SUMMARY REPORT

of the research project

Development and evaluation of advanced welding technologies for multi-material design with dissimilar sheet metals

Acronym: InnoJoin

Project nr. 130368

Collective research - CorNet

<u>Participating research performers</u> :

BWI : Belgian Welding Institute

KU Leuven : Katholieke Universiteit Leuven represented by KU Leuven Research & Development, Thomas More, Campus De Nayer, Research Group on Advanced Manufacturing

CEWAC : Centre d'études wallon de l'assemblage et du contrôle des matériaux

LWF : Laboratorium für Werkstoff- und Fügetechnik, Universität Paderborn (leadership for german project part)

SLV Hälle : Schweißtechnische Lehr - und Versuchsanstalt Halle GmbH

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TABLE OF CONTENTS

1 Introduction

Global trends force the industry to manufacture lighter, safer, more environmentally friendly, more performant and cheaper products: the machine construction sector is aiming at more performant machine components, for the consumers and construction products, increased integration of functionalities provides a competitive advantage and in the transport sector, weight reduction is pursued. Combining conventional metals with others or even new materials, offers designers solutions where a design consisting out of one material fails. A multi-material design exploits the material with desired properties for each part of the component or product.

Multi-material design is however hindered by challenges in the field of joining technology. The prerequisite for the production of such multi-material components is the availability of suitable joining technologies. New developments for a range of welding processes have however provided the possibility to join dissimilar metals. The capabilities and limitations of these joining processes need to be understood to enable companies to use these processes for realising multi-material hybrid components. It is often impossible for companies, and especially for SMEs with limited research budget or available time, to identify the optimal technology for the specific requirements of their products.

This project opens a window of new opportunities for manufacturing hybrid components, by validating the proposed technologies for joining dissimilar sheet metals. Systematic and reliable knowledge and data has been created about the applicability of these promising new joining processes for industrial applications. The proposed processes were examined in a structured way for three representative industrial material combinations, together with the determination of appropriate boundary conditions and process parameter and the evaluation of the advantages and disadvantages of the techniques.

This project aimed at enabling for the individual companies to make a technically and economically justified decision on whether or not to implement one of the processes in their production. This research project was application-oriented, resulting in a better understanding of the process flexibility and allowing a rapid and fluent industrial introduction.

Future users of the joining processes profit from the project results by an increased know-how about these innovative new processes. This allows the creation of complex or new products, impossible to produce using conventional joining techniques. The processes also make it possible to manufacture products with a better performance, a lighter weight or a combination of functionalities, and thus a higher added-value. Companies will be able to produce these products in a fast, efficient and cost-effective way, which leads, especially for the SMEs, to a competitive advantage and a stronger position on the European and global markets.

2 Project partners

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3 Project objectives

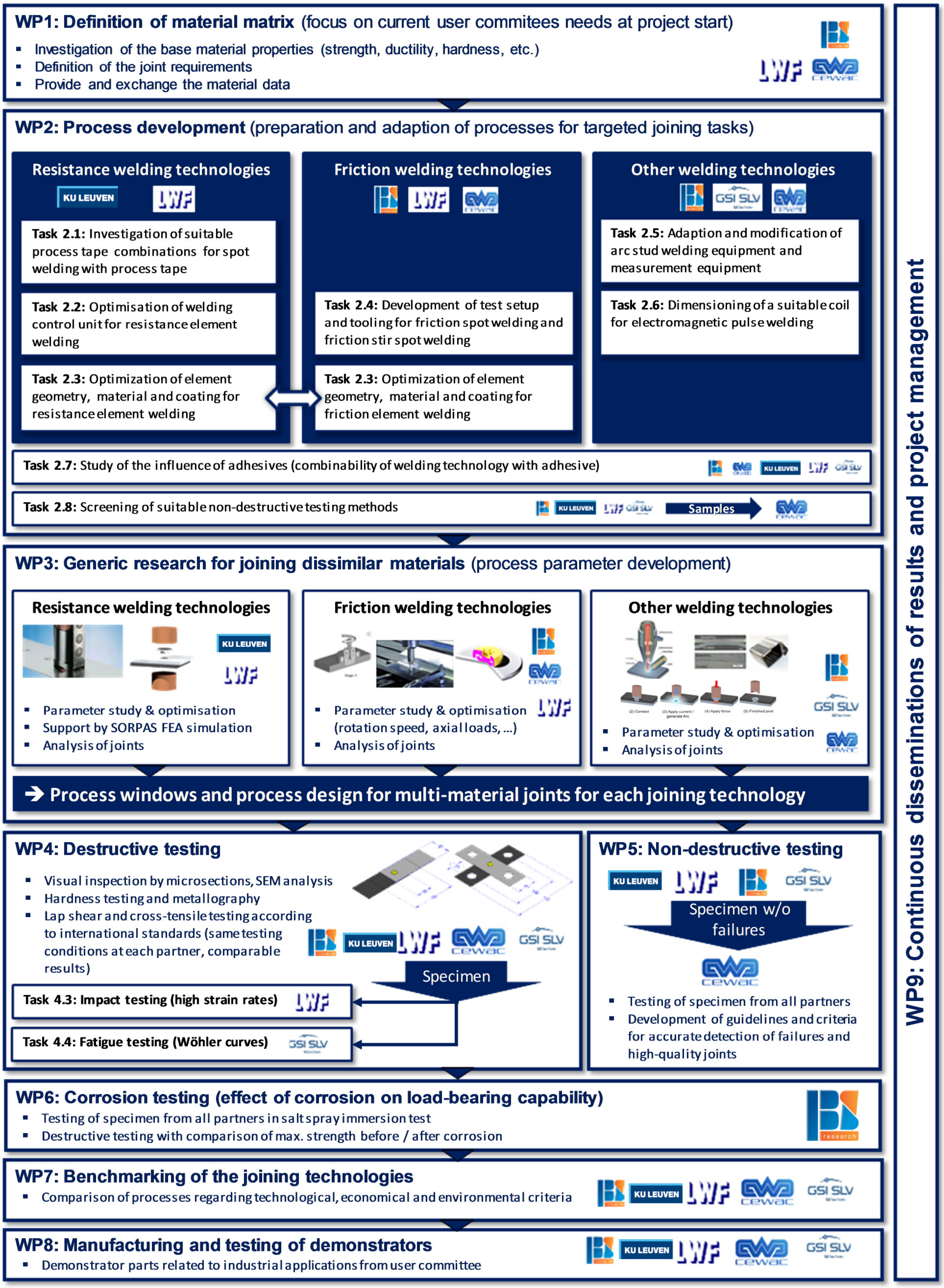
The scientific-technological added-value provided by this project for the participating companies is situated in the following domains:

