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Ni_3Al alloy's properties related to high-temperature brittleness

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ABSTRACT

Purpose: The purpose of this paper was to experimentally determine the brittleness temperature range of an alloy based on the intermetallic Ni-Al 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 20 ºC/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 Ni_3Al alloy which was found to be situated between 1340 ºC and the liquidus temperature for the heating stage, and down also to 1340 ºC for the cooling stage.

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.

Practical implications: Presented results and conclusions have been applied to work out the technology for welding of intermetallic Ni_3Al.

Originality/value: Using a Gleeble 3800 type simulator for the examination of an Ni_3Al 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 Ni_3Al l phase.

Keywords: Metallic alloys; Intermetallic; Ni_3Al

MATERIALS

1. Introduction

One of the most often encountered abnormalities in the process of creating welded joints of materials are intercrystalline cracks. The cracks are formed in the joint's area as a result of tensile stresses growing The state of stress depends on a number of factors, of which the following require mentioning: the thermophysical properties of solidifying metal, the joint's rigidity, its elastic and plastic properties, and the welding technology and parameters [1].

Metal's plasticity during crystallization can be linked to quantitative changes in the co-existing liquid and solid phases. A quantitative analysis of changes in metal's plasticity requires taking into account the crystals' geometry, liquid's viscosity and surface tension on interfaces, i.e. factors which determine the properties of liquid films. Metal deformation can be presented as movement of crystallites suspended in a liquid under the influence of static stresses (τ) (Fig. 1) [2-7].

Movement of crystals is a result of the movement of liquid between solid phase crystals in channels I – I and II – II, until the moment they contact one another. Further deformation without crack generation is possible only where the liquid's strength is higher than shearing stresses in the crystals [2-4].

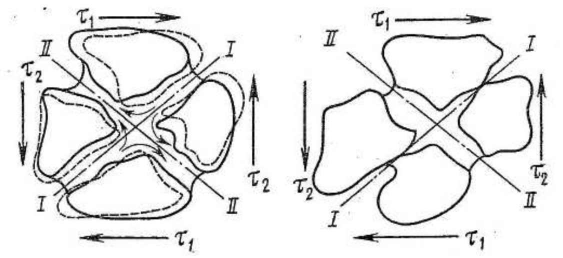

Fig. 1. Diagram of metal deformation in the period of liquid and solid phases' co-existence [2]

In the initial phase of crystallization, the fusion weld's solidification plasticity is determined by the liquid metal's properties. A temperature reduction causes a clear reduction of plasticity and potentially contributes to intercrystalline cracking. Further reduction of the temperature results in an increase of intercrystalline strength (σ_{mk}) due to growing viscosity and surface tension. At this stage, intracrystalline strength (σ_{wk}) grows, the growth being however slower than that of intercrystalline strength (σ_{mk}), which leads to intracrystalline cracking (Fig. 2).

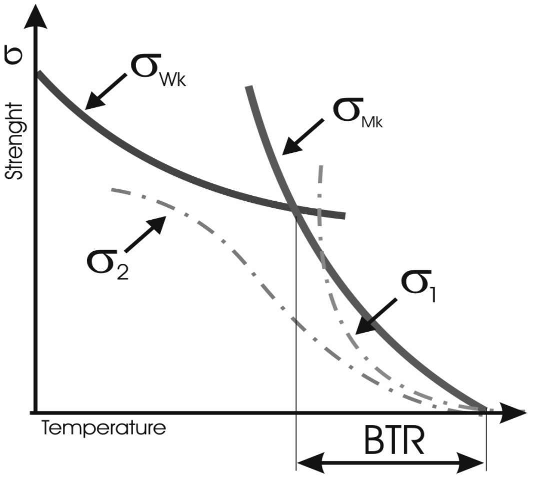

Fig. 2. Nature of changes in alloys' strength and stress in the crystallizaton process [6]

The temperature at which intracrystalline strength equals the intercrystalline strength is called the effective solidus temperature and determines the lower threshold of the brittleness temperature range (BTR) [2]. Where deformation increases in accordance with curve σ_1, cracks form in the fusion weld, whereas where deformation increases in accordance with curve σ_2, no cracks occur (Fig. 2) [3, 4].

Over the past two decades, designers have shown a growing interest in intermetallic phase-based alloys, often called intermetallics. It is Ti-Al, Ni-Al and Fe-Al alloys that are most often used for technological applications [1, 5-7].

The Ni-Al alloys are applied mostly in power engineering, for the construction of blades for internal combustion turbines, since their resistance to carbonizing as well as high fatigue strength ensure their considerably longer durability compared to typical turbines [1, 7-9].

Intermetallic phase-based alloys belong to a group of alloys hard to weld due to the possible formation of crystallization and polygonization cracks [8-13].

The aim of the study was to assess the alloy's high-temperature brittleness range and based on the assessment, to determine the alloy's susceptibility to hot cracking during welding.

