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Joining of CrNi steel and AlMg alloy without interlayers

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Abstract. The paper describes the substance-to-substance joining of the material combination CrNi steel and AlMg alloy. The joint was created through a thermal joining procedure in the solid state without interlayers. Material characteristics such as thermal strain and hardness were investigated. The investigations were conducted in the transition areas of the joining zones depending on the joining parameters. The joining quality of the surfaces was especially assessed and the diffusion zones were classified by means of the scanning electron microscope. Crack-free and homogeneous joining zones, which guarantee a high-quality joint with adequate strength, were the primary objective of the investigations.

Key words: CrNi steel, AlMg alloy, diffusion joining, strain, hardness.

1. INTRODUCTION

The manufacture and application of innovative dissimilar material joints with specific characteristics require continuous development of the joining technology. Presently, however, there is a predominance of similar material joints. Comprehensive investigations on the substance-to-substance joining of dissimilar materials with dissimilar characteristics still have to be conducted.

Diffusion joining in the solid state was used as a joining technology for dissimilar material joints. The joints were created with and without interlayer materials below the melting temperature of the joining partners.

Composite constructions have become a focal point in the optimization of lightweight constructions regarding their stability, due to the fact that in this way the characteristics of dissimilar materials can be optimally exploited. The joining of dissimilar materials, e.g. CrNi steels and AlMg alloys poses a special challenge in the field of joining technology. The following requirements on the joining are to be met:

– manufacture of substance-to-substance joints,
– reduction of and avoiding the creation of intermetallic phases,
– balancing of different melting temperatures,
– reduction and absorption of stress in the joint.

A distinction between similar and dissimilar materials is made in order to characterize joined components. Similar materials are structural steels with different yield stresses. Dissimilar materials are, e.g., steels with light or heavy metals such as the combination of steel and aluminium [1,2].

Diffusion joining is currently a very promising joining procedure to manufacture dissimilar material joints without creating a mutual melt. That is why the creation of intermetallic phases from the melt can be prevented within dissimilar material joints. Such phases influence the strength in the material joint [3]. Besides intermetallic phases, also various material properties have an impact on the joint strength. With dissimilar material joints these are:

– thermal expansion,
– heat conductivity,
– melting temperature,
– porosity and hardness.

One important criterion in the diffusion joining of dissimilar materials is the change of properties of the materials in the joining zone. Gradual changes to the properties occur on boundary surfaces. They strongly depend on the diffusion joining parameters (joining temperature, joining force and joining time). Figure 1a shows the change of properties of dissimilar materials before the diffusion joining process. After the joining process the changes are no longer sudden. Examinations have shown that the properties change gradually, exponentially or parabolically (Fig. 1b). The creation of a diffusion zone leads to a material concentration balancing depending on the joining parameters. This results in a partial balancing of property changes in dissimilar material joints. Stress in the joint is reduced, which leads to a higher joint strength [4,5].

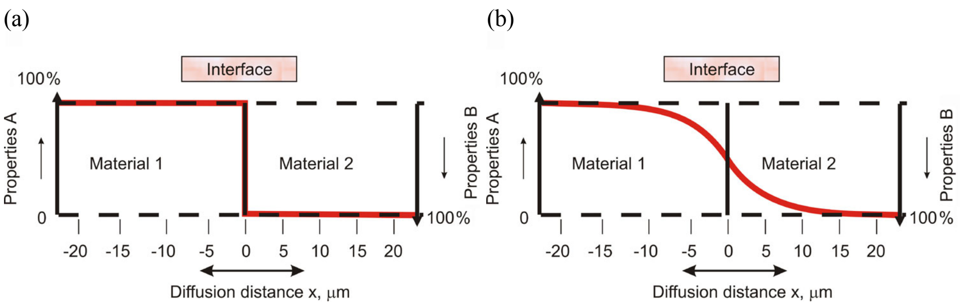

Fig. 1. Schematic illustration of properties before the joining process (a) and after the joining process (b).