- Extensive knowledge about the technical feasibility and applicability of the proposed innovative joining processes for a number of clearly defined requirements, material combinations and thicknesses.
- Knowledge concerning the joint properties (mechanical properties, quality, metallographic structure, hardness).
- Knowledge regarding the process parameters for defect-free joining of the proposed material combinations.
- Comparison of the potentials of the processes with those of the conventional processes, both on a technical and an economic level (cost-benefit analysis).
- Publications and technical reports in which the available techniques, including the advantages and disadvantages, are compared with the conventional joining processes, the expected properties, the application area, the required investments, the potential cost reduction, etc.
- Encouragement of the use of the new processes in the Belgian and German SMEs and in other companies, through lectures on national and international conferences and by the preparation of the proposed demonstration workpieces, which are representative for potential industrial applications.
- Implementation of the processes in the Belgian and German industry in order to achieve economic benefits.

4 Project overview

In order to validate the proposed joining methods for dissimilar sheet metal combinations, and to increase the processes applicability, further application-oriented research was performed. The feasibility of the use of the processes mentioned in §5 was investigated for representative industrial material combinations and applications.

The scheme on the following page demonstrates the relation between the different work packages and the cooperation between the project partners.



WP1: Definition of material matrix (focus on current user commitees needs at project start)

- Investigation of the base material properties (strength, ductility, hardness, etc.)
- Definition of the joint requirements
- Provide and exchange the material data

WP2: Process development (preparation and adaption of processes for targeted joining tasks)

Resistance welding technologies

Task 2.1: Investigation of suitable process tape combinations for spot welding with process tape

Task 2.2: Optimisation of welding control unit for resistance element welding

Task 2.3: Optimization of element geometry, material and coating for resistance element welding

Friction welding technologies

Task 2.4: Development of test setup and tooling for friction spot welding and friction stir spot welding

Task 2.3: Optimization of element geometry, material and coating for friction element welding

Other welding technologies

Task 2.5: Adaption and modification of arc stud welding equipment and measurement equipment

Task 2.6: Dimensioning of a suitable coil for electromagnetic pulse welding

Task 2.7: Study of the influence of adhesives (combinability of welding technology with adhesive)

Task 2.8: Screening of suitable non-destructive testing methods

Samples

WP3: Generic research for joining dissimilar materials (process parameter development)

Resistance welding technologies

- Parameter study & optimisation
- Support by SORPAS FEA simulation
- Analysis of joints

Friction welding technologies

- Parameter study & optimisation (rotation speed, axial loads, …)
- Analysis of joints

Other welding technologies

- Parameter study & optimisation
- Analysis of joints

➔ Process windows and process design for multi-material joints for each joining technology

WP4: Destructive testing

- Visual inspection by microsections, SEM analysis
- Hardness testing and metallography
- Lap shear and cross-tensile testing according to international standards (same testing conditions at each partner, comparable results)

Specimen

Task 4.3: Impact testing (high strain rates)

Task 4.4: Fatigue testing (Wöhler curves)

WP5: Non-destructive testing

Specimen w/o failures

- Testing of specimen from all partners
- Development of guidelines and criteria for accurate detection of failures and high-quality joints

WP6: Corrosion testing (effect of corrosion on load-bearing capability)

- Testing of specimen from all partners in salt spray immersion test
- Destructive testing with comparison of max. strength before / after corrosion

WP7: Benchmarking of the joining technologies

- Comparison of processes regarding technological, economical and environmental criteria

WP8: Manufacturing and testing of demonstrators

- Demonstrator parts related to industrial applications from user committee

WP9: Continuous disseminations of results and project management

5 Investigated welding processes

5.1 Resistance spot welding with process tape

Resistance spot welding (RSW) equipped with intermediate layers (process tape) in between the electrodes and the workpieces is a further development of the conventional resistance spot welding process. The presence of the intermediate layers, available in a range of different alloys with different electrical and thermal conductivities, enables to gain substantially more control on the heat input and the welding output. The latter improvement in combination with the servo-electric mechanical actuator and the powerful MFDC interactive process control increases the range of successful applications of the spot welding process in a wide variety of material combinations. The basic process setup is shown in Figure 1.

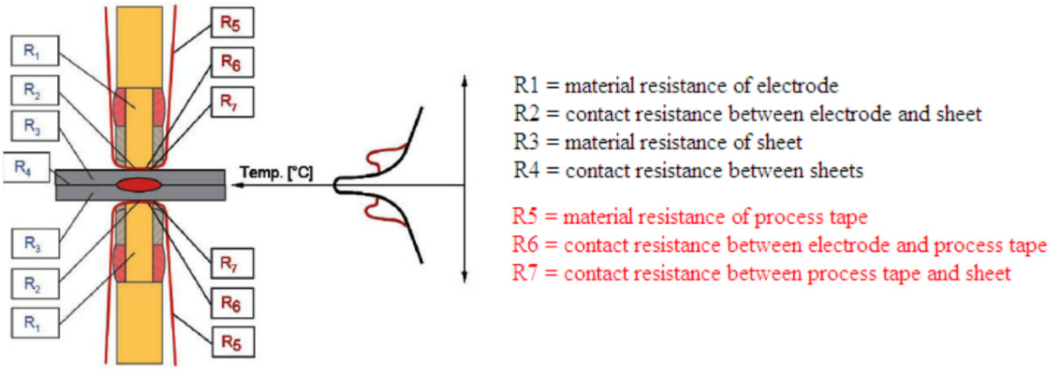


Figure 1: Principle of resistance spot welding with process tape

In this schematic representation of the process, the presence of additional resistances can be noticed in the immediate vicinity of the materials to be welded. The resulting heat generation can be seen in the right side of the image with (red curve) and without (black curve) the application of a process tape.

