# Processing of intermetallics with $Al_2O_3$ or steel joints obtained by friction welding technique

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## Abstract

The development of technologies for joining advanced materials is connected with an introduction of new materials and new applications of their bonds, to work in ever more difficult conditions. One of possibilities of obtaining this type of joints is using the friction welding technique. This paper presents the results of joining intermetallics (Fe-Al and Ni-Al type) with steel (S235JR) and ceramics ($Al_2O_3$) using friction welding technique. The focus of the investigations was selecting: appropriate rotational speed (10000-25000rpm) of joining elements, welding pressure and time (1500-4500ms) of its application and swelling time (1000-7000ms). The paper presents the results of microstructure investigations, investigations of microhardness (perpendicularly to joint surface) and mechanical properties (tensile strength).

**Keywords:** friction welding, intermetallics, microstructure of joints, microhardness, tensile strength.

## Introduction

Intermetallics have drawn enormous attention due to their ability to provide significant advantages in manufacturing processes, technologies, and as well as commercial products. The ordered nature of intermetallic compounds exhibits attractive high-temperature properties (excellent oxidation and corrosion resistance) due to the presence of long-range-ordered superlattices, which reduce dislocation mobility and diffusion processes at elevated temperatures. Aluminides of transition metals posses sufficiently high concentrations of aluminum, to form a continuous, fully adherent alumina layer on the surface when exposed to air or oxygen atmosphere. The amount of aluminum in aluminides can range from 10 to 30wt.% and is significantly higher than the concentrations in conventional alloys or superalloys. In the case of nickel and iron aluminides, the alumina layer formed on the surface of the materials is responsible for the excellent oxidation and carburization resistances even at temperatures as high as 1000°C or higher. Therefore, aluminides, unlike conventional steels and superalloys based on nickel, iron, and cobalt do not necessarily require chromium to form an oxide layer on the surface of the material to protect against high-temperature oxidation and corrosion. [1,2,3,5,6,9]. Alumina is much more thermodynamically stable at high temperature than $Cr_2O_3$. Interestingly, the chemistry of aluminides is much simpler than superalloys'; subsequently, they form long-range-ordered crystal structures. Apart from their oxidation and carburization resistances, aluminides posses lower densities, high melting points, and exhibit interesting mechanical properties due to their ordered crystal structures. The strength of some intermetallics increases with temperature instead of a decreasing; thus, they are ideally suited for high-temperature applications [10,11,12].

The full potential of nickel and iron aluminides can only be reached by development of advanced joining techniques. The development of these processes plays an important role in practical application of such alloys. However, for example: welding of iron aluminides is difficult due to its inherent low temperature ductility and poor weldability. Cold cracks can be initiated from the weld even for low energy input process such as laser welding.

One of possibilities of obtaining this type of joints is using the friction welding technique. This technique belongs to profitable (low costs) and eco-friendly (lack of additional materials such as solders etc.) joining method [8].

This paper presents the developed conditions of friction welding technique for iron and nickel aluminides to steel and alumina joints. The results were compared with joints obtained by brazing and diffusion bonding technique [4,7]. The paper includes selected results of microstructure, microhardness (perpendicularly to joint surface) and mechanical properties (tensile strength) investigations.

## Experimental

The samples of iron and nickel aluminides which were used in joining process were produced by vacuum casting method from mixture with appropriate composition included Fe or Ni, Al, Zr and B (the casting blocks were cut in the shape of cylinder - 12 mm in diameter and 18 mm in length). The selected mechanical and physical properties of produced $Fe_3Al$ and $Ni_3Al$ are listed in table 1.

**Table 1** The mechanical and physical properties of $Fe_3Al$ and $Ni_3Al$.

| Material | $T_m$[°C] | Density [g/cm$^3$] | E [GPa] |
|---|---|---|---|
| $Fe_3Al$ | 1540 | 6.72 | 141 |
| $Ni_3Al$ | 1390 | 7.50 | 179 |

The samples of S235JR steel and alumina ceramics (99% $Al_2O_3$) were 10 mm in diameter and 40 mm in length. The chemical composition and selected mechanical properties of steel are listed in table 2.

