Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Physics Procedia 12 (2011) 142–149

Physics Procedia

LiM 2011

Laser Beam Welding with High-Frequency Beam Oscillation: Welding of Dissimilar Materials with Brilliant Fiber Lasers

Mathias Kraetzsch, Jens Standfuss*, Annett Klotzbach, Joerg Kaspar, Berndt Brenner, Eckhard Beyer

Fraunhofer IWS Dresden, Winterbergstrasse 28, 01277 Dresden, Germany

Abstract

Brilliant laser beam sources in connection with a high frequent beam oscillation make it now possible to join metallic material combinations, which have been conventionally non-laser weldable up to now. It concerns especially such combinations like Al-Cu, where brittle intermetallic phases occur. Extreme small weld seam with high aspect ratio leads to very short meld pool life time. These allow an extensive reduction of the heat input. On the other side the melting behavior at metallic mixed joint, seam geometry, meld pool turbulence and solidification behavior can be influenced by a high frequent time-, position- and power-controlled laser beam oscillation.

Keywords: Brilliant laser; high frequent beam oscillation; metallic material combinations

1. Introduction

1.1. State of the Art

Welding of different metallic materials regardless of the procedure is a very interesting topic in research and practice. A review of metallurgical and manufacturing bases, including several embodiments for welding of material combinations are among others as a German-language reference work [1]. Phase diagrams give information of occurring phase transitions, thermodynamic balances and possible diffusion processes and are necessary tools for assessment of welded joints of dissimilar materials. Welding defects and different types of cracking such as hot cracking, cold cracking, shrinkage cracks, relaxation cracks, hydrogen induced cracks and disbonding can be explained in this context.

---

* Corresponding author. Tel.: +49-351-83391-3212; Fax: +49-351-83391-3210
E-mail address: jens.standfuss@iws.fraunhofer.de

doi:10.1016/j.phpro.2011.03.018

Electron beam welding of material combinations

In the past electron beam welding was the state of the art for beam welding technology, which allows on one side producing welds with extreme narrow seam, nearly parallel fusion face, short melt pool life time and very low line energy. On the other side for electron beam welding varying the spot size and meld pool geometry by beam oscillation is state of the art, too. Regarding the possibilities for welding of dissimilar materials, this technology has been extensively studied and documented in the 1960's [2]. The principal technical advantages of electron beam welding for joining dissimilar materials are among others [3]:

- exactly controllable energy input, high focusing ability and high positioning accuracy for monitoring the resolution of the involved material components
- low heat input to reduce residual welding stress and distortion and
- advantages of high-purity environment and the reduced heat dissipation, especially in materials with high thermal conductivity such as copper.

Procedural technical limitations in electron beam welding of different metal materials are e. g. the beam deflection caused by asymmetric electrostatic or electromagnetic fields. Basic scientific studies to the electron beam welding of dissimilar joints of the ISF-Aachen are concerned with the welding material combinations such as steel-aluminum, copper-tungsten, steel-molybdenum and steel-tungsten [4]. Distribution of heat and energy application were specifically changed with the help of several rays, and varying the modulation shape and frequency, in order to achieve material adapted temperature fields, to influence of diffusion and distribution of stress in the weld seam.

Laser beam welding of material combinations

Now solid state laser beam sources with 3...10 fold optical efficiency compared to conventional laser beam source and brilliant beam quality (M^2 ~1.1) available. A spot size of 0.015 to 0.05 mm allows laser beam welding with significant lower line energy. The challenges for laser beam welding with new brilliant laser beam sources compared to electron beam welding are technologies and welding heads for welding with high frequent beam oscillation. Further research is needed for laser beam welding of dissimilar metals to get results similar to electron beam welding [6, 7]

The research on laser beam welding of dissimilar materials in the area of macro-materials processing primarily focuses technologies and welding heads on potential applications in the automotive and aerospace industry for thin sheet applications. A high potential for application of laser beam welding is shown, for example, for the material combinations steel-aluminum and aluminum-titanium. With appropriate process control and the typical laser deep welding effect, it is possible to form only a minimum intermetallic phase hem and thus achieve good mechanical properties of the joint. The reduced heat input of pulsed Nd:YAG laser sources compared to cw-lasers shows advantages when welding the material combination titanium-austenitic steel [8]. Currently only laser roll cladded steel-aluminum transition joints are industrially used. By this technology the formation of intermetallic phases is largely suppressed [9]. Laser beam welding of iron-based mixed compounds is industrially used for different steels and cast iron, especially in the automotive powertrain.