Dissimilar material joints of ceramics, metals and monocrystals with and without interlayers are studied in [6–8]. Dissimilar material joints of CrNi steel and AlMg alloy are under examination for technical applications in the field of nuclear technology. The joining zone must not be influenced by additional alloy elements in order to guarantee a high safety standard. A substance-to-substance joining without interlayers is necessary in order to prevent material failure in the joining zone. Diffusion welding provides an innovative approach where the joint is created through solid state diffusion as well as dislocations in the crystal structure. Joining in the solid state and optimization of joining parameters enables the achievement of joint strength and ageing stability similar to the base material. This is, however, a precondition in order to meet the high quality requirements for applications in the aerospace industry or for material joints in nuclear technology.

2. EXPERIMENTAL

The material properties are essential for the definition of the process parameters in the diffusion joining in order to manufacture high-quality dissimilar material joints (Table 1).

The lowest melting temperature of the joining component AlMg3 (below 620 °C) defines the joining temperature. Matching face centred cubic (fcc) space lattices are advantageous in order to activate diffusion processes in real crystals along dislocations or grain boundaries. The diffusion is isotropic for joining partners with cubic elementary cells irrespective of their orientation. Additionally, vacancy mechanism and dislocation density are the primary joining mechanisms with metals.

The number of primary slip systems in the face-centred cubic lattice (Fig. 2) is limited to 12 in one elementary cell. Each of the 4 slip planes has 3 slip directions, along which the stress, necessary for a deformation, is the lowest. Slip planes are those with the highest number of atoms. Elastic as well as plastic deformations initially occur along these slip directions. Thus a material, which is

Table 1. Thermophysical properties

Parameter	CrNi steel X5CrNi18-10	AlMg alloy AlMg3
Density, g/cm^3	7.93	2.7
Space lattice	fcc	fcc
Melting point, °C	1400–1455	620
Thermal expansion at 20–100 °C, K^{-1}	18×10^{-6}	23.5×10^{-6}
Heat conductivity at RT, Wm^{-1} K^{-1}	16.3 at RT	125
Vickers hardness, HV	175	75
Modulus of Elasticity, GPa	190–210	71
Tensile strength, MPa	460–1100	300–450

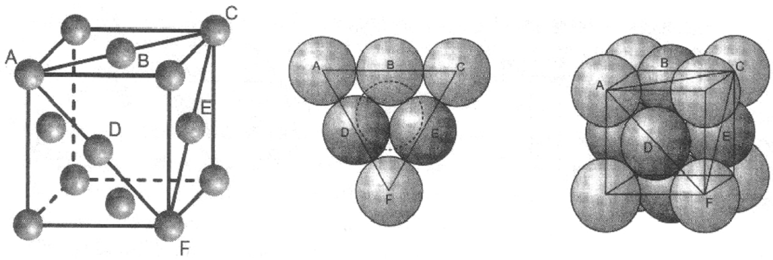

Fig. 2. Face-centred cubic space lattice (fcc) with slip systems.

under pressure during the diffusion process, is elastically deformed along these directions. However, the deformation ability is limited by the size of the interstitials.

A thermal process has to take place in order to initiate diffusion processes between the joining partners. The joining force triggers a forced diffusion. The diffusion in metals is a process where atoms are moved due to concentration differences with a tendency to balance them.

The joining experiments were carried out in a high temperature graphite furnace with integrated press (Fig. 3). The dimensions of the test pieces were $20 \times 20 \times 5$ mm, which corresponds to a joining surface of 400 mm^2. A joining force of 2000 N equates to a joining pressure of 5 MPa. The heating and cooling rates were $10\ K \cdot min^{-1}$ in a pre-vacuum atmosphere at about 10^{-1} mbar. Joining time and temperature were varied (Table 2). Solid dissimilar material joints could be manufactured as a result of the joining experiments. The joint strength and form stability strongly depended on the joining temperature and joining force due to the low hot compressive strength of the AlMg alloy.