**Table 2** The chemical composition and mechanical properties of steel type S235JR.

| Material | Chemical composition [wt.%] | Tensile strength [MPa] | Yield point [MPa] |
|---|---|---|---|
| Steel type S235JR | 0.17C; 1.4Mn; 0.035P; 0.035S; 0.012$N_2$; rest Fe | 510 | 235 |

The scheme of joining process is presented in Fig.1.

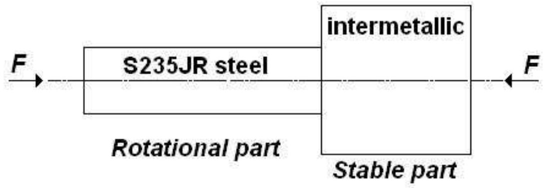



**Fig.1** The scheme of joining process.

The joining process were conducted using friction welding instrument (HWH RSM200) in a wide range of experiment conditions: rotational speed of joining elements from 100000 to 25000 rpm, joining time from 1500 to 4500 ms, swelling time from 1000 to 7000 ms. The table 3 comprises the friction welding optimum conditions of three material systems and Fig.2 the selected image from computer monitor showed rotating speed (red), force (blue), pressure (yellow) and swelling (green) as a function of time.

**Table 3** Conditions of friction welding processes.

| Material system | Pressure I (MPa) | Pressure II (MPa) | Rotational speed (rpm) | Friction time (s) | Sweelling time (s) |
|---|---|---|---|---|---|
| $Ni_3Al$-steel | 102 | 132 | 20000 | 4 | 5 |
| $Fe_3Al$-steel | 54 | 79 | 17000 | 2 | 3 |
| $Fe_3Al$-ceramics | 0.1 | 0.1 | 10000 | 3.2 | 1 |

* Pressure I – pressure in the friction stage, Pressure II – pressure in sweelling stage.

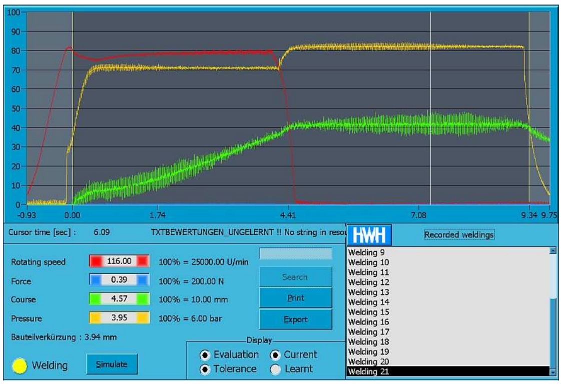



**Fig.2.** The graph of friction welding conditions as a function of time (image from computer monitor).

The joints $Ni_3Al$-steel and $Al_2O_3$(covered by Al)-steel produced in optimally conditions are presented in Fig.3.

a)

