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WELDABILITY OF TITANIUM AND ITS ALLOYS – PROGRESS IN JOINING

ABSTRACT

The weldability aspects of the some advances materials, such as Titanium and its alloys: Titanium Aluminide – Intermetallics, still require further research and development. The power beam welding processes are considered in this work since these processes are capable of joining a wide range of new materials of interest in aerospace industry as well as in the many other industrial applications and offer remarkable advantages over conventional fusion welding processes. In this paper have been defined the following questions: - the weldability of Ti and its alloys, a new class of titanium alloys and their weldability, welding metallurgy and processes for joining.

Key words: *weldability of Ti and alloys, power beam welding, joining Ti and its alloys.*

INTRODUCTION

Welding of the materials always caused changes of the microstructural and mechanical properties of the base materials at the joining region. New or advanced materials such as Ti and its alloys generally require superb joining techniques with used: laser welding, electron beam welding and plasma welding. The topic of weldability and extensive characterisation of the welded joints of Ti and its alloys is a promising applied Research & Development (R&D) area which may attract considerable industrial interest. The weldability aspects of Ti still require further research and development. The power beam welding processes are generally classified as those which are capable of delivering an energy density of greater than 10 $kWmm^{-2}$ to the workpiece [1, 2, 3].
The laser is now attracting a great deal of interest as a heat source as a result of its potential capability for extremely high density in energy. Laser welding using a high power CO_2 or pulsed Nd: YAG laser can easily weld the specimen under atmospheric conditions [3, 4, 5].
A recognised characteristic of laser welding is deep penetration, narrow bead width and narrow heat affected zone typical of high power density welding. The similar notes concern also the employment methods: electron beam welding and plasma stream welding.

WELDABILITY OF Ti AND ITS ALLOYS

Titanium can exist in two crystal forms. The hexagonal close-packed (hcp) structure or alpha (α) phase, occurs from room temperature to ~ 880 ^{0}C, whereupon it transforms to the body-centred cubic (bcc) structure or beta (β) phase at the temperature called the beta transus. Furthermore, alloying elements may combine either interstitially or substitutionally with titanium. Alloying elements for titanium are classified into two categories depending on how they affect the crystal structure or phase stabilisation – Tab.1 [6]. Carbon, hydrogen, nitrogen and oxygen form interstitial solid solution with titanium. Carbon, nitrogen and oxygen are more soluble in the α phase and thus classified as α stabilisers. Hydrogen, more soluble in the β phase, behaves as a beta stabilising element.

Table 1. *Classification of alloying elements in Titanium alloys [6]*

Alpha-phase stabilizers	Beta-phase stabilizers	Neutral
	Substitutional alloying	
Aluminium	Chromium Niobium Copper Iron Manganese Molybdenum Nickel Palladium Silicon Tantalum Tungsten Vanadium	Tin Zirconium
	Interstitial alloying	
Oxygen Nitrogen Carbon	Hydrogen	

Beside C, H, N and O all occur as impurities in titanium and its alloys. These interstitial elements are the impurities that contaminate titanium during welding. Nitrogen is the most effective strengtheners for unalloyed titanium. Oxygen is next in effectiveness, followed by carbon. In two-phase, α + β titanium alloys, the action of interstitial elements becomes more complex. The strengthening effect of interstitials on alpha-beta alloys is greatly dependent on the relative amount and distribution of the alpha phase. Hydrogen is only slightly soluble in alpha titanium at room temperature. Beta titanium dissolves substantially more hydrogen than alpha titanium. Alpha-beta alloys are able to dissolve a considerable amount of hydrogen without the formation of hydrides.

While hydrogen can play a role in contamination cracking, it can also lead to a more insidious from of embrittlement know as delayed cracking or hydrogen embrittlerment. Assuming a microcrack is present in the weld, hydrogen atoms will diffuse to the crack tip. Because the hydrogen embrittlement sequence requires diffusion of hydrogen, the rate of crack advancement is dependent on time and temperature. Hydrogen cracking of welds can be avoided by minimizing exposure of the weld to hydrogen. Hydrogen

concentrations on the order of 200 ppm [6] are know to cause cracking problems. The combined presence of other interstitials (e.g. oxygen or nitrogen) may lower this tolerance limit. Post weld heat treatment is beneficial in relieving residual stress, thus reducing the driving force for crack advancement.
Beside weld metal porosity originates at the trailing edge of the weld pool, where interstitial elements (oxygen or hydrogen) are partitioned between dendrites during solidification. Partitioning occurs because solubility of oxygen or hydrogen is greatly reduced during solidification of the molten weld pool. Porosity is prevented by avoiding exposure of the molten weld pool to oxygen or hydrogen during welding.