The image below shows a robotic spot welding gun equipped with integrated process tape guide system.

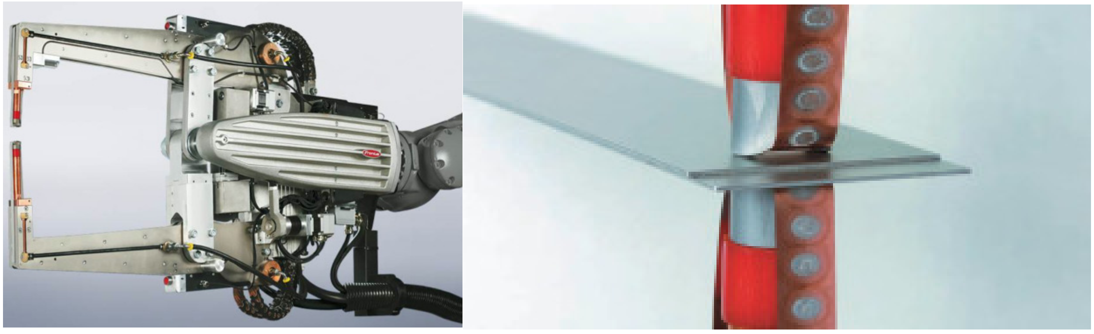


Figure 2: Resistance welding with process tape (Source: KULeuven)

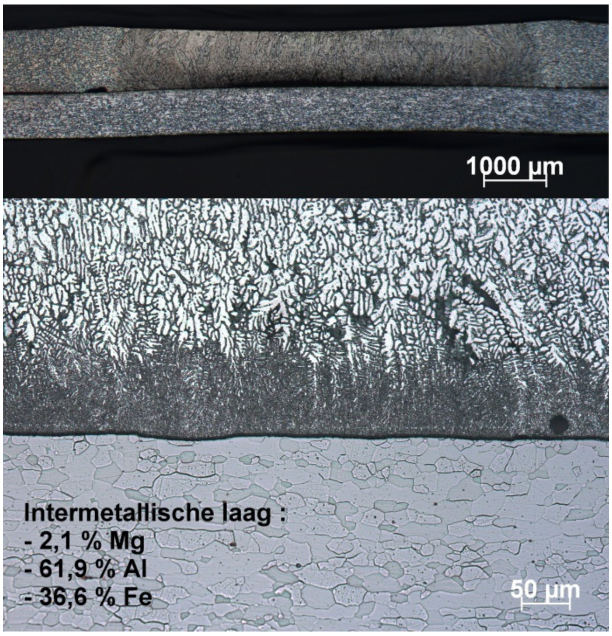


Figure 3: Weld of aluminium to steel using resistance welding with process tape (Source: KULeuven)

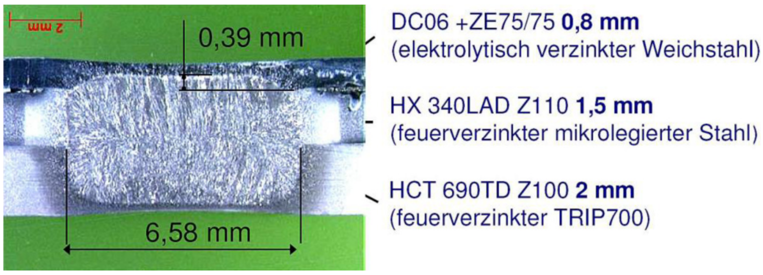


Figure 4: Resistance welding with process tape of sheets with different thicknesses (Source: KULeuven)

5.2 Resistance element welding

Resistance element welding (REW) is a further development of the conventional resistance spot welding process. It combines both thermal and mechanical joining principles, by creating a metal bond between an auxiliary joining element and the bottom plate, in combination with a force- and form-locking connection of the auxiliary joining element with the top plate [1],[2]. The process principle is shown in Figure 5.

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[1]: O. Hahn, G. Meschut, V. Janzen. Weiterentwicklung des Schweißnietens für die Anbindung von Leichtbaumetallen und faserverstärkten Kunststoffen an Stahlstrukturen. Tagungsband 1. Fügetechnisches Gemeinschafts-kolloquium 2011, Garbsen.

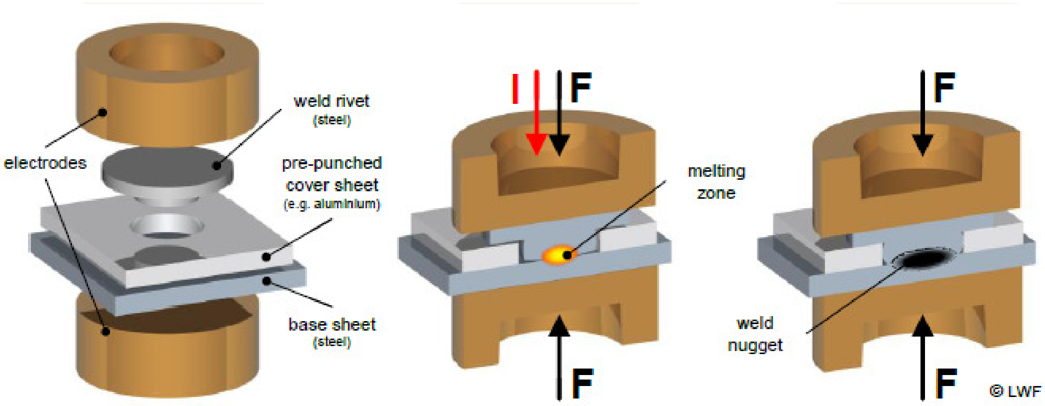

Figure 5: Process sequence for resistance element welding (Source: LWF)

After creating a pre-hole, the auxiliary element, called weld rivet, is inserted or positioned in the hole. The top electrode is lowered onto the rivet and the other is positioned onto the bottom sheet. Pressure and electric current are applied simultaneously. Heat generated by electrical resistance creates a weld nugget in the contact zone between the weld rivet and the base sheet and creates the connection. An increase of the electrode force leads to a deformation of the weld rivet in axial direction and therefore to a tight force connection (surface pressure) between rivet head and cover sheet. A frictional connection is obtained at the contact between the rivet shaft and the cover sheet and between the rivet head and the cover sheet (surface pressure). The individual process stages can be controlled by variation of the parameter settings (weld time, current, force), generally used in state-of-the-art mid-frequency spot welding equipment.