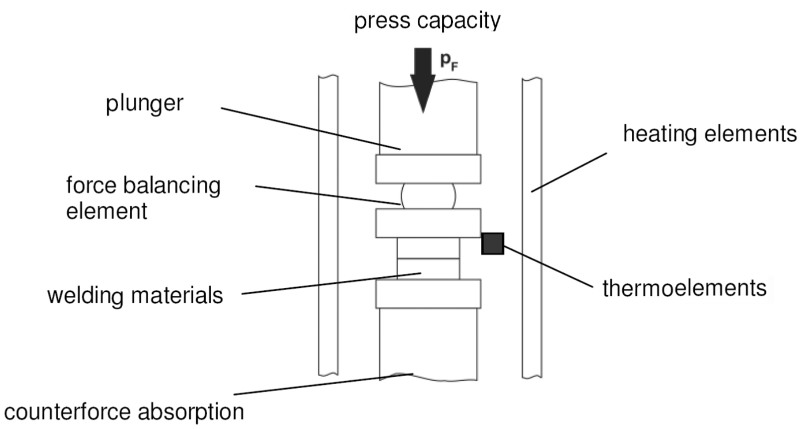

Fig. 3. Schematic of experimental test set-up for diffusion welding.

Table 2. Experimental joining parameters of the dissimilar material joint CrNi steel with AlMg alloy

No. of the experiment	Joining temperature *T*, °C	Joining time *t*, h	Joining force *F*, N
1	450	2	2000
2	500	2	2000
3	550	2	2000
4	450	12	1000
5	500	12	1000
6	550	12	1000

3. RESULTS AND DISCUSSION

Expansion and contraction of the joining parts in a thermal process define the state of stress in the joint. Metals can absorb stress due to their ductile behaviour. Examination on dissimilar material joints showed that, depending on the material behaviour, different expansions of up to $\Delta\alpha = 10 \times 10^{-6}$ K^{-1} can be compensated. Figure 4 illustrates the expansion progression of the dissimilar material joint of CrNi steel and AlMg alloy from room temperature to joining temperature. Expansion coefficients *CTE* were measured by means of an Absolut-Dilatometer *Linseis L* 75/20 under air with a heating and cooling rate of 5 K · min^{-1}. With the above-mentioned material joint the expansion coefficients differ from 6 to 8×10^{-6} K^{-1} up to the joining temperature range. No hysteresis effects in the expansion behaviour could be observed after the measurements. Depending on the temperature, expansion and contraction are almost constant, which permits to join the surfaces and minimizes the creation of cracks.

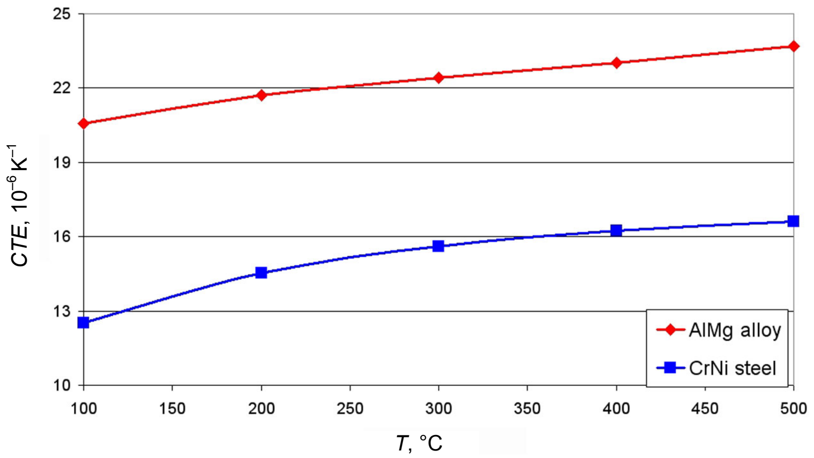

Fig. 4. Expansion progression of the dissimilar material joint of CrNi steel and AlMg alloy.