2. Research material

A Ni_3Al intermetallic phase-based alloy was used for the research. Its chemical composition and basic physical and mechanical properties are presented in Table 1. The alloy's phase composition for individual heats has been confirmed based on an X-ray analysis of the phase composition [15].

3. Research methodology and results

For the determination of the high-temperature brittleness range (HTBR), it is necessary to determine the liquidus and solidus temperatures, as well as:

- NST, i.e. the temperature during heating, at which material strength approaches zero,
- NDT, i.e. the temperature during heating, at which material plasticity approaches zero,
- temperature DRT, defined as the temperature during cooling, at which the material becomes plastically deformable,
- the crack resistance coefficient $R_f=(T_l-NDT)/NDT$ [14].

The liquidus and solidus temperatures were determined through the DTA method on a Setaram's thermal analyzer SETSYS. Description of the research is presented in paper [grant]. Based on the DTA curve analysis, the critical points were determined during cooling and heating of the alloy, corresponding to the temperatures of:

- the beginning of material stability loss – beginning of liquid phase occurrence in the alloy - 1376°C,
- liquidus – corresponds to the maximum on endothermal peak - 1399°C,
- beginning of occurrence of first crystals of solid phase - 1357°C,
- solidus – corresponds to the maximum on exothermal peak - 1324°C.

High-temperature brittleness examination of the Ni_3Al alloy was conducted with a Gleeble 3800 device in accordance with the procedure described in paper [14]. Tests were performed at deformation speeds of 1 mm/s and 20 mm/s.

The determined temperatures and crack resistance coefficient values are juxtaposed in Table 2. A diagram of the strength changes as a function of temperature during heating and cooling of the discussed material is shown in Fig. 4.

Table 1.
Chemical composition and mechanical properties of the investigated alloy

Alloy	Chemical composition [% weight]									
	Ni	Al	Fe	Cr	C	Mo	Zr	B		
Ni$_3$Al	rest	13,3	-	-	-	-	-	-		
	Mechanical properties […]									
Ni$_3$Al	ρ [g/m^3]	T_m [^{o}C]	$\alpha \bullet 10^6$ [1/K]	λ [W/m ^{o}C]	c_p [J/kg ^{o}C]	R_m [MPa]	R_e [MPa]	A_5 [%]	ν	E [GPa]
	7,5	1390	12,5	21,4	n.d.a.	1200	500	19	0,30	179

where: ρ – density, T_m – melting temperature, α – thermal expansion coefficient,, $\tilde{\lambda}$ -heat conduction coefficient, C_p- specific heat, R_m – material strength, R_e- yield point, A_5 – elongation , ν – Poisson fraction, E – Young's modulus

Table 2.
Characteristic BTRs for the Ni$_3$Al alloy

Temperature which characterized ZKW [^{O}C]								
T_l	T_{lR}	T_{sR}	T_s	NST	NDT	DRT	R_f	ZKW
1399	1376	1357	1324	1343	1340	1340	0,04	1343-1340

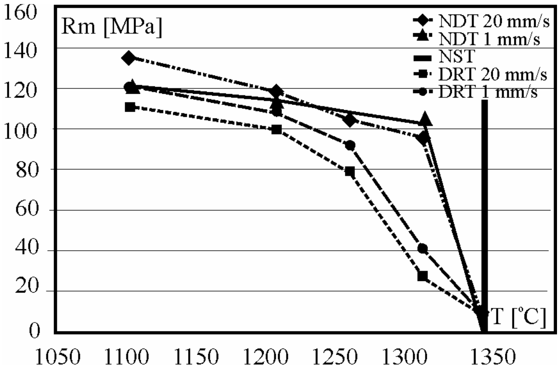

Fig. 3. Ni$_3$Al alloy's strength as a function of temperature

4. Metallographic examination

Metallographic investigations were conducted on a light microscope OLYMPUS GX71 in polarized light (LM), using filter α/4, and on a Hitachi S-3400 scanning microscope (SEM). Example structures are presented in Fig. 4.

5. Analysis of results

An evaluation of the high-temperature brittleness range (HTBR) was made for the Ni$_3$Al alloy (Table 2), using a Gleeble 3800 simulator. HTBR examinations were preceded with the determination of solidus and liquidus temperatures and in the NST test, the alloy's strength temperature was determined (Table 2). Each test was conducted on at least five samples. The test results quoted in the paper are the average values of all measurements. For an evaluation of BTR's lower boundary, defined by the plasticity recovery temperature (DRT), a deformation test was performed during cooling at different speeds, i.e. at 1 mm/s and 20 mm/s (Table 2). Another test was made to determine the plasticity temperature during heating (Table 2). As the tests' results show, the alloy is characterized by a very narrow HTBR, i.e. from 1344 to 1340^{o}C. Changes in strength within the alloy's solidification temperature during heating and cooling were also identified (Fig. 3). It was found that the alloy has higher strength during heating at both 1 mm/s and 20 mm/s deformation speeds in relation to its strength during cooling (Fig. 3). These parameters are decisive as regards the technological possibilities of welding the Ni$_3$Al alloy.