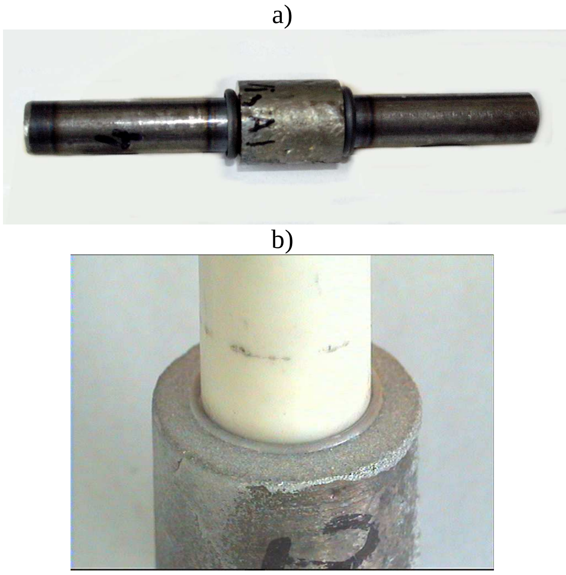



**Fig.3** The joints obtained by friction welding technique: a) $Ni_3Al$-steel, b) $Fe_3Al$-$Al_2O_3$(covered by Al).

## Results and Discussion

The tensile strength (INSTRON; speed of load 2mm/min) test shows the average value 219 MPa of $Fe_3Al$-steel joints and 79MPa of $Ni_3Al$-steel joints. Fig.4.shows fracture surfaces of $Fe_3Al$-steel joint after tensile test.

**Fig.4**. Fracture surfaces of bonded elements.

The results of tensile strength test both $Fe_3Al$-steel and $Ni_3Al$-steel joints showed the brittle character of fractures. The joints were damaged inside of intermetallic compounds and outside of joints' area. The microhardness of joints were measured perpendicularly to joint surface (Fig.5). Figure 6 shows the results of measurements.

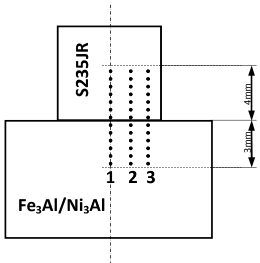
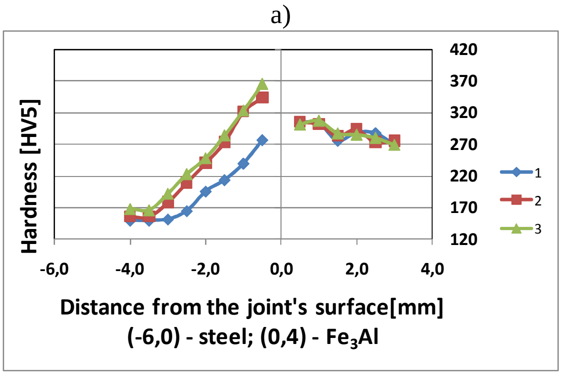



**Fig.5.** Scheme of microhardness measurements.

a)




b)

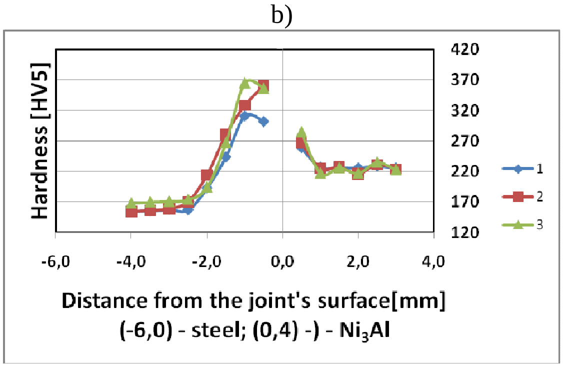



**Fig.6.** Distribution of microhardness across the joints: a) $Fe_3Al$-steel, b) $Ni_3Al$-steel.

The results of microstructure investigations of obtained joints are presented in Fig.7, 8 and 9.

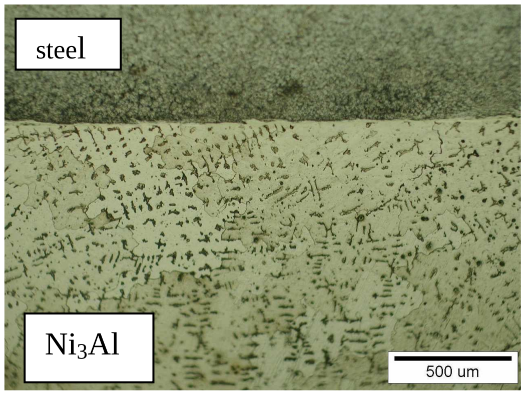



**Fig.7.** Microstructure of the $Ni_3Al$-steel joint.

In the structure of $Ni_3Al$ are visible the boundaries of dendrite's grain; near the joint boundary you can observe distorted grains (but less than in other intermetallic compounds, because of the characteristic, for this material, limited increase of the yield point with increase of temperature) in comparison with ordered $Ni_3Al$ phase.