A NEW CLASS OF TITANIUM ALLOYS

During the last time an extensive effort has been devoted to developing titanium aluminides, are based on the Ti_3Al, designated as α_2 and TiAl, designated as γ intermetalics. All titanium aluminides possess good high temperature strength and oxidation resistance. However, their limited ductility at low temperatures preclude their use in load bearing structures. It is essential to comprehend the features of the Ti-Al equilibrium phase diagram in order to interpret the complex welding metallurgy of these alloys. It is surprising that the Ti-Al phase diagram is not fully known, and until very recently, even the most important parts of the titanium rich end were controversial. For example, the phase diagram for the Ti-Al system is shown in Figure 1 [7].

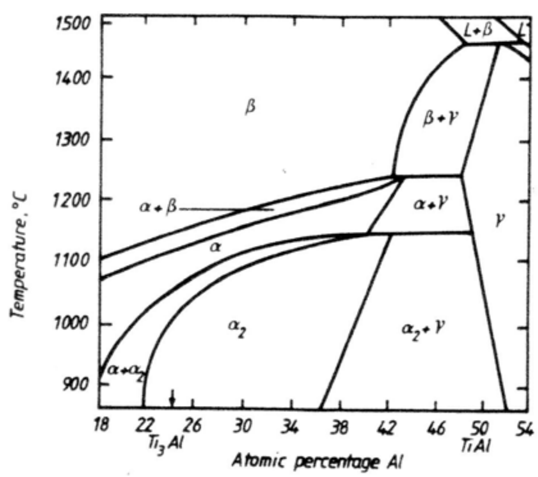

Fig. 1. Ti – Al phase diagram proposed by Martin et al [7]

The most striking controversy, which can be seen in Figure 1, is related to the extent of the β phase field in the Ti-rich end of the diagram, and to whether the α phase field extends as for as the γ field [1,7]. The greatest progress has been made in the Ti-Al alloys based on the α_2 (Ti_3Al) intermetalics. On cooling from elevated temperatures, it is believed transform to a disordered α phase, with long range order (α_2) being established at a slightly lower temperature. Intensive research activity has been undertaken to improve the physical properties of titanium aluminides and some examples are characterized below [1, 2, 7]:

- α_2 (Ti_3Al) Aluminides,
- γ (TiAl) Aluminides,
- ($TiAl_3$) Aluminides.

Alloy systems based on Ti_3Al – Nb(α_2) and super α_2 (Ti_3Al-Nb-Mo-V) demonstrate the potential of microstructural control are now available in pre-production quantities for evaluation and although alloy development is still underway, it is unlikely that the compositions will change markedly in the near future [1, 2].

The γ (TiAl) aluminides possess superior properties to those of the α_2 alloys, such as lower density, higher elastic modulus, and better high temperature mechanical properties and oxidation resistance, but their room temperature ductility is lower. Attempts to improve the room temperature ductility of (TiAl) have involved alloying with various additional elements, and selecting alloy compositions which lead to two-phase microstructures consisting of α_2-Ti_3Al and γ-TiAl [8]. The mechanical properties of the two-phase alloys are superior to those of single phase material with strength and ductility being particularly dependent on the volume fraction of the lamellar colonies [9].

Two-phase (α_2 + γ) alloys are heated in the $\alpha+\gamma$ phase field to yield a microstructure consisting of two distinct morphologies [1, 2].

Recently super plastic behaviour in TiAl has been attained [13]. A structure composed of TiAl with 3 vol. % Ti_3Al was obtained in a titanium aluminides containing 36 wt % Al after undergoing a compressive strain of 80 % at 1000^0C with a strain rate of $10^{-3}s^{-1}$ and subsequently held at 925^0C to 24 h.