Beam oscillation

An influence of the temperature field during welding can be useful for crack-sensitive materials. Beam oscillation and power modulation allows the influence of the temperature field at the electron beam welding [8, 9]. For the modulation of capillary geometry oscillation frequencies up to 2 kHz and oscillation amplitudes of up to 2 mm are generally used [10]. Similar approaches to the high-frequency 1D-oscillation are pursued at the laser beam welding for improved process stability [11]. First investigations of the 2D-oscillation at the laser beam welding with fiber lasers and modulation frequencies up to 1.5 kHz system showed the technical feasibility [12].

1.2. Objectives and Approaches

The overall objective is to develop an easy-to-handle integrated laser tool for solid state lasers with high beam quality. In first studies, the process and system engineering requirements for quality–oriented and effective laser welding of dissimilar materials was investigated by using a prototype. Commercially important material combinations were selected, which are yet not conventionally weldable or are restricted as to weld. The objective regarding the process technology is to be achieved by utilizing the extremely good focusing ability of the laser beam. Brilliant fiber lasers enable extremely narrow welds with very high depth to width ratios at extremely short lifetime of the melt pool. They also offer the possibility of a flexible material-optimized, high frequency temporal and spatial beam manipulation and power modulation. Using these properties of brilliant fiber lasers, the process parameters such as degree of mixing, turbulence of melt pool, the melting of the two parts, the heat input, the seam geometry and the solidification sequence should be controlled so that current welding limits can be overcome. The weldability is limited both by the formation of coarse brittle intermetallic phases and the formation of hot and cold cracks. Very different thermophysical properties of the joining partners such as melting temperature, thermal conductivity and thermal expansion coefficient also may restrict the weldability.

2. Technical System Development

The objective regarding the system development was to design and test a welding head with a control system, implemented in the laser beam source. This welding head should have an integrated high dynamic seam finding system, a high frequency 2D scanning and a highly accurate beam positioning unit. The requirements of the welding head are to generate reproducible even at usual component tolerances the locally required degree of mixing. Also the shape of melt pool and weld seam should be varied by a high frequency motion with keyhole simultaneously superimposed sweeps.

The first step of the investigation for laser beam welding of dissimilar materials with high-frequency beam oscillation was to develop a prototype system called "lasertronic®SAO-fast 1.0x (1D)" and corresponding software for controlling the scanner and the power modulation (Figure 1). Using a multi-kW-single-mode-fiber-laser and with respect to a desired image scale of 1:1, collimation and focusing each with a focal length of 200 mm was designed. Adjustments are possible due to the modular design. The galvanometer scanner is used for the high-frequency beam oscillation. The complete system includes an integrated mirror and optical cooling; hence the thermal design allows appropriate laser sources with a power of 5 kW (Figure 1).

