The NST was determined as the average temperature, at which cracks appeared for six individual test samples. This was found to be 1342 ^{o}C (variability coefficient 0,07%).

2.4. The determination of NDT and DRT

The nil-ductility temperature (NDT) was determined during the heating of a cylindrical sample measuring ø10 x 120 mm in an argon atmosphere to a set temperature and the following tension at a set constant rate (Fig. 4).

The ductility recovery temperature (DRT) was determined during the cooling of test samples from the NST range to a set temperature and the following tension at a set constant rate. Table 2 shows the basic parameters of the tests executed.

The plots of strain change vs temperature during heating and cooling are shown in Fig. 5. The NDT value was accepted as 1367^{o}C and the DRT value as 1375 ^{o}C.

2.5. Fractographical research

The fractographical research was conducted on the samples' fractures after the tests. A scanning electron microscope of the Hitachi S3400N type and magnifications of 10x-5000x were used. The results are shown in Fig. 6.

3. Final remarks

One of the most important characteristics of a material, determining its susceptibility to hot cracking during welding is the nil-strength temperature. This temperature has been determined during a NST test. For the examined material, it equals to 1352 ^{o}C (Fig. 5). This means, that above this temperature the material (welded joint) is unable to endure any stress. The fractographical research revealed intercrystalline fractures on the surface of the tested specimens after the NST test. The grains on the examined surface were covered in a thin layer of a solidified liquid.

Table 1.
Chemical composition and mechanical properties of material for research

	Chemical composition [% wt.]						Mechanical properties			
Fe-38Al	Fe	Al	Mo	Zr	C	B	R_m [MPa]	R_e[MPa]	A_5[%]	E [GPa]
	balance	38	0,20	0,05	0,10	0,01	1000	400	6	261

Table 2.
Parameters and experiment results for the determination of NDT and DRT temperatures

		NDT test								
	sample	T_{nag} [^{o}C]	v_{nag} [^{o}C/s]	T_d [^{o}C]	$t_{wyg.}$[s]	$v_{odk,}$ [mm/s]	d_r [mm]	Δl [mm]	R_m [MPa]	Z [%]
NDT test	ND619	1250	20	1300	5	20	0	19.96	22.83	100
	ND621	1250	20	1310	5	20	5.52	8.82	20.97	44.8
	ND627	1250	20	1330	5	20	7.99	4.80	19.27	20.1
	ND626	1300	20	1340	5	20	8.92	3.01	20.75	10.8
	ND625	1300	20	1350	5	20	10.00	0.11	11.21	0
DRT test	DR626	1200	20	1250	5	20	1.86	13.03	24.43	81.4
	DR627	1200	20	1260	5	20	3.57	10.78	20.10	64.3
	DR624	1200	20	1280	5	20	8.05	1.86	18.53	19.5
	DR623	1200	20	1310	5	20	9.3	1.58	14.92	7.0
	DR622	1200	20	1330	5	20	9.95	1.03	15.11	0.5

where: $T_{nag,}$ – heating temperature, $T_{chłodz,}$ – cooling temperature, v_{nag} – heating rate, $t_{wyg,}$ – soaking time, T_d –test temperature, V_{odk} – strain rate, d_r – neck diameter, Δl – sample length increase, R_m – modulus of rupture, Z – reduction of area

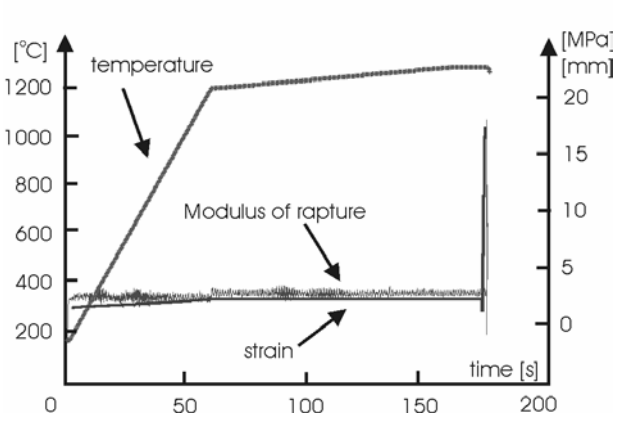

Fig. 4. NST Test, Gleeble 3800 (sample ND 619): temperature, stress and strain during the experiment