Research for resistance element and friction element welding focussed on the material combinations aluminium-steel and aluminium-carbon fibre reinforced polymers [3,4,5,6,7].

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[2]: G. Meschut, O. Hahn, T. Olfermann. Joining technologies for multi-material design – a key to efficient future mobility. Online-Tagungsband “Materialien des Karosseriebaus 2012”, Automotive International Circle, Bad Nauheim 2012.

[3]: G. Meschut, F. Flüggen, T. Olfermann, V. Janzen. Mechanical joining and adhesive bonding of automobile lightweight constructions. Tagungsband zur Tagung "Eurojoin 8", 25.05.2012, Pula, Kroatien.

[4]: G. Meschut, O. Hahn, V. Janzen, F. Flüggen, T. Olfermann, S Süllentrop. Innovative Joining Technologies for Multi-Material Structures. Vortrag auf der IIW 2012, 09.07.2012, Denver, USA.

[5]: G. Meschut, O. Hahn, V. Janzen, F. Flüggen. Resistance Element Welding - Technology Development for Multi-Material Joints. Vortrag auf der IIW 2012, 09.07.2012, Denver, USA.

[6]: G. Meschut, D. Teutenberg, T. Olfermann. Innovative Fügetechniken für elektromobile Leichtbaustrukturen. VDI-Tagung Materials Sciene and Engineering 2012, SideEvent "Multimaterialsysteme fügen", 26.09.2012, Darmstadt.

[7]: G. Meschut, T. Olfermann. Innovative Fügetechnologien - ein Beitrag zum bezahlbaren Leichtbau. 3rd International CTI Conference “Efficient Lightweight Solutions", 21./22.11.2012, Stuttgart.

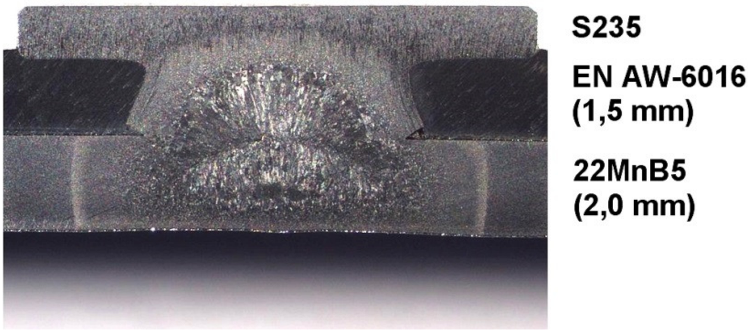

Figure 6: Example of an aluminium-steel weld [8]

First series application of the resistance element welding process with pre-assembled joining elements takes place in the car body of the Volkswagen Passat B8. Here, the aluminium parcel shelf is joined by 51 resistance elements with the surrounding steel construction, see Figure 7.

Figure 7: Resistance element welding in Volkswagen Passat B8 [9][10]

5.3 Friction spot welding

A three-component tool comprising a pin, sleeve and clamping ring is used to join two or more sheets in the overlap configuration. The clamping ring initially fixes the sheets against a backing plate while the pin and sleeve begin to rotate in the same direction, while pressing on the upper surface (Figure 8a). The rotating pin and sleeve are moved in opposite direction of each other (one is plunged into the material while the other moves upwards), creating a cavity where the plasticised material through frictional heat is accommodated (Figure 8b). After reaching the pre-set plunge depth, the pin and sleeve return to their initial position forcing the displaced material to completely refill the keyhole (Figure 8c). Finally, the tool

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[8]: O. Hahn, G. Meschut, V. Janzen. Resistance Element Welding for Joining Aluminium to Steel Lightweight Constructions. Vortrag im Rahmen des Werkstoff-Forums Intelligenter Leichtbau, Hannover Messe, 27.04.2012.

[9]: Website: http://magazine.volkswagen.com/passat-model-change.html

[10]: www.Autoscout24.de: http://ww2.autoscout24.de/erste-infos/vw-passat/volk-s-klasse/44275/420973/mz-2014-21-vw-passat-3.jpg

rotation is stopped and the tool is withdrawn from the joint leaving a flat surface with minimum material loss (Figure 8d).

The most important process parameters of this process are the rotational speed, the axial load, the plunge depth, the welding time as well as the pin and sleeve position.

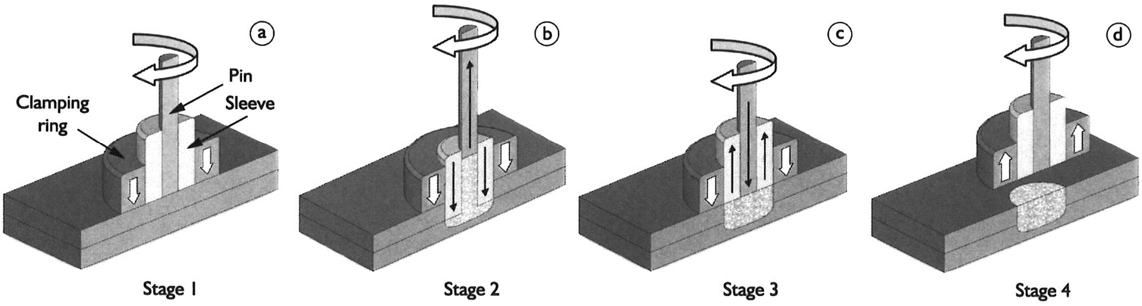

Figure 8: Working principle of friction spot welding [11],[12]