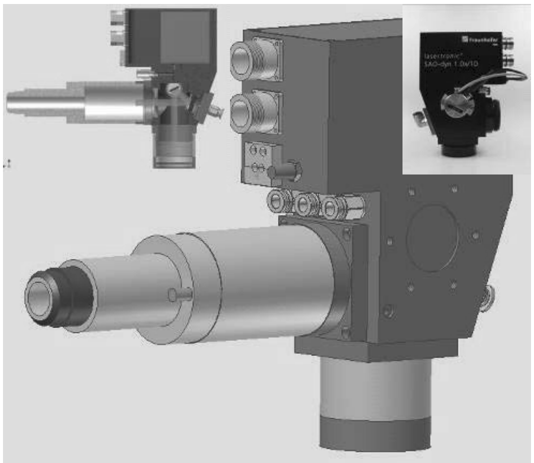
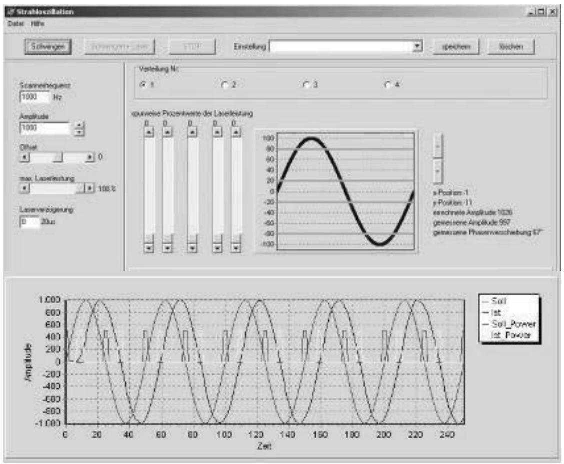


Figure 1: Prototype system for high-frequency beam oscillation"lasertronic®SAO-fast 1.0x (1D)"



Einstellung

Scannerfrequenz 1000 Hz

Amplitude 1000

Offset 0

max. Laserleistung 100 %

Laserverzögerung 0 20us

x-Position -1
y-Position -11
errechnete Amplitude 1026
gemessene Amplitude 997
gemessene Phasenverschiebung 67°

Figure 2: Software for scanner- and laser power control adapted on application

The control of the scanner and the laser beam source was performed with software which can be adapted to the specific application and the use of RTC5 controller from scanner made by Scanlab. This software, developed at the Fraunhofer IWS Dresden, is characterized by the following features (Figure 2):

- freely programmable scan-frequencies up to 2.5 kHz with power modulation or
- freely programmable scan-frequencies up to 5 kHz without power modulation,
- automatic adjustment of required and actual positions of the desired scan amplitude,
- variable adjustment of laser power profiles,
- visualization of the measured signals of required and actual values of scanner position and laser power.

For the welding and system test trials a 2 kW single mode fiber laser FL020 by ROFIN SINAR with a 20 µm core fiber diameter was used. The laser is a diode-pumped Ytterbium single-mode fiber laser with a maximum output power of 2 kW and a beam parameter product of ≤ 0.4 mm x mrad. A measurement of the respective intensity profiles was performed exemplary at a predetermined scan width of 1.0 mm and a scanning frequency of 1.5 kHz without and with laser power modulation (Figure 3).

System test trials (scanning width 1 mm / frequency 1.5 kHz)