The metallographic investigations performed on a light and scanning electron microscope have shown a difference in the fracture morphology during alloy's heating to the strength loss temperature (NST) (Fig. 4a,b) and during cooling to the plasticity recovery temperature (DRT) (Fig. 4c).

An analysis of the observed structures and the Ni$_3$Al alloy's fracture shows that cracking takes place exactly perpendicular to the specimen's axis (Fig. 4a). The fracture line is not developed (Fig. 4a). Scarce cracks were found along crystals' boundaries (Fig. 4c). Examinations on a scanning electron microscope corroborate that cracking is induced by a loss of cohesion of a thin liquid film formed from partly melted crystal boundaries (Fig. 4b). Such manner of cracking is characteristic of materials with a directional crystal growth, e.g. in a weld.

As regards heating, a fracture with distinct elements of a dendritic structure is observed, i.e. dendrite branches are clearly visible, especially when observation is conducted on a scanning microscope (Fig. 4b). Lack of the so-called "recovery" processes may results from a very small difference between the solidus temperature T_s and liquidus temperature T_l for the investigated alloy. In the discussed case, crystallization practically takes place in the peritectic region [7] and therefore, the dendritic structure visible on the fracture is so distinct (Fig. 4b). This phenomenon shows a very narrow HTBR (ca. 4^{o}C), which results in limited weldability of the examined Ni$_3$Al alloys.

A different phenomenon occurs when cooling the alloy. At the moment of sample's failure, a film of liquid is present on the fracture surface, which solidifies on the cracking surface grain, thus forming a typical intergrain fracture (Fig. 4c).

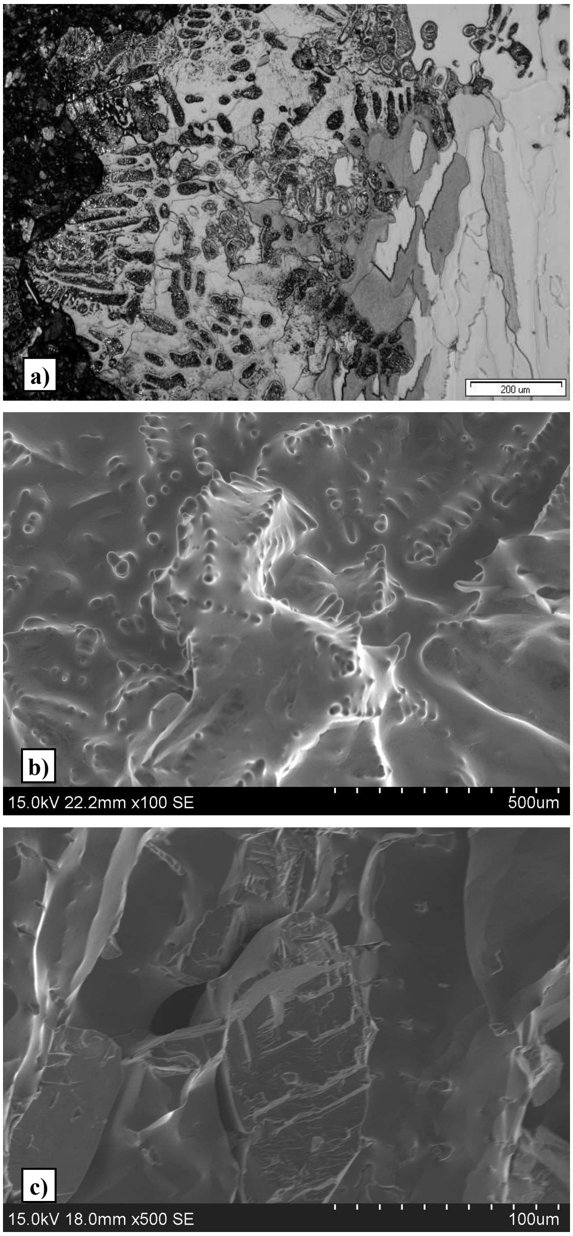

Fig. 4. Fracture of Ni_3Al after Gleeble simulation: a) structure after NST test, (LM), b) fructure after NST test (SEM), c) fracture after DRT test (SEM).

This phenomenon corroborates solidification at peritectic temperature (ca. 1340°C) and shows limited weldability of the alloy investigated.

6. Conclusions

1. A very narrow HTBR was found (ca. 4°C) in the case of heating and cooling of Ni_3Al alloy samples examined on a Gleeble 3800 simulator. The effect of the specimens' destruction process in HTBR is the occurrence of distinct dendrites on heated surfaces. It results from alloys' crystallization in a range of temperatures close to the peritectic temperature.
2. The described phenomena show limited weldability of the investigated Ni_3Al alloy and its limited usefulness for welding.

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