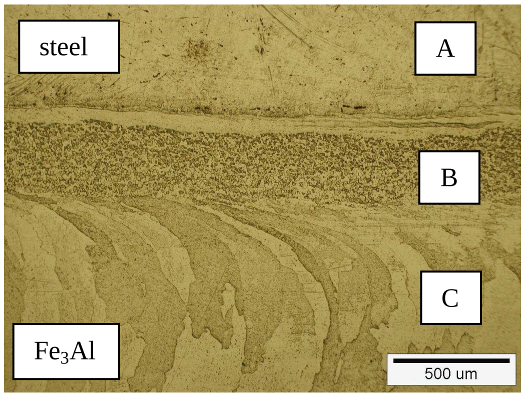
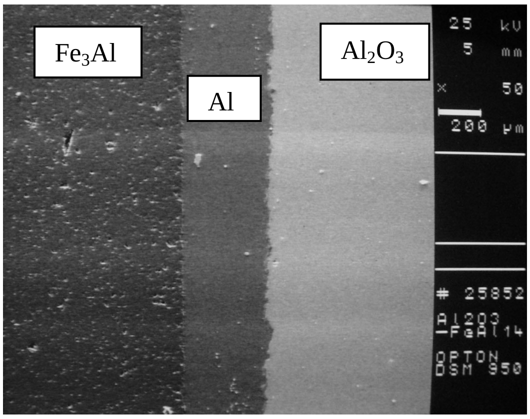



**Fig.8.** Microstructure of the $Fe_3Al$-steel joint.

In Fig.8 you can observe three areas: A – pearlitic-ferritic steel, B – grinded (typical for welded plastic materials) mixture of $Fe_3Al$ and steel, C - $Fe_3Al$ with deformated and elongated (parallel to sample radius) grains. It can be stated that the mechanism of formation of the joint is rather of diffusion type.

a)




b)

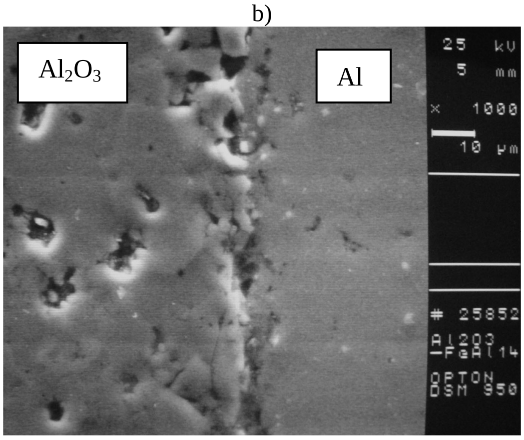



**Fig.8.** SEM of the $Fe_3Al$-$Al_2O_3$ (covered by Al)-steel joint: a) mag. x200, b) mag. x1000.

In Fig.8 you can observe SEM of the $Fe_3Al$-$Al_2O_3$ (covered by Al)-steel joint; in part a) whole imagine of the joint (mag. x200) and in part b) transition layer $Al_2O_3$/Al (mag. x1000).

## Conclusions

On the basis of the presented results following conclusion can be drawn:

1. Friction welding is suitable technique for processing: intermetallic compounds – steel and intermetallic compound – alumina joints
2. The properties of joints obtaining using this green technology (tensile strength) are comparable with joints obtained by brazing (e.g. the average value of tensile strength of friction welded $Fe_3Al$-steel joint - 219 MPa, the average value of tensile strength of brazed ($T_b$-1040°C) the same joint – 259 MPa.
3. The right condition of friction welding comprises table 3. The conditions strictly depend on the type of intermetallic, precisely - on the structure's level of ordering
4. The hardening of steel and intermetallics was found in transition layer, near of the joint. This is the result of pressure and heat operating during the joining process
5. It was found that the mechanism of formation of the joint is rather of diffusion type.

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