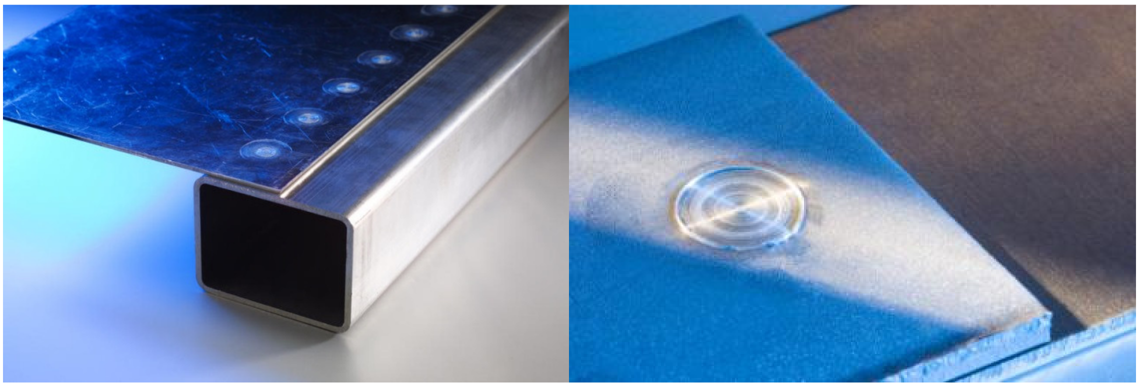

Figure 9: Example of a friction spot welded components (Source: Riftec gmbh)

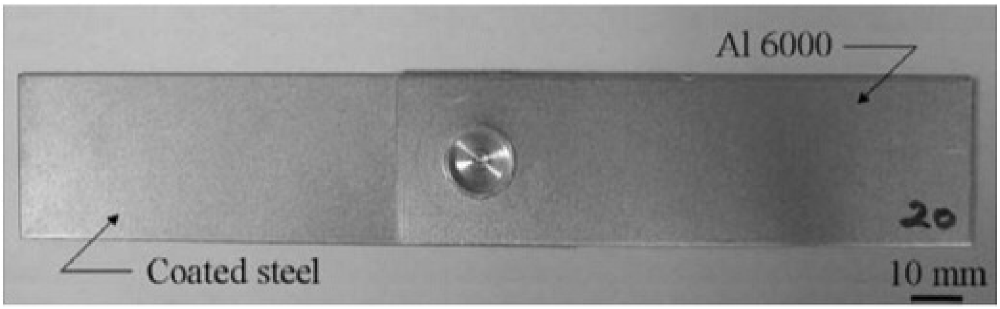

Figure 10: Example of a friction spot weld of aluminium to steel (Source: SLV)

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[11]: T. Rosendo, B. Parra, M.A.D. Tier, A.A.M. da Silva, J.F. dos Santos, T.R. Strohaecker, N.G. Alcântara. Mechanical and microstructural investigation of friction spot welded AA6181-T4 aluminium alloy. Materials & Design 32(3):1094-1100.

[12]: P.B Prangnell, D. Bakavos. Novel Approaches to Friction Spot Welding Thin Aluminium Automotive Sheet. Materials Science Forum Vols. 638-642 (2010) pp 1237-1242.

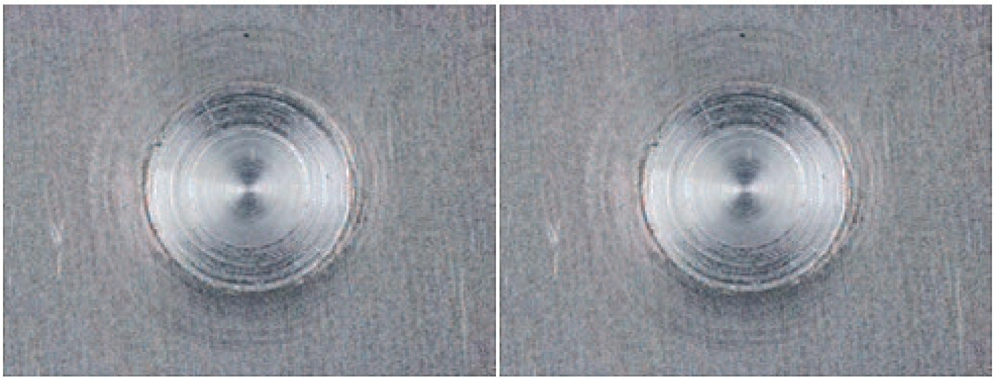

Figure 11: Example of friction spot welds [13]

5.4 Friction stir welding and friction stir spot welding

Friction stir welding (FSW) is a solid-state joining method meaning that no melting occurs during the process. A rotating tool, composed of a pin and a shoulder, is positioned on the top sheet and is pushed into the material. The frictional heat generated by this penetration action softens the workpiece material to a plastic condition, making it flow around the pin. The tool is then moved along the joint line while maintaining the downward pressure, thus plastically deforming the material around the tool and intimately stirring the welding zone. After cooling down, the components are welded together.

One of the variants of conventional FSW is friction stir spot welding (FSSW) where no longitudinal movement is applied, but only a rotation and an up-and-down movement (material entry and exit).

Although this process was originally developed for joining non-ferrous materials, machine and tool material developments have made it possible to apply this welding method to other materials like steel and titanium and material combinations like aluminium to steel [14],[15],[16],[17] or copper to aluminium [18],[19],[20],[21].

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[13]: F. Zech, H. Cramer, M. Dudziak. Reibpunktschweißen von Überlappverbindungen an Aluminiumknet- und -gusslegierungen im Vergleich. Fachausschusssitzung, 22.10.2008, Forschungsvorhaben DVS 5.041 (AiF 15.317 N).

