

# **Characterization and Properties of Dissimilar Metal Combinations of Fe/Al and Ti/Al-Sheet Materials**

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## **Abstract**

Within the last years there was a rising interest in dissimilar metal combinations. The main goal of these developments are weight reduction, properties optimization or the tailoring of properties for specific applications.

The joining of dissimilar metals such as aluminum to steel and aluminum to titanium can be realized by laser welding due to a very localized energy input of the welding source. Localized energy input leads to a controlled heat distribution and to a minimized interaction of the joined materials. Comparable to conventional thermal joining technologies, intermetallic phases are formed during the joining process. These intermetallic phases have a size and a composition dependent influence on the properties of the joints. Due to locally restricted energy input, high joining speed and accompanying high cooling rates laser beam welding prevents an excessive formation of intermetallic phases. The formation of intermetallic layers can be limited to a size below 10  $\mu\text{m}$  which leads to desirable mechanical properties including higher ductility of the joint.

Within this paper the phase formation in Al/Fe-joints is described. The characterization was carried out by trans- and scanning electron microscopy. Additionally, the mechanical properties of Ti/Al and Fe/Al-joints are presented. Finally, potentials for industrial application for dissimilar metal combinations are given.

## **Introduction**

Since several years, new concepts for the production of light weight and high strength joints of dissimilar materials were developed /JAR96, KLE98, BER00/. The introduction of tailored blanks is one of the first concepts based on the idea of an optimized material usage with respect to its mechanical properties. The development of dissimilar material joints is a consequent advancement of the concept of tailoring blanks. Besides a further optimized material exploitation

concerning the mechanical properties, additionally offers benefits under functionality requirements.

Actually, the potentials of constructions consisting of dissimilar materials are evaluated within R&D projects in the field of automotive and aerospace technologies /SEP01/. In the latter, the material combination aluminum and titanium presents high potentials for efficient light weight solutions in corrosively and mechanically highly loaded components. E.g., conventional constructions could be replaced by parts made of titanium for high stiffness and corrosion resistance and aluminum alloys as stiffening elements of fuselage areas in aircrafts.

Also in the fields of automotive components, a wide variety of possible applications for dissimilar material combinations is obvious. At present, the main focus in this area is aiming car body concepts for weight reduction and higher stiffness due to the locally use of aluminum sheet materials (higher specific strength). For power train components the combination of aluminum parts with thin walled steel pipes offers the opportunity for a significant reduction of the rotating masses. Under this concern, a higher product efficiency could be realized.

However, the utilization of laser technology to produce dissimilar material joints offers specific advantages in production but also problems which both will be reported in the following sections.

### **Phase formation during joining of dissimilar materials**

During joining, thermal conductivity, different melting points and solubilities of the materials with each other are playing an important role for the mechanical characteristics of the resulting joint. Interesting material combinations for industrial applications are Al/Fe and Al/Ti, respectively. According to the specific material properties, there is a large difference between melting points and thermal conductivities of these material combinations which lead to severe problems during joining with conventional welding technologies such as MIG and TIG. These problems are the formation of intermetallic phases, crack formation within the joining zone with subsequent failure of the joint /BAY69, GHA68/.

The phase diagram of the binary Fe/Al-system is shown in Fig. 1. On the left hand side of the diagram it can be seen that the solubility of Al in Fe is in the range of several percent. Exceeding an Al-content of 12 vol.-% intermetallic phase formation occurs. On the contrary, the solubility of iron in the aluminum is close to zero, which results in a very early interfacial phase formation when iron is dissolved in aluminum. Depending on the aluminum content the phases  $Fe_3Al$ ,  $FeAl$ ,  $FeAl_2$ ,  $Fe_2Al_5$  and  $FeAl_3$  are formed, respectively. From thermodynamic calculations it can be assumed that the aluminum-rich phases will be preferably formed /SCH98/. Generally, these phases have a high hardness in the range of 600-1100 HV that is increasing with rising aluminum content.