The surfaces of the joining parts or their atoms have to come as close as 10^{-6} to 10^{-7} mm in order to achieve atomic interaction. In reality this closeness is impeded by microroughnesses, form imperfections and layers of dirt and/or adsorption layers. All types of form deviations, which restrict the number of possible bonds in the joining zone, are reduced in the activation phase, i.e., physical interactions occur, in order to manufacture a high-quality joint. This can be achieved by surface pre-treatment or cleaning. At the same time the surface is extremely altered depending on the degree of deformation, which also affects pollution layers on the surface as well as layers near the surface. The procedures are very complex and the joining parameters are mutually linked.

The joining surfaces were mechanically ground and polished with a diamond paste in order to meet these requirements. The surface analysis was carried out by means of an autofocus sensor AF16, made by OPM GmbH Karlsruhe, coupled with an optical measuring system and it was used for optical length and profile measurement (topography illustration). Manufacturing quality and final state of the joining surfaces were measured (Table 3).

The mean roughness R_a and the arithmetical mean deviation of the filtered roughness profile over the measurement range were analysed, resulting in $R_a \leq 0.225$ µm, which meets the surface requirements for the diffusion joining of metals.

The joining and diffusion zones were characterized by means of SEM examinations. All the tests showed the same characteristic. Closed and flawless diffusion zones were achieved. Figure 5 shows the joint at a temperature of

Table 3. Surface characterization of the dissimilar material joint of CrNi steel with AlMg alloy

Surface parameters	CrNi steel		AlMg alloy	
	Manufacturing quality	Final state	Manufacturing quality	Final state
R_a, µm	0.834	0.109	0.298	0.225

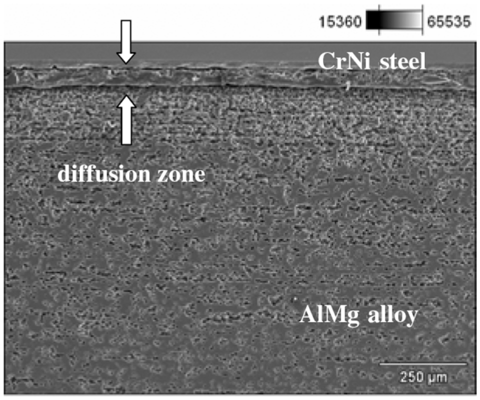

Fig. 5. Joining zone of the dissimilar material joint of CrNi steel and AlMg alloy (joining parameters: $T = 500\,°C$, $t = 12$ h).

500 °C and a joining time of 12 h. The material structure of the CrNi steel is compact, the structure of the AlMg alloy, however, is porous. The surfaces were homogeneously joined and a diffusion zone can be seen. The results of the joining tests showed no cracks parallel to the joining zone due to the different expansion behaviour. The ductile behaviour of the joining partners compensated the stress in the joining zone.

EDX-analysis in the diffusion zone or in neighbouring areas enables a qualitative examination of the diffusion behaviour of dissimilar material joints. Figure 6 illustrates the element distribution over the joining zone. The analysis showed that the concentration difference of the alloy elements forms a step in the measurement area. The left side of the diagram shows the CrNi steel with Fe, Cr, Si, Ni and a low Mn proportion. The right side of the diagram shows the AlMg alloy with high Al and low Mg proportion. The concentrations on the left (CrNi steel with alloy elements) are nearly constant. The concentration progressions from maximum to minimum exhibit a diffusion range *x* of over 100 µm.

Distribution of the joining parameters helps to optimize the joining process and to meet the requirements of the practice. The development of the diffusion areas *x* of the dissimilar material joints depends on the joining pressure, joining time and joining temperature, as shown in Fig. 7. The diffusion distance depends also on the joining time and the joining force. The joint stability cannot be concluded from the width of the diffusion zone and has yet to be proved in stability tests.