[14]: K. Kimapong, T. Watanebe. Friction stir welding of aluminium alloy to steel. Welding Journal vol. 83 (10), 277-282, 2004.

[15] : M. Fukumoto, K. Miyagawa, M. Tsubaki, T. Yasui. Spot welding between aluminum alloy and steel by friction stirring. Materials Science Forum, 638 - 642, January 2010.

[16]: R.S. Coelho, A. Kostka, S. Sheikhi, J. dos Santos, A. R. Pyzalla. Microstructure and mechanical properties of an AA6181-T4 aluminium alloy to HC340LA high strength steel friction stir overlap weld. Advanced Engineering Materials, Volume 10, Issue 10, pages 961–972, October, 2008.

[17]: A. Kostka. Microstructure characterisation of dissimilar Al to Steel friction stir welds. 1st IPSUS Progress Meeting, Hamburg, 2007.

[18]: A. Galvão, D. Loureiro, D. Verdera, D. Gesto, D. Rodrigues. Influence of tool offsetting on the structure and morphology of dissimilar aluminum to copper friction-stir welds. Metallurgical and Materials Transactions A, p. 1–10, 2012.

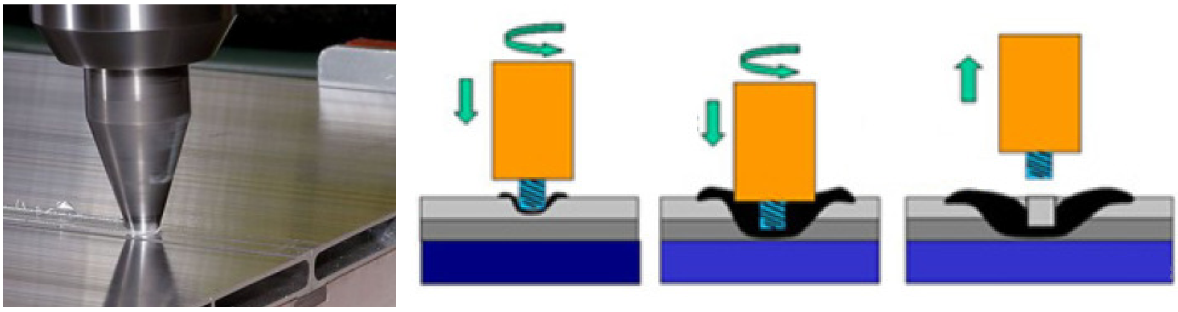

Figure 12: Friction stir welding (left) and friction stir spot welding (right) (Source: CEWAC)

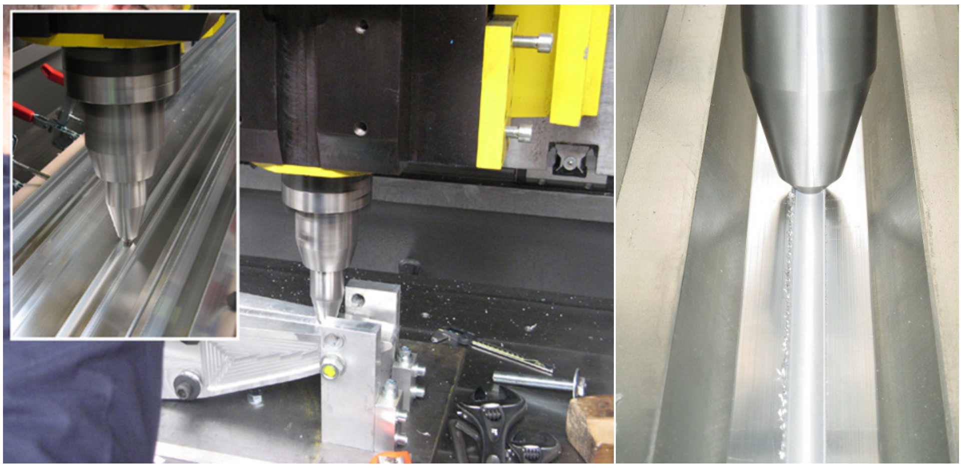

Figure 13: Friction stir welding equipment (Source: CEWAC)

Since the workpiece materials don't melt during the process, this method is very appropriate for joining of dissimilar metals, where metallurgical issues or different melting temperatures might be problematic. Welding equipment using this process is typically CNC or robot based, resulting in an automated process which is robust and productive.

The main machine settings and parameters are:

- penetration depth or pressure setting (interaction between tool and workpiece),
- rotation speed and dwell time,
- penetration speed and welding speed.

With this spot welding method, also certain geometrical forms can be followed by the tool during welding thereby influencing the weld quality and process performance

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[19] : S. Kahl, W. Osikowicz. Composite aluminum-copper sheet material by friction stir welding and cold rolling. Journal of Materials Engineering and Performance, February 2013.

[20]: K. Savolainen, J. Mononen. A preliminary study of friction stir welding of dissimilar metal joints of copper and aluminium. 6th International Friction Stir Welding Symposium, Saint-Sauveur, Canada, 2006.

[21]: C. Thaiping, L. Wei-Bang. A prime study on FSW joint of dissimilar metals. Proceedings of the 11th International Congress and Exposition, Orlando, Florida USA, June 2-5, 2008.