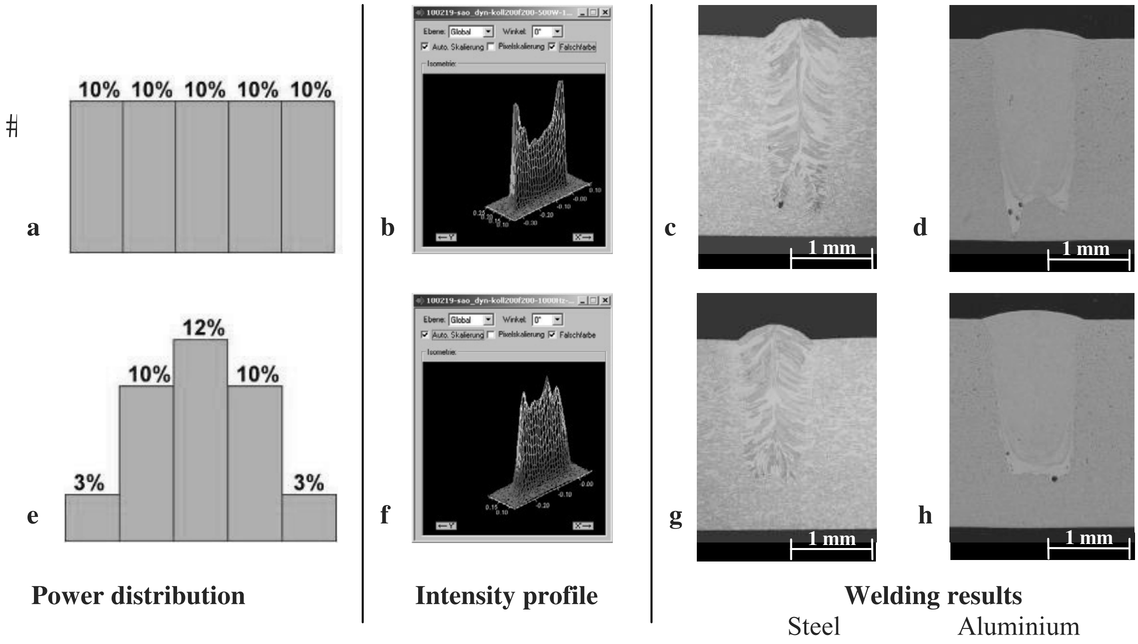
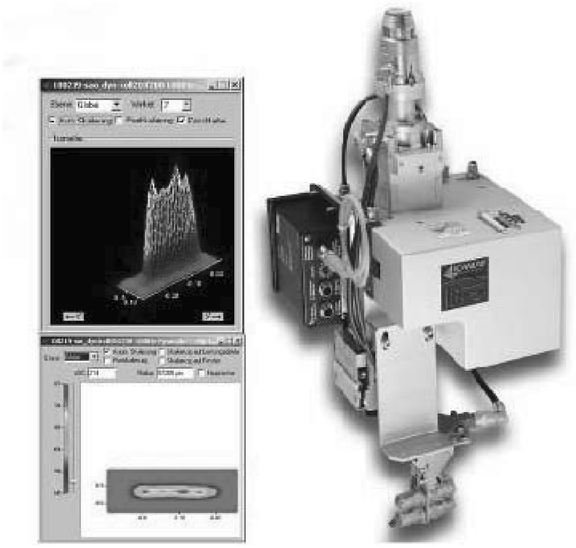


Figure 3: Influence of high frequent beam oscillation with power modulation on weld seam geometry at bead-on-plate welds

The higher local impact time of the laser beam at the turning points of the scanning movement leads to local intensity peaks. This property is illustrated by the measured intensity profiles (Figure 3 b). A position-dependent reduction of laser power in this area and the adjustment of laser power in the zero position allows the generation of a uniform intensity profiles (Figure 3 f). This is possible up to a scanning frequency of 2.5 kHz. Figure 3 c, d, g, h shows welding of structure steel S355 and the aluminum alloy AlMg3 respectively. The flanks of the weld seams have the aspired parallel form and a homogenous weld depth over the whole seam width (Figure 3 g, h). The laser welding system described above is also used for welding of the following material combinations and with respect to possible applications:

- aluminum (Al99.5) – copper (Cu99.5OF) for electrically conductible joints, joints for heat sinks, a. s. o.
- stainless steel (1.4301) – copper (Cu99.5OF) for heat exchanger, vacuum apparatus
- aluminum (5052) – magnesium (AZ31) for automotive or aerospace applications.

A broad industrial applicability needs an easy-to-handle integrated system and parameter data base (see Figure 4). The system (integrated laser tool) and process development during the WELDIMA-project shows first results. Further development steps for evaluation of the system for industrial applications are in progress [7]. The possibilities for the influencing of the welding process will be extended with the availability of the integrated laser tool. This concerns the more reproducible and more precise positioning of the laser beam in relation to the joint by means of high-resolution weld seam sensor system. It is also expected that due to high-frequency 2D beam oscillation, the influence at the mixing ratio and at the element-distribution in the melting zone will be increased. First welding trials with the new integrated laser tool confirm an advanced weldability of dissimilar materials.



Technical data:

- Fiber laser ROFIN SINAR FL020 S
  - diode-pumped Ytterbium single-mode fiber laser
  - maximum output power 2000 W
  - beam parameter product ≤ 0.4 mm x mrad
  - fiber core diameter 20 µm
  - integrated Controller for 2D Scanner
- 2D scan system SCANLAB intelliSCAN® 20 FC
  - High-dynamic 2D beam oscillation and position control > 2 kHz
  - wavelengths 1030 nm – 1090 nm
  - focussing focal length 245 mm
  - collimation focal length 140 mm
  - tolerable laser power 4000 W (single mode)
  - scan field: 10 x 10 mm^2 (high dynamic range: 1.5 x 1.5 mm^2)
- optical weld seam tracking system FALLDORF
  - custom lighting
  - image analysis in real time
  - high resolution and short processing time

Figure 4: Integrated laser tool, developed in the WELDIMA-project

3. Results and Discussion: Laser beam welding of dissimilar materials with high frequency beam oscillation on the example Al-Cu

Dissimilar joints between copper and aluminum are interesting for a variety of applications in the field of electrical engineering and electronic as a replacement for mechanically joined connections. An improvement is expected in the first place in terms of electrical conductivity and heat transfer. The material combination of aluminum/copper is usually not weldable. This is caused by the occurrence of very brittle intermetallic phases which have only a poor ductility. The suppression of the formation of intermetallic phases to a large extent improves the chance of the weldability of such conventionally not weldable metal material combinations. By using a high-frequency beam oscillation and lateral beam displacement it has been attempted to influence the formation of intermetallic phases by varying the mixing ratio in the weld. At first, investigations were performed on Al/Cu overlap joints to determine the degree of mixing for different parameters of beam oscillation (Figure 5). Furthermore butt joints of Al/Cu have been welded, which were investigated in tensile tests concerning their static strength (Figure 6). After optimization, the following parameters were used for the welding trials:

- laser power: 2000 W
- welding speed: 4000 mm/min
- scan frequency: 2500 Hz
- scan width (butt joint): 0.4 mm
- scan width (overlap joint): 0.7 mm / 0.9 mm

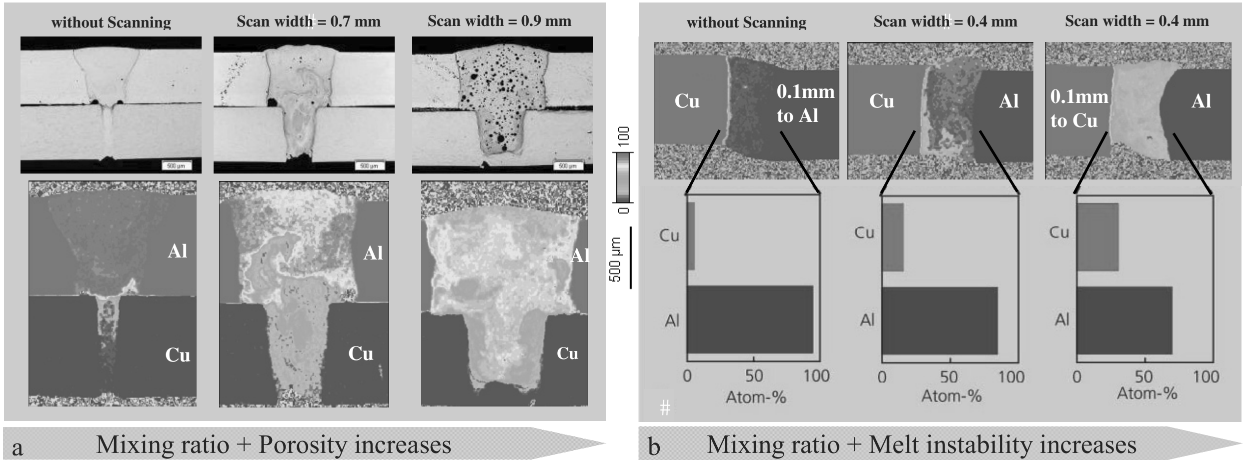


Figure 5: mixing ratio for different parameters of beam oscillation for Al/Cu overlap joints (a) and for butt joints of Al/Cu (b)

EDX color spectral images were performed in a SEM to visualize the distribution of elements in the melting zone of overlap joints (Figure 5, a). In this case, a 20-fold split color scale (copper = blue, aluminum = red) is used. A color change occurs when the local mixture ratio changed by 5 at%. The recordings show that without scanning an adequate mixture into the weld zone is not achieved. The recordings also show that using high-frequency beam oscillation and increased scan width can produce welds with homogeneous mixed melt zone, however with increased porosity. The butt joints were welded with high frequency scanning with a scan width up to 0.4 mm as well as without scanning. Additionally, the relative position of the weld seam to the joint was varied in defined steps in a lateral direction for both materials. Since aluminum has a lower yield strength compared to copper, welding residual stress can be better absorbed. This leads to a drastically reduced cracking during the cooling of the melt and *a higher static strength can be achieved.*

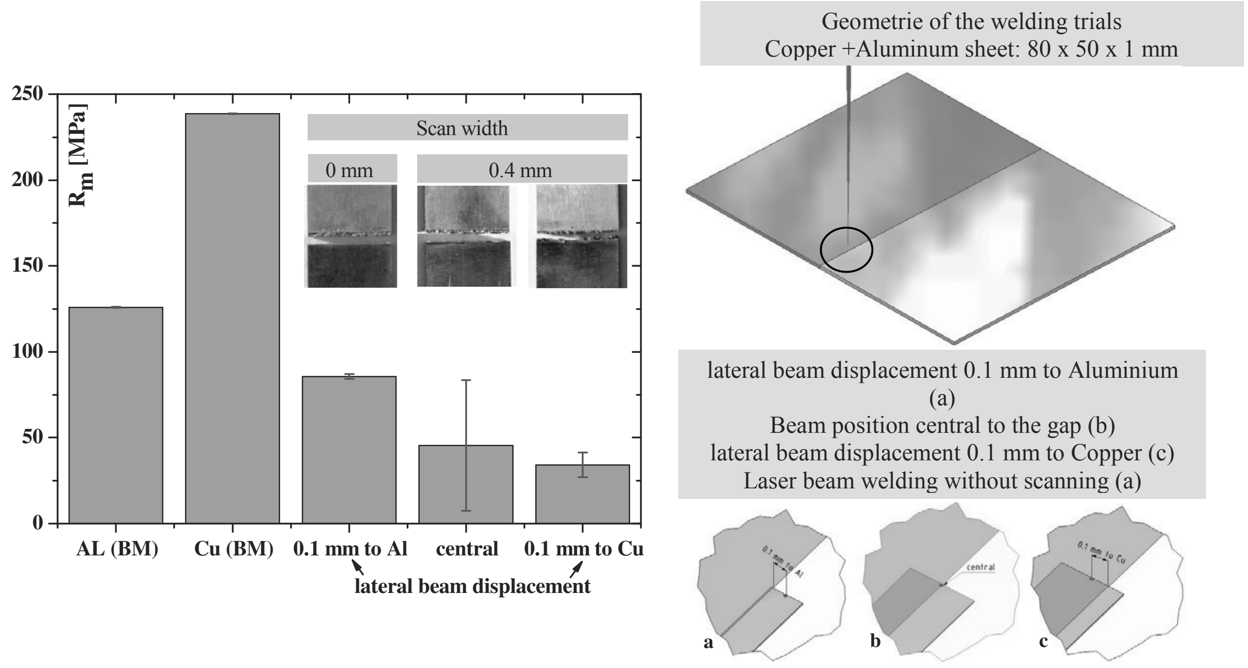


Figure 6: Static strength of laser beam welded Al/Cu-butt joints depending on scan width and depending on a lateral beam displacement relative on the gap

With increasing lateral beam displacement in the direction of the copper material, the welding process behaves more anxious, which leads to a correspondingly irregular formation of final pass and weld root. The maximum static strength of the welded dissimilar joints was achieved with a minimum of copper in the melting zone. The lowest mixture ratio of Cu/Al with 5:95 at% was measured without scanning and a lateral beam displacement from 0.1 mm in aluminum (Figure 5, b). The highest strength of approximately 80 % of the base material level of aluminum was measured in tensile test for welding samples with these parameters. The location of failure in the tensile test was always in the area of the intermetallic phase hem. For central welding position and lateral beam displacement in direction of aluminum, the location of the intermetallic phase hem can be observed at the fusion line on the side of the copper material and springs with increasing lateral beam displacement in the direction of copper, to this material side.

The welding without scanning of dissimilar materials with brilliant beam sources, in accordance with the conditions of the industry, can not be realized for usual component tolerances due to the very small spot diameter $\leq$ 40 microns. The high-frequency beam oscillation ensures sheet edge engagement also for very small spot diameter and allows a reproducibly welding. The welding results with the 1D prototype system show, that the static strength of approximately 80 % of the base material level of aluminum can be achieved in principle. In the tensile test measured fluctuations in strength can be explained by the limited possibilities of 1D beam oscillation with respect to the influence of mixing ratio and element-distribution in the melting zone as well as problems with the precise laser positioning.

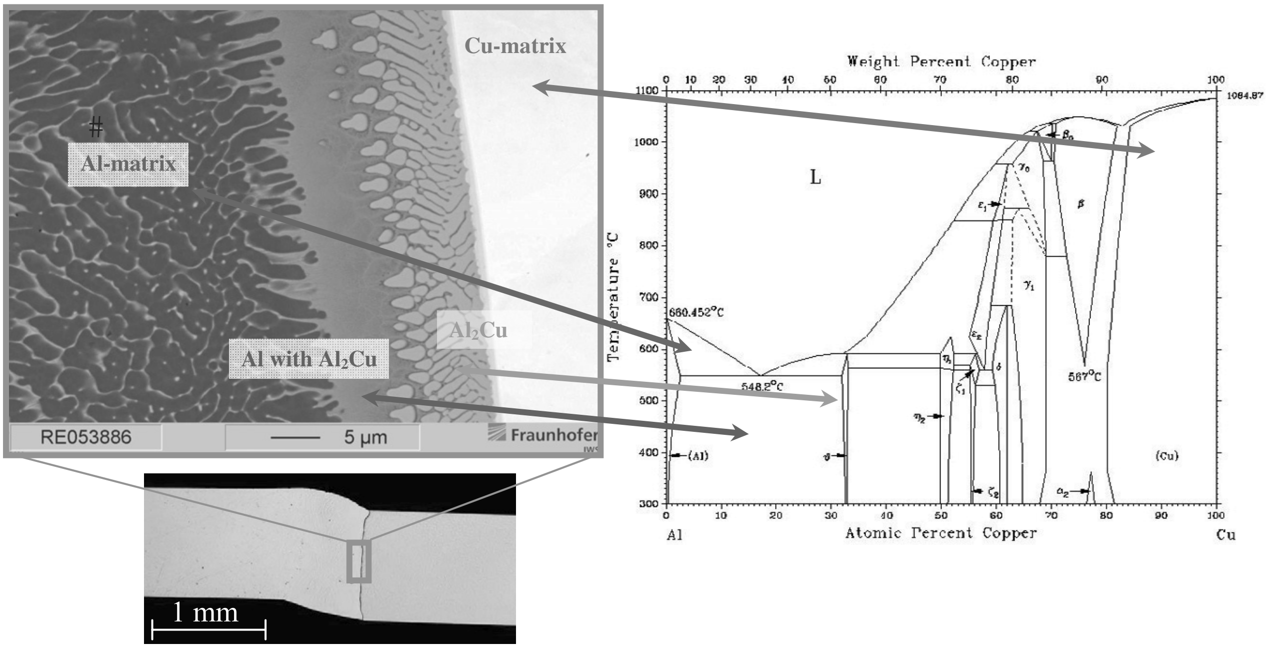


Figure 7: Influence of high frequent beam oscillation with power modulation of weld seam geometry at bead-on-plate welds

In detailed electron microscopically investigations were proven, that the crack starts at the small intermetallic phase hem at the fusion line at the Cu side. Figure 7 shows the aluminum-rich side of the phase diagram Al-Cu. Aluminum solid solution (α) and the intermetallic phase Al$_2$Cu (ϑ) occur as solid phases. The phase diagram Al-Cu shows a decreasing solubility of aluminium solid solutions on copper with dropping temperatures. With heating above 660 °C all copper atoms in the aluminum solid solution are dissolved. During the cooling process after welding, the brittle intermetallic phase Al$_2$Cu will be precipitated, according to the phase diagram, after falling below the solubility line. In the border range of the weld the brittle intermetallic phase Al$_2$Cu is extreme fine disperse embedded in the ductile Al-matrix (see Figure 7 eutectoid range of binary phase diagram), followed by ductile Al with eutectoid phase mixture.

The static strength of approximately 80 % of the base material level of aluminum is to achieve, when the intermetallic phase hem is located at the fusion line on the copper side, at a thickness lower than 5...10 µm. For this conventionally non-fusion weldable material combination, normally the strength level of fusion-welded Al-Cu is quite low or failed brittle after welding. The metallographical results also show that regardless of positioning the laser beam to the joint, the formation of small pores could not be suppressed.

4. Conclusions

For the material combination Al-Cu crack-free welds were achieved (Figure 5). The static tensile strength of laser welded material combination is at the same level like the weakest material Al99.5. Tensile tests show, that the laser welded Al-Cu joints failed directly at the fusion zone on the copper side. At the overlap configuration for laser beam welding of Al-Cu, the element distribution in the weld zone strongly depends on the scanning parameter like shown in figure 5. In both cases, brilliant fiber laser and the use of high speed scanning head with power modulation offers possibilities for crack free welding of dissimilar metals comparable to the electron beam. Examples for different combinations of conventionally non-weldable dissimilar metal combination are given [7].

References

[1] Pohle, C.: Schweißen von Werkstoffkombinationen. In: Fachbuchreihe Schweißtechnik, Volume 140, DVS-Verlag (1999),

[2] Wiesner, P.: Elektronenstrahlschweißen. In: Technisch-wissenschaftliche Abhandlungen ZIS Halle Nr. 64 (1971)

[3] Sun, Z., Karppi, R.: Electron beam welding of dissimilar metals. In: VTT Research Notes 1544, Technical Research Finland (1994)

[4] Dilthey, U.: Elektronenstrahlschweißen metallischer Werkstoffkombinationen. In: DFG-Final Report Di434/67-1 (2006)

[5] Beyer, E., Brenner, B., Standfuß, J.: Laser beam welding with High Power Fiberlaser. In: 25th International Congress on Application of Lasers & Electro-Optics (ICALEO), 2006

[6] Dobeneck, D.v., Schultz, H.: Neuentwicklungen und Einsatzmöglichkeiten des Elektronenstrahlschweißens. In: Schweißtechnisches Fachwissen, DVS-Verlag (2001) 136-146

[7] Standfuss, J., Klotzbach, A., Heitmanek, M., Kraetzsch, M..: Laser beam welding with high-frequency beam oscillation: welding of dissimilar materials with brilliant fiber lasers. In: International Laser Symposium Fiber & Disc (FiSC), Dresden 5./6. Oct. 2010

[8] Hiraga, H., Fukatsu, K., Ogawa, K., Nakayama, M., Muto, Y.: Nd:YAG laser welding of pure titanium to stainless steel. In: Welding International, Volume 16, Issue 8 (2002) 623-631

[9] Polzin R., Poprawe, R., Pircher, H., Prange, W.: Kritische Verbindung. Aluminium-Stahl-Anschluß im Fahrzeugbau. In: Laser-Praxis, Issue Oktober (1995) LS77-LS78

[10] Wiesner, P., Ehrhardt, H.: Elektronenstrahlschweißen mit Strahlpendeln. In: ZIS-Mitteilungen 1/83

[11] Meier, O.: Hochfrequentes Strahlpendeln zur Erhöhung der Prozessstabilität beim Laserstrahlschweißen. In: Final Report AIF-Vorhaben 13600N (2006)

[12] Klotzbach, A. Pfohl, P.: Remote Processing with Fiber lasers. In: 2nd International Workshop in Fiber Lasers, Dresden (2006)