The microsection of the diffusion-joined dissimilar material joint, shown in Fig. 8, shows the indents in the joining materials and in the joining zone. The Vickers hardness HV 0.1 of the dissimilar material joint was determined with the

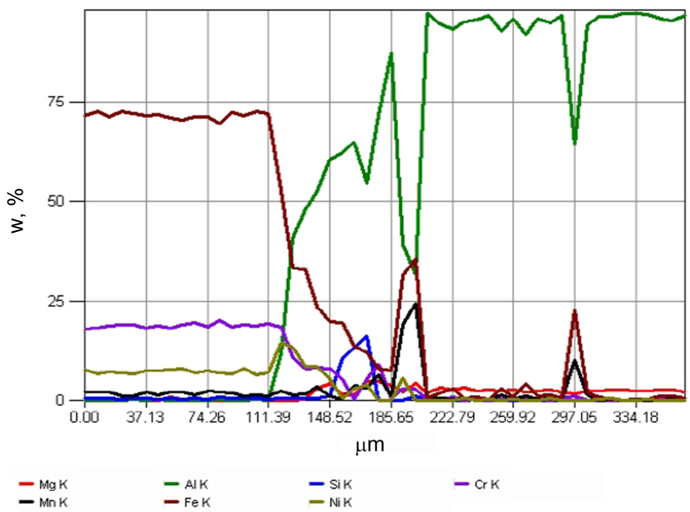

Fig. 6. EDX-analysis of the diffusion zone of CrNi steel and AlMg alloy (joining parameters: $T = 500$ °C, $t = 12$ h).

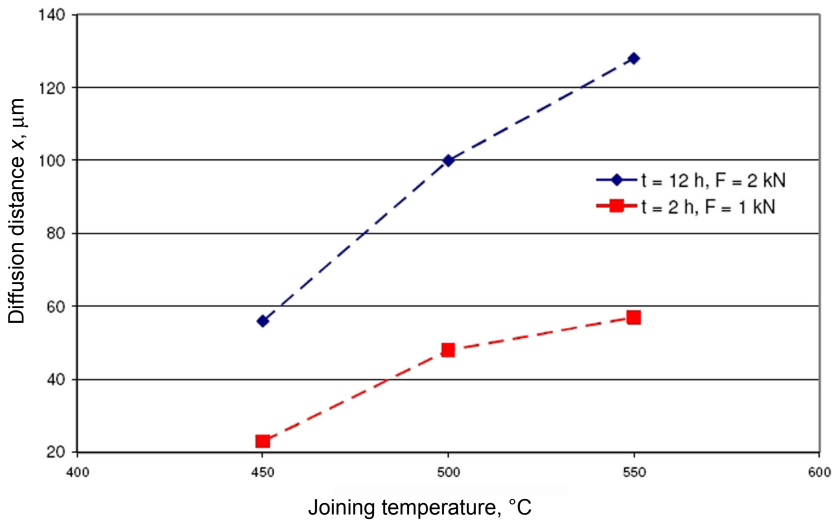

Fig. 7. Variation of the diffusion distance with the joining parameters and temperature.

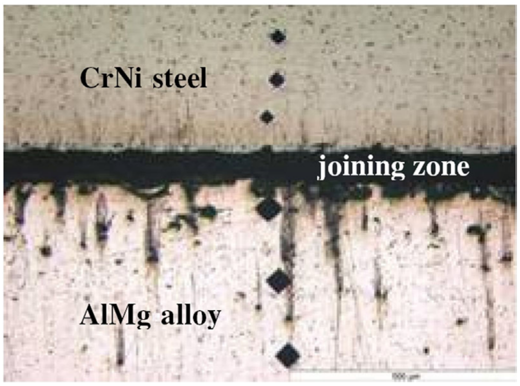

Fig. 8. Hardness progression over the joining zone (joining parameters: $T = 500\,°C$, $t = 12$ h).

joining parameters $T = 500\,°C$, $t = 12$ h by means of a small load hardness measuring device *Zwick* in compliance with EN ISO 6507-1.

In diffusion joining the material is stressed through a thermal process. This can either lead to an increase or decrease of the hardness, which affects the joint strength. Prior to the experiments the initial hardnesses were determined (CrNi steel 178 HV10, AlMg alloy 60 HV10) on thermally non-stressed joining partners. Figure 9 shows the hardness progression of the dissimilar material joint after the diffusion joining.

The examinations showed that the hardness in the joining materials is nearly constant. The hardness of the CrNi steel increases sharply near the joining zone up to 250 HV0.1. The Vickers hardness forms a step in the joining zone. This hardness increase is a sign of intermetallic phases in the joining zone. The thickness of these phases strongly depends on the joining time (Fig. 10). The intermetallic phase is about 20 µm thick. On the steel side it is mainly Fe_2Al_5 and on the aluminium side $FeAl_3$. The intermetallic phase $FeAl_3$ forms above 350 °C, has an aluminium concentration between 74–76 atom% and a complex monoclinic, bodycentred cubic structure. Furthermore, this phase is characterized by a columnar crystal shape. In contrast, the aluminium concentration in the intermetallic phase Fe_2Al_5 lies between 69–73 atom%. For comparison, the aluminium concentration in the joining zone of the sample, which was joined at 500 °C, was ca 59 atom%.

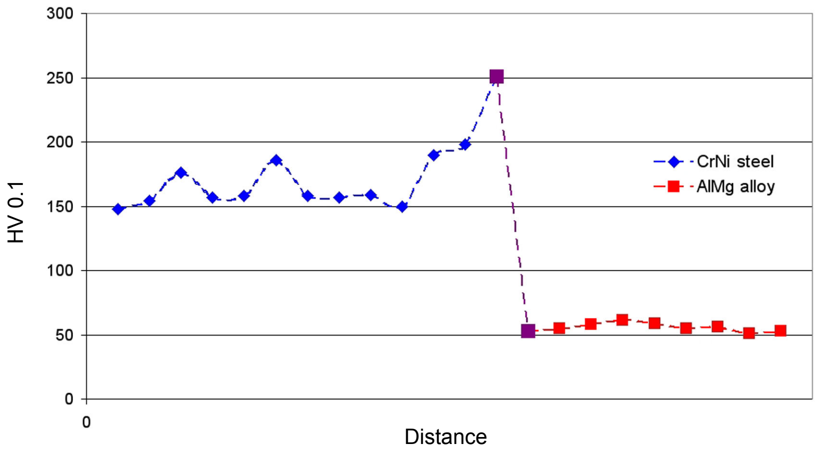

Fig. 9. Hardness progression over the joining zone of CrNi steel–AlMg alloy (joining parameters: $T = 500$ °C, $t = 12$ h).

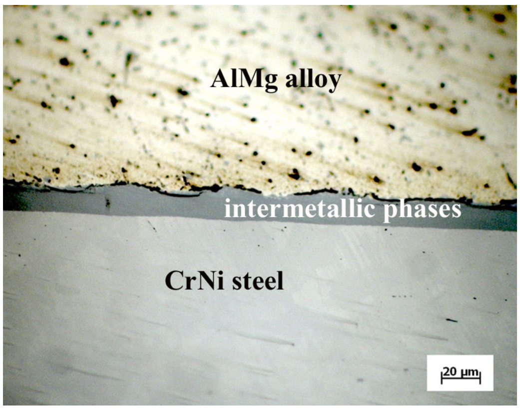

Fig. 10. Intermetallic phases between the CrNi steel and AlMg alloy (joining parameters: $T = 500$ °C, $t = 2$ h).

(a) (b)

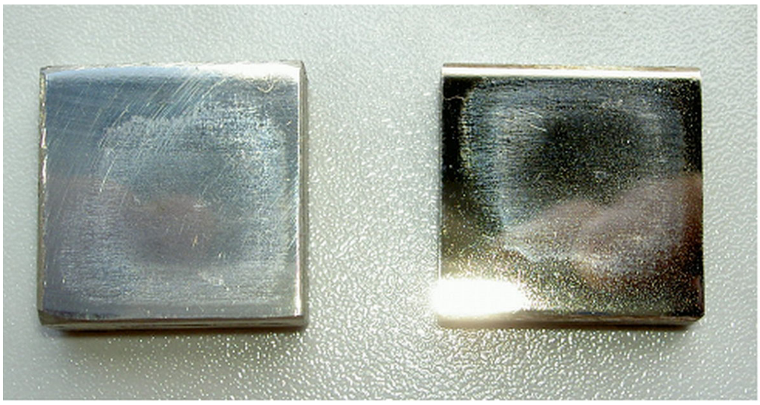

Fig. 11. Oxide layer on the joining surfaces: a – CrNi steel, b – AlMg alloy (joining parameters: $T = 500\,°C$, $t = 2$ h).

Figure 11 shows a broken joint after a stability test. An oxide layer, based on aluminium oxide, could be detected on the surfaces. The residual oxygen concentration in the pre-vacuum of 10^{-1} mbar caused the creation of the oxide layer, which was not broken due to the low joining temperatures [5]. These oxide layers additionally function as diffusion barriers and extend the joining time.

4. CONCLUSIONS

The examinations proved that through diffusion joining interlayer-free and crack-free dissimilar material joints can be manufactured between CrNi steel (X5CrNi18-10) and AlMg alloy ($AlMg_3$) at joining temperatures lower than 600 °C. Ground and polished surfaces are a precondition for an optimal joining process.

Different hardness and expansion behaviour (different expansion coefficients) of the joining parts enabled the manufacture of homogeneous and mechanically stable joints. Hardness and expansion behaviour are closely linked with each other and they are essential for achieving a low-tension joint. The creation and the characteristics of the joining zone depend on the Mg and Al content as well as on the alloy elements of the CrNi steel. The joining parameters (temperature, time and joining force) show functional interdependence, which results in the creation of different diffusion areas. The process parameters have a direct influence on the creation of intermetallic phases in the joining zone. Currently no conclusions can be made on the creation of intermetallic phases in a system with a variety of elements like in the examined case. That is why the examinations on the creation of intermetallic phases were restricted mainly on the system Fe-Al. The creation of intermetallic phases in the Fe-Al system is based on the almost absolute insolubility of iron and aluminium in the solid state. A short heat impact stimulates mainly the formation of intermetallic phases Fe_2Al_5 and $FeAl_3$.

Examinations on intermetallic Al-Fe phases as well as the inclusion of further alloy elements and the prevention of an oxide layer on the $AlMg_3$ will be subject of future research.

ACKNOWLEDGEMENTS

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CrNi-terase ja AlMg-sulami vahekihita difusioonkeevitus

Steffen Dahms, Priit Kulu, Renno Veinthal ja Ursula Basler

On käsitletud metallisulamite liitetehnoloogiat. Vaadeldavaks materjalipaariks oli CrNi-teras ja AlMg-sulam. Uurimistöö põhieesmärgiks oli difusioonkeevituse tehnoloogiliste parameetrite määramine defektivabade ja koostiselt homogeen-

sete difusioonliidete saamiseks. Materjalide liitmiseks kasutati tardfaasilist vahekihita difusioonkeevitust. Uuriti liites tekkivate termopingete ja difusioonitsooni kõvaduse sõltuvust liitetehnoloogia parameetritest. Erilist tähelepanu pöörati liitepindade kvaliteedile. Difusioonitsoonide iseloomustamiseks viidi läbi SEM-i uuring koos EDX-i analüüsiga. Leiti, et difusioonliitmisel kasutatavate tehnoloogiliste parameetrite (temperatuur, aeg ja survejõud) koostoime määrab tegeliku liitepinna suuruse ning neil on otsene mõju liitetsoonis tekkiva intermetalliidse faasi kogusele.