Figure 14: Friction stir welding of copper to brass to aluminium (sheet thickness = 0,5 and 0,8 mm((source: CEWAC)

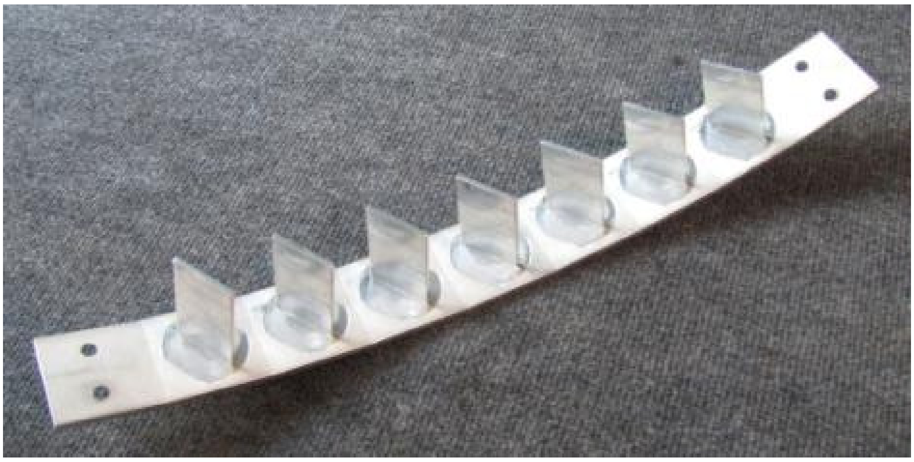

Figure 15: Friction stir welded component from the aeronautics industry (aluminium 2xxx to aluminium 6xxx) (Source: CEWAC)

5.5 Friction element welding

Similar to resistance element welding, friction element welding (FEW) also combines thermal and mechanical welding principles by the use of an auxiliary joining element, creating a rigid metal bond and force- and form-lock of the materials to be joined. The main difference with resistance element welding is the generation of the necessary process heat, which is done by friction. Figure 16 schematically shows the process principle for creating a friction element-welded connection. The main parameters are the tip geometry of the element, penetration depth, force, rotation speed and friction time.

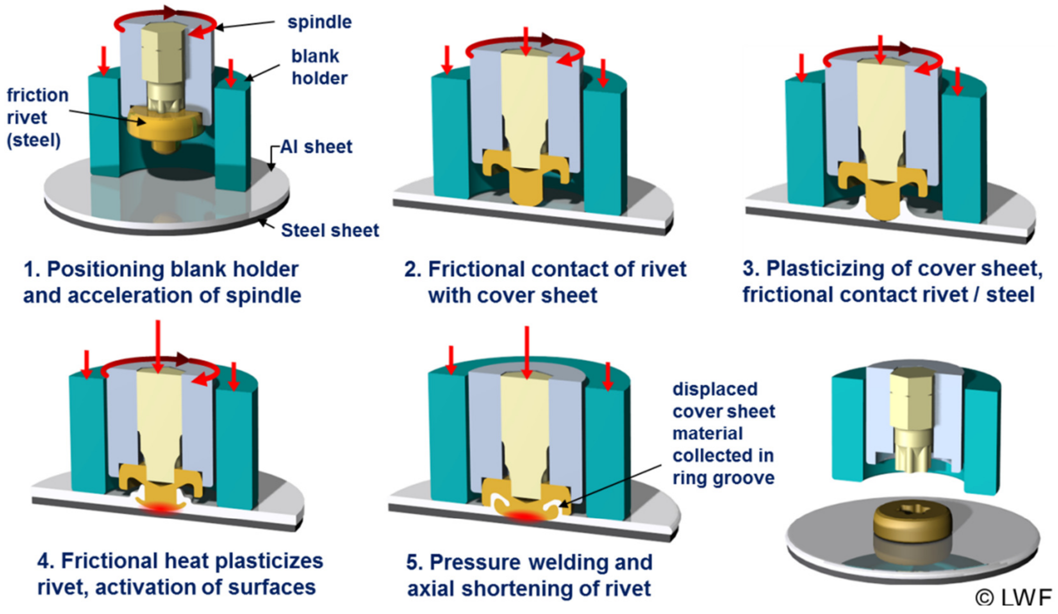

Figure 16: Process sequence for friction element welding (Source: LWF)

A rotationally symmetrical joining part, named the friction element, is accelerated to a high rotation speed (10.000 - 20.000 rpm) and is then pressed against the surface of the upper sheet. The frictional heat causes a plasticisation of the top sheet and allows to penetrate the material without any pre-hole operation or melting. When contacting the surface of the underlying base sheet, the friction and therefore the temperature increases significantly, forming the characteristic so-called upset. The sliding surface of the upset clears and activates the surface of the lower sheet. After a certain shortening of the friction element, the rotation is stopped and the axial force is increased. By diffusion, the cleaned pure metal surfaces connect in a rigid metal bond. The decreasing temperature also causes an axial shrinking, creating a force-lock between the element and the cover sheet. The displaced material from the cover sheet fills the underhead groove of the friction element causing a solid positive lock [22],[23].

The same material combinations as for resistance element welding were investigated [2],[3],[4],[6],[7].

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[22]: U. Alber. Friction element welding – Innovations for hybrid body parts". In: Online-Tagungsband "Fügen im Karosseriebau 2012", Automotive International Circle, Bad Nauheim 2012.

[23]: K. Koglin. Die Karosserie als Initiator für den Fahrzeugleichtbau, Vortrag auf der VDI-Tagung Leichtbaustrategien für den Automobilbau, 07.-08.07.2011, Ludwigsburg

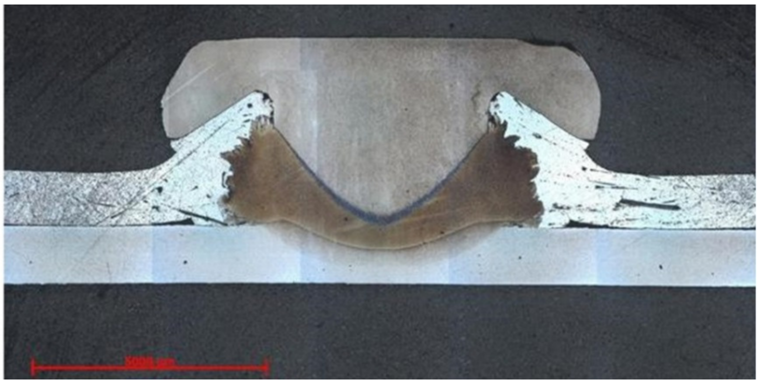

Figure 17: Connection of aluminium alloy with steel (sheet thicknesses: 1,2 and 1,5 mm) (Source: EJOT EJOWELD®)

5.6 Electromagnetic pulse sheet welding

This joining technology uses electromagnetic forces for deformation and joining of workpieces. Electromagnetic pulse welding (EMPS) is an automatic welding process, which can be used for tubular and sheet metal applications, placed in the overlap configuration.

Electromagnetic pulse welding belongs to the group of pressure welding processes. A power supply is used to charge a capacitor bank; when the required amount of energy is stored in the capacitors, it is instantaneously released into a coil, during a very short period of time (typically 10-15 µs). The discharge current induces a strong transient magnetic field in the coil, which generates a magnetic pressure, which causes one workpiece to impact with another workpiece.

The deformation takes place at a very high velocity, like in explosive welding. The explosive deformation force is however created in a safe way, by using electromagnetic forces generated by an induction coil.

It is also a solid-state welding process, which means that the materials do not melt during the creation of a bond, which provides the opportunity to join dissimilar materials.

The process parameters of the magnetic pulse welding process are:

- Geometrical parameters, such as the air gap between both sheets, the axial position of work pieces in the coil or the overlap distance of the workpieces to be joined.
- Electrical parameters, such as the charging voltage defining the energy level, the discharge frequency (adjustable by using a transformer or other coils).

Advantages

Since this technology doesn’t use heat but pressure to realise the bond, it offers important advantages compared to the conventional thermal welding processes:

- Joining of conventionally non-weldable materials, in a quick and cost-effective manner, such as dissimilar material joints [ ].

- Development of complex workpieces or new products, which were previously not possible with conventional joining processes.
- Magnetic pulse welding is a "cold" joining process. Temperature increase is very local (in the order of 50 µm), so the workpieces reach no more than 30-50°C at the outer surfaces. This means that after welding, parts can immediately be unloaded and further processed with other equipment.
- High repeatability; constant joint quality.
- High production rate possible.
- Contact-free: no marks of forming tools, making processing of coated or sensitive materials possible.

The technology has a much lower negative environmental impact and is much more environmentally friendly compared to conventional welding technologies:

- There is no heat, radiation, gas or smoke, shielding gas, which is less harmful for the operator.
- In hostile environments machines can perform the joining operation, avoiding supplementary investments in operator safety.
- It is possible to improve the work conditions of the welder or operator, since the technology is environmentally clean.
- The magnetic pulse welding process consumes less energy.

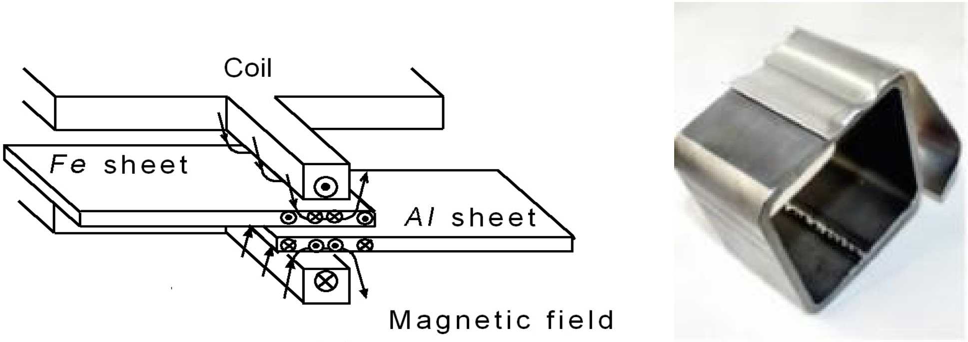

Figure 18: Electromagnetic pulse sheet welding (Source: PST Products)

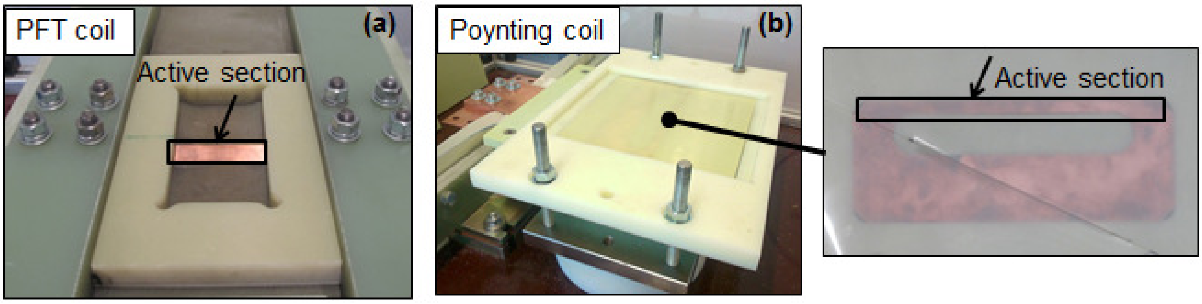

Figure 19: Coil for sheet forming or welding (Source: BWI)

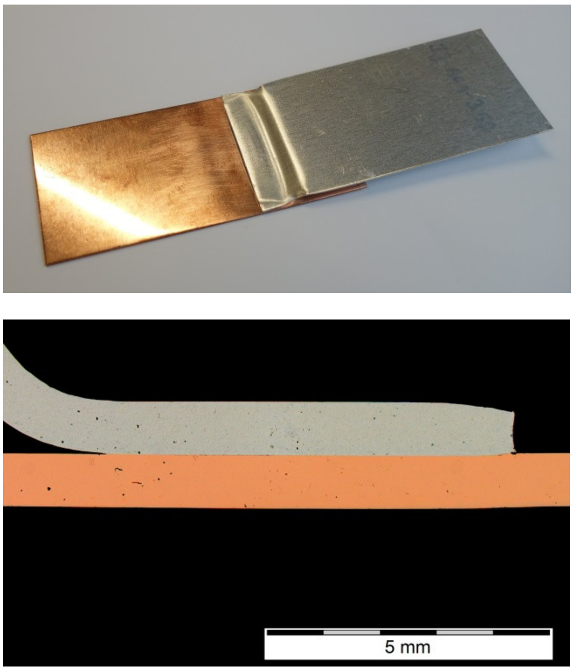

Figure 20: Joining of aluminium to copper and stainless steel (Source: BWI)