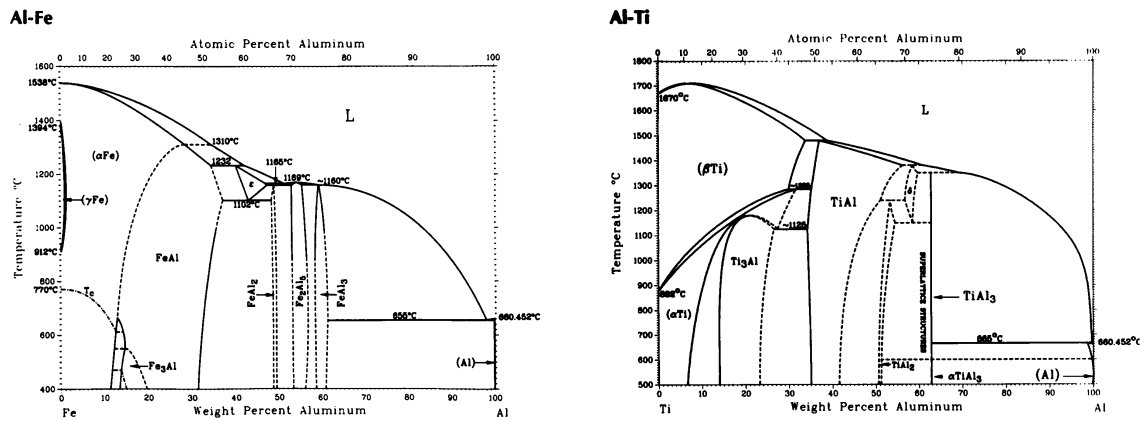


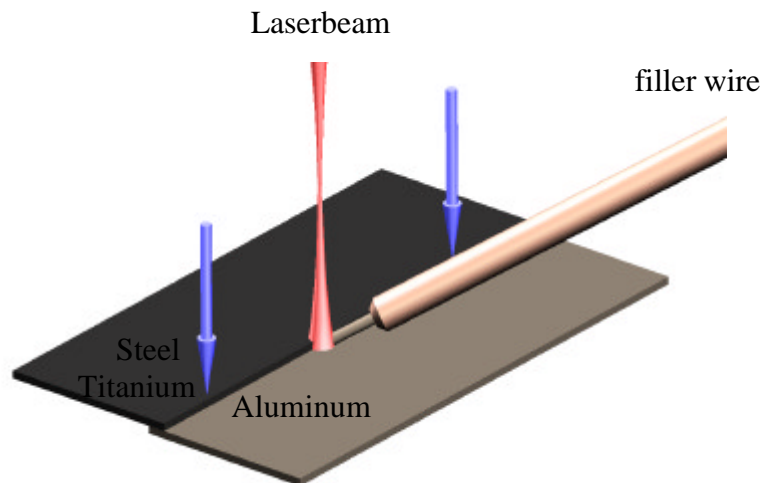
Fig. 1 Binary phase diagram of Fe/Al and Ti/Al /HAN58, MUR88/.

The binary Ti/Al-system (Fig. 1) shows a comparable phase formation behavior. On the titanium-rich side a slightly lower solubility for aluminum is obvious. Exceeding an aluminum content of app. 10 at.-% in the titanium a composite of Ti and  $Ti_3Al$  will be formed. With rising aluminum content phases like  $TiAl$ ,  $TiAl_2$  and  $TiAl_3$  are formed respectively. On the aluminum-rich side of the diagram, the low solubility of titanium leads to an early formation of the intermetallic phase  $TiAl_3$  when the titanium content exceeds app. 2 at.-%. Based on thermodynamic assumptions, it is predicted that the  $TiAl_3$  phase is formed preferably.

During thermal joining of dissimilar material combinations, the formation of intermetallic phases plays a significant role. In dependence on the process related temperature and time cycle, a severe intermetallic phase formation occurs. Accompanied with the phase formation, an embrittlement of the joining zone is observed. However, if material joints with high toughness and strength are required, the intermetallic phase formation has to be limited to a minimum size /RAD97, SEP99/. The main parameters are the limitation of the overall heat input and the reduction of melting pool dimensions. Under these considerations, laser joining provides an excellent tool for these technical demands. Due to the small spot diameter of laser beams, locally high energy densities are reached, which finally result in a significant improve of joining speed and a reduction of the melt pool diameter. Due to the high thermal gradients during laser beam joining, the resulting rapid cooling of the melt pool has also a positive influence on the limited phase formation.

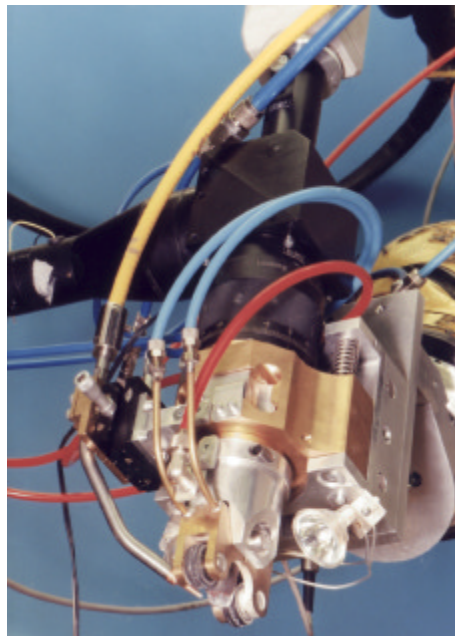
## Processing

This paper focuses on overlap joints of thin sheet materials. The configuration of the sheets is shown in Fig. 2. The higher melting sheet material, Ti or Fe, respectively, is positioned on top of the aluminum sheet with an overlap of 1.5 mm. The joining is carried out with a 1.6 kW Nd:YAG-laser and a defocused laser beam with a diameter of about 8 mm. During processing, the induced energy heats mainly the steel or titanium material, respectively, and by thermal conduction the aluminum sheet starts to melt and wets the upper sheet material. When Al/St is joined, the joining zone is additionally coated with non corrosive flux. Optional filler wire AlSi12 ( $\varnothing$  1 mm) is used to improve the mechanical properties of the joint. For the Al/Ti-system no flux is required.



*Fig. 2 Schematic for joining dissimilar materials in overlap configuration.*

To achieve homogenous joints high requirements on the processing stability are set. The critical parameters are a constant positioning of the laser and a technical zero gap between the sheets. For improved processing control a special working head was developed (Fig. 3). The main part of this working head is a mechanical seam tracking system that ensures an accurate positioning of the laser beam. Additionally, to ensure a close contact between the sheet materials perpendicular forces can be applied to the sheet surfaces /KRE01/.



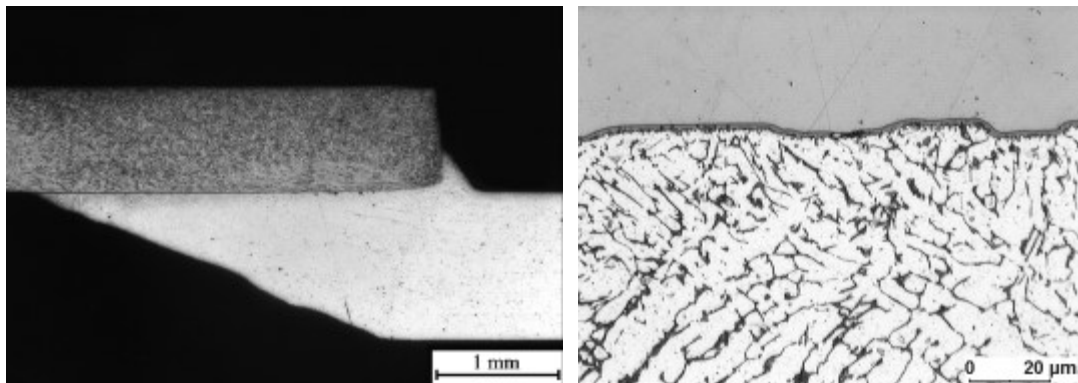
*Fig. 3 Special working head for joining dissimilar material combinations.*

## Properties

With the laser joining process defect free dissimilar material joints of the material combinations Fe/Al and Ti/Al have been achieved.

### Fe/Al-joints

In Fig. 4 a cross section of the joining zone of a Fe/Al-joint is shown. As sheet materials deep drawing steel St14 and an aluminum AA6xxx with a thickness of 1 mm were used. This joint was prepared without the use of filler wire. The overview of the joint shows that a homogenous defect free wetting zone is formed. In the detailed view of the interface, a thin phase layer can be detected between the steel (upper side) and the aluminum. The thickness of the seam is in the range of 3  $\mu\text{m}$ .



*Fig. 4 Cross section of a St14/AA6xxx-joint.*

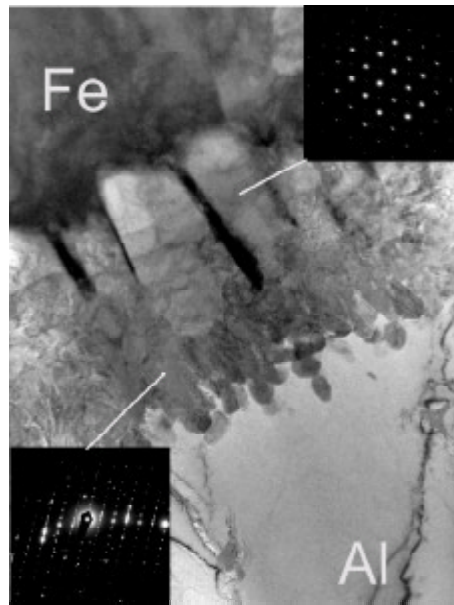
By backscatter electron microscopy a more detailed observation of the interface can be realized. The interface layer appears gray and has a relatively rough structure. The microstructure of the phase seam differs between the steel (upper side of the picture) and the aluminum side (lower side). On the aluminum side, a fine grained microstructure is formed, while towards the upper side a rounded and jagged interface to the steel sheet material is formed.



*Fig. 5 Backscatter electron microscope picture of a St14/AA6xxx-joint.*

The grain boundaries of the solidified aluminum (lower part of the picture) are nearly continuously covered with a thin Fe-containing phase. Due to the small dimension, an accurate determination of the phase composition within the scanning electron microscope is not possible.

For a further more detailed description of the morphology of the interface transmission electron microscopic investigations were carried out. The micrograph in Fig. 6 shows in the upper part the steel material and in the lower part the aluminum material. For these investigations samples made of St14 and pure aluminum (AA1050) were used to suppress irritation effect from additional alloying elements, e.g. Si and Mg. By these observations, it can be verified, that the interface between Al and Fe shows two different microstructures. The lower part of the phase seam shows the already mentioned fine globular microstructure. Towards the steel side, a second area with a columnar microstructure can be detected. By EDX and electron diffraction measurements the phases were characterized. For the phase seam near to the steel side a composition of 67,4 at.-% Al and 32,6 at.-% was measured by semi quantitative EDX. This result is in between the stoichiometric formation area of  $\text{Fe}_2\text{Al}_5$  and  $\text{FeAl}_2$ . Electron diffraction measurements also lead to a clear result, because the diffraction pattern does not allow an accurate phase identification. Characterization of the phase seam near the aluminum side identified  $\text{FeAl}_3$  as intermetallic phase, as expected.



*Fig. 6 TEM-micrograph of the interface of a St14/AA1050-joint .*

Tensile testing was carried out to investigate the mechanical characterization of these Fe/Al-joints. For this material combination St14/AA6xxx an average fracture strength of about 170 MPa is measured (Table 1). Maximum strength of the samples was nearly 200 MPa. Failure of the samples occur within the heat affected zone of the aluminum near the steel sheets.

Table 1 Values of tensile testing of Fe/Al-joints. Materials: St14/AA6xxx

average value	171 N/mm <sup>2</sup>
maximal value	198 N/mm <sup>2</sup>
nr of samples	50

### Ti/Al-joints

Recent investigations proved that concerning the joining behavior of the system Ti/Al results comparable to the Fe/Al-system can be achieved. Under controlled inert gas protection, smooth defect free joints of Ti and Al can be realized. In contrast to the Fe/Al-System no flux has to be used to achieve a good wetting behavior. This bases on the high reactivity of titanium which probably leads to a reduction of the oxide layers of the aluminum material and subsequently to a reactive wetting process. The cross section shown in Fig. 7 proves the good wetting behavior of the aluminum and the titanium sheets. Within the joining zone a thin interfacial layer can be detected (Fig. 7, right). This newly formed phase is assumed to be an intermetallic TiAl<sub>3</sub>-phase [WÖH95]. Since it is known that this phase is very stable, a reduction of the diffusion related phase growth is evident.

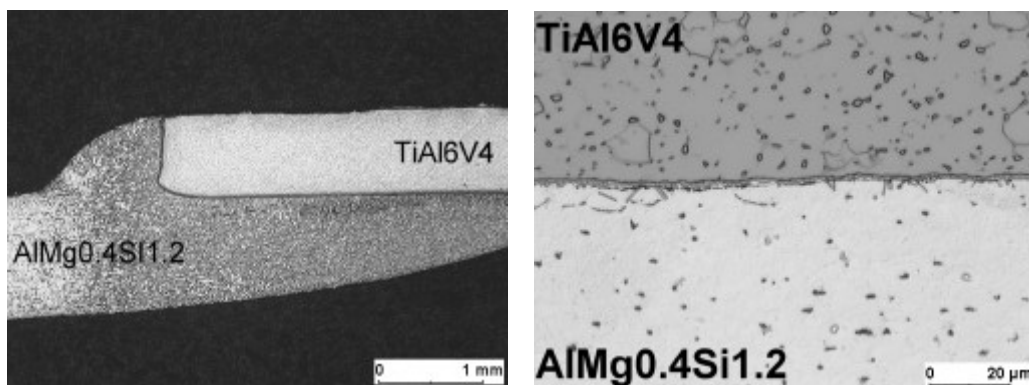
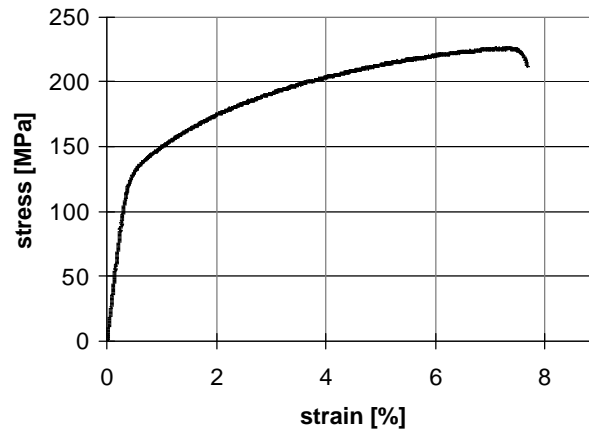


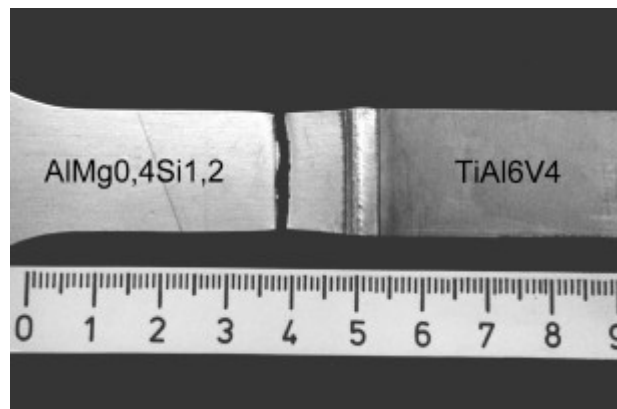
Fig. 7 Cross section of a Ti/Al-joint. Material combination TiAl6V4 and AlMg0.4Si1.2

In tensile tests, fracture stresses of 220 MPa are measured in combination with a relatively large plastic deformation. After testing the sample show an overall strain of about 6 % related to the shaft length of the sample. It becomes obvious in Fig. 9 that the elongation is mainly located on the aluminum side of the sample and is additionally restricted to a relatively small area. However, it can be concluded that the local deformations of the aluminum are much higher.



*Fig. 8 Stress-strain-curve of a Ti/Al-joint. Materials: Ti6Al4V, AlMg0.4Si1.2.*

The failure of the samples occurs on the aluminum side of the joint outside of the heat affected zone of the material. This leads to the assumption that the aluminum base material is strength limiting. Comparatively, the thin phase seams in Ti/Al-joints have minor influence on the mechanical properties of the joint. A detailed simulation of the stress distribution within the sample under constrained conditions due to the different Young's modulus of Ti and Al have not been performed. It can be expected, that based on simulation datas, an accurate prediction of the failure behavior will be possible.



*Fig. 9 Fractured sample of a Ti/Al-tensile testing sample. Materials: Ti6Al4V, AlMg0.4Si1.2.*

## Conclusion

An advanced joining process was developed, which provides several advantages concerning process stability and mechanical properties of the produced joints. The application of a modified working head leads to a reproducible laser positioning with respect to focal position and beam position on the sheet material. Additionally, the applied forces ensure a technical zero gap between the sheets in the heated zone and an improved thermal conduction is provided. This leads to a stable joining process and homogeneous joints can be realized.

For Fe/Al-joints additionally non corrosive flux should be used to achieve joints with desirable mechanical properties. At present, fracture stresses up to 200 MPa are reached. Focussing on the material combination Ti/Al, the developed joining process provides some unique results: For the process no filler wire or flux has to be used. Between the materials a very good wetting behavior is observed and the thickness of the intermetallic layer is limited to a size in the range of 2  $\mu\text{m}$ . The strength of the joints is higher than the strength of the aluminum sheet material, thus failure of the samples occurs in the aluminum.

Further investigations concerning the phase formation during joining are on the way. A deeper understanding of the phase formation mechanism is required in order to improve the mechanical properties by a further optimized processing control. Finally, the assembling of materials with tailored mechanical properties should be realized for future applications.

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### **Biography**

Dipl.-Ing. Florian Wagner studied mechanical engineering at the TU Hamburg-Harburg (TUHH). In 2000 he finished his PhD on the topic of metal/ceramic composites at the TUHH. Since 2000 he is working at the BIAS in the field of laser materials processing of dissimilar materials.