The alloys based on the $TiAl_3$ and stoichiometric composition have been development, yet those alloys are not as well optimised as other titanium aluminides and are still a long way from commercial production. However, its low density, high specific strength, good elevated temperature properties and excellent oxidation resistance have provided an incentive for alloy development. Mechanical data about $TiAl_3$ alloys are very scarce but properties comparable to or better than TiAl alloys have been reported at ambient and elevated temperatures [10].

WELDING METALLURGY OF TITANIUM ALLOYS

a. α_2(Ti_3Al) Aluminides

Although published data about α_2(Ti_3Al) is limited, there is no evidence to suggest that the α_2 based alloys suffer from any major weldability difficulties in terms of susceptibility to hot and cold cracking, etc. [11, 12, 13]. The most significant factor in the joining of α_2 alloys is the β to α phase transformation, which is comparatively sluggish, and much slower than the similar γ to α transformation which is critical in the welding of ferrous alloys. Baeslack and Broderick [14] have also proposed a preliminary CCT diagram for α_2 and super α_2 alloys, which is given in Fig. 2. This diagram clearly demonstrates the effect of various alloy compositions on the rate of transformation in these alloys.

Beside, there is considerable evidence to suggest that the ductility of α_2 [15] and super α_2 [16] aluminides can be influenced by hydrogen. It is suggested that hydrogen embrittlement is associated with the formation of a hydride phase.

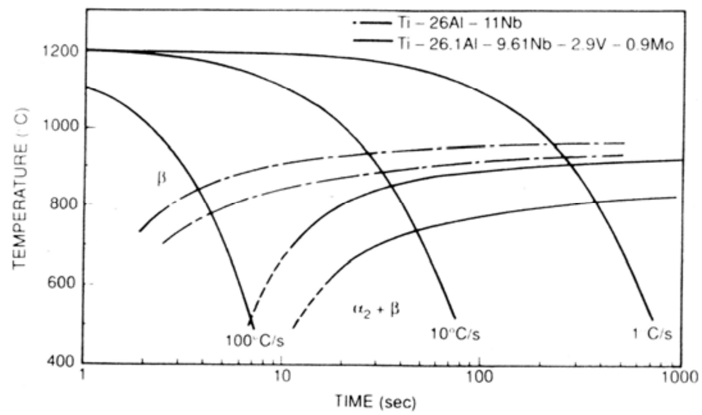

Fig. 2. CCT diagram for α_2 and super α_2 alloys, as determined by dilatometry [7]

It is possible that any effects of hydrogen will be most significant in joining processes in which high hardness α_2 martensite is formed.

b. γ(TiAl) Aluminides

There is virtually no published data on the welding metallurgy of these alloys:
- no solidification cracking problem is reported, but the major challenge will again be to cope with the lack of ambient temperature ductility,
- non – equilibrium solid state phase transformations are not fully investigated, but it is well established that significant changes in the equilibrium α_2/γ ratio will take place on heating, and a phase transformation to α will occur at high temperatures.

Beside, it has been described that hydrogen can form previously unknown hexagonal hydrides in some γ alloys under high pressures and temperatures [17].

c. $TiAl_3$ Aluminides

No considerations on the weldability or welding metallurgy of $TiAl_3$ based alloys have been reported, but it is known from the studies on the processing of these alloys that any operation involving rapid cooling of the joint is likely to lead to cracking. No information is available on the nonequilibrium cooling and possible transformations which may take place [8]. The complexity of the binary Ti-Al phase diagram in the range between the Ti-Al and $TiAl_3$ – Fig. 1, where several other intermetalic compounds may exist, will also have a significant effect on the microstructure. This aspect will obviously require further investigation when progress has been made on the more critical shortcome of the undesirably low ductility of these alloys.

WELDING PROCESSES FOR JOINING TITANIUM

The joining process used in micro-and macro-joining very often are based on the methods: micro- and macro-plasma welding, electron beam welding, laser welding.

Temperature fields are required to predict welding and surface treatment processes, microstructures, residual stresses and distortion of work pieces. Experimental determination of the temperature distribution and cooling rates in a weldments during and after welding is extremely difficult. Therefore, in recent years, there has been considerable interest in quantitatively determining the detailed temperature by mathematically modelling the physical phenomena that occur in correct form.