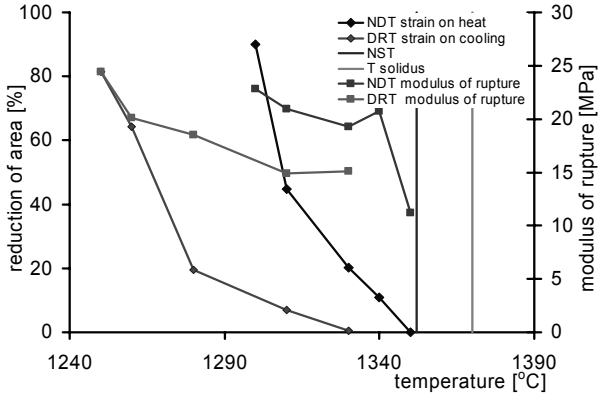

Fig. 5. Change in the reduction of area and modulus of rupture vs temperature for the examined alloy

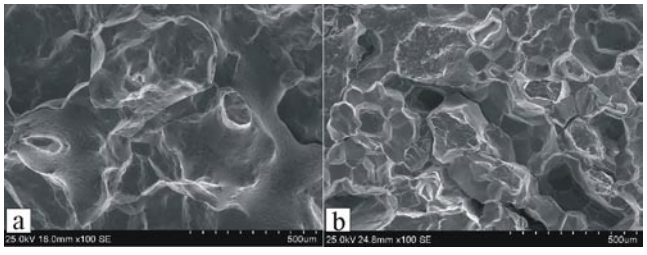

Fig. 6. Sample fracture surface after NST test

This indicates, that the loss of strength was a result of a partial melting of the grain boundaries, which in consequence lead to the disruption of a thin layer of the intercrystalline liquid (Fig. 6).

The brittleness temperature range for the examined alloy according to the results of [14] equals ca. 22 °C. However, considering welding processes, the temperature at which first crystals appear in the weld should be accepted as the upper limit. In this case, the brittleness temperature range lies between 1420 and 1330 °C, eg. 90 °C (Fig. 5).

In this range of temperatures the welded joint is prone to hot cracking, both over (in the weld) and below (in the heat affected zone) the solidus temperature. The R_f index was found to be 0.05.

4. Conclusions

The conducted research using the Gleeble 3800 simulator allowed to determine the brittleness temperature range. For the examined FeAl alloy this range equals 90 °C and it is wider in comparison with for example the 2205 steel.

Acknowledgements

The research was executed as a part of a research project financed by budget resources Nr 4T08C04024.

References

[1] V.K. Sikka, D Wilkening J. Liebetrau, B Mackey, Melting and casting of FeAl-based cast alloy, Materials Science & engineering, A 258, Elsevier, 1998, 229-235
[2] B.V. Reddy, S.C. Deeve, Termophysical properties of Fe-Al (Fe-40%Al), Intermetallics, 8 Elsevier 2000, 1369-1376
[3] J. Bystrzycki, Static recrystallization of shock-wave deformed Fe-40at% Al-Zr-B intermetallic, Intermetallics, 8, 2000 89-98
[4] R. Varin, Structural and Functional Intermetallics, Conference Intermetallic matrix alloys, Warsaw 2000, 1-14
[5] A. Jordan, O. Uwakweh, P. Maziasz, R. Reed, Weld thermal simulation and its effect upon the macrostructure of as-cast Fe-Al materials, Materials Characterization, 43 Elsevier 1999, 227-233
[6] N.N. Prohorow, Technological strength of materials in welding process, Welding process, nr 4, 1962 (in russian)
[7] A. Fasching, R. Burt, G Edwards S. David, Weldability of polycrystalline aluminides, Final report, Center for welding and joining research, Colorado School of Mines, 1996
[8] H. Neumann, TIG welding of iron Aluminide Fe_3Al, Advance Metallic and Their Joining, Bratislava 2004, 140 -CD
[9] W. Liu, Computational analysis and prediction of semi-solidification cracking, Computational Materials Science, 4, Elsevier 1995, 211-219
[10] J. F. Lacaster, The Metallurgy of welding process , WNT, 1966, 62-68 (in polish)
[11] Mazur W.: Welding metallurgy, Silesian University of Technology, nr 1679, 1992, 81-103 (in polish)
[12] S. Wu, X. Wu, Z Xiao, A model of growth morphology for semi solid metals, Acta Materiala, 5, Elsevier 2004, 3519-3524
[13] D. Eskin, Suyitno, L. Katgerman, Mechanical properties of semi-solid state and hot tearing aluminum alloys, Progress in Materials Science, 49, Elsevier 2004, 629-711
[14] Gleeble 3800 Applications, Welding Process Simulation, DSI, New York 2000, 52 - 66
[15] I. Telejko: Brittleness of cast steel in semi-solid state, WN Akapit, Cracow 2004