The recent developments in computational weld mechanics now enable the heat transfer in real welding situations to be analysed or simulated accurately, perhaps more accurately than the data can be measured.

The fundamental rule of any correct modelling procedure is an estimation of physic phenomenon during welding process, practically results in examining reciprocal relations between extensive and intensive parameters. The transport process of extensive magnitudes requires observations and estimation of intensive parameters during welding and realised by using such procedures as transient Lagrangian or steady state Eulerian formulations of thermal cycle. A good model for the weld heat source in the analysis of the thermal cycle under laser welding is required. In this purpose we can use the cylindrical-involution-normal (C-I-N) heat source model. The C-I-N heat source model was constituted and analysed in [18]. This heat source model is favourable for imitation of the welding process with high concentrated energy such as laser, electron beam, stream of plasma.

Then the theoretical structure of research object is defined with the use of [18a]:

- physic (calculating) model, describing the real object,
- mathematical model, an equation or system of equations, describing some correctness of processes together with boundary conditions, characteristic for given phenomenon and established for C-I-N heat source temperature fields.

In order to fulfil similarity criterions it is necessary to execute computer calculations with temperature dependent physical parameters: α-the thermal diffusivity, λ-the thermal conductivity, ρ-the density of material, c_p – the specific heat of material. In this situation some extended consideration about analytic-numerical methods conforming has taken place and it is obvious that [18b]:

- with an application of C-P-N heat source model we can obtain very effective temperature field solutions specially for laser and electron beam welding,
- with appropriate algorithms, calculations are very attractive and can be quickly executed by PC computers,
- knowledge of thermal cycle enable analysis of microstructure in titanium welded joints.

All this makes analytical solutions very competitive with numerical ones and makes them very useful in science and engineering practice [19].

The power beam welding processes in titanium generally are susceptible to the same discontinuities experienced with other metals. Electron beam welding is a low-heat-input process relative to GTA welding. An evaluation of the electron beam welding (EBW) process for a specific titanium application must give consideration to the applicable mechanical properties such as fracture toughness and tensile strength. Typical mechanical properties for EBW welds in Ti-6Al-4V alloys are given in Table 2 [6].

Aged welds in α-β titanium alloy have higher tensile strength and lower ductility than the unwelded base metal.

Table 2. *Typical room-temperature mechanical properties of EB welds in Ti alloys {6}*

Alloy	Thick-ness	Type of specimen	Heat Treat-ment	Tensile Test				Fracture Toughness		
				TS	YS	Elong.	RA	Specimen Type	Specimen orientation	K_{IC}
-	mm	-	°C	MPa	MPa	%	%	-	-	$MNm^{3/2}$
Ti-6Al-4V	25.4	BM	MA	1027	972	14	22	CT	T - L	110
		W	704	1020	951	14	20	CT	T - L	63
Ti-6Al-4V	50.8	BM	MA	938	869	9	10	CT	T - L	116
		W	704	917	869	10	18	CT	T - L	91

where: BM-base metal, W-weld, MA-annealed material, CT-compact tension, T-L-orientation of specimen.

The microstructures and mechanical properties of laser beam welds do not vary significantly from those of electron beam welds. Beside the weld and heat-affected zones (HAZ) have higher tensile strengths than the base metal, but exhibit lower values of fracture toughness [20]. The reduction in weld fracture toughness encountered with Ti-6Al-4V alloy is about the same with laser beam welds as with electron beam welds [21].

CONCLUSION

Numerical weldability analysis is new powerful research and development tool which is useful for metallurgists technologist and design engineers. Weldability denotes the possibility to join parts by welding under defined conditions of design, materials and manufacture. Weldability is conventionally ascertained and further developed by testing – empirical basis. This process can be enhanced and made more efficient by mathematical modeling and numerical analysis – theoretical basis. Strictly speaking, the numerical analysis of weldability comprises thermodynamic, thermo-mechanical and micro-structural modeling of the welding process. The result of this operation is the different step of susceptibility of the material on welding process which physical measurement is the fracture resistance and decides on the utility of welded joints of titanium and its alloy. The mathematical modeling of property-determining processes presents a modern and powerful tool to improve engineering materials and their processing such as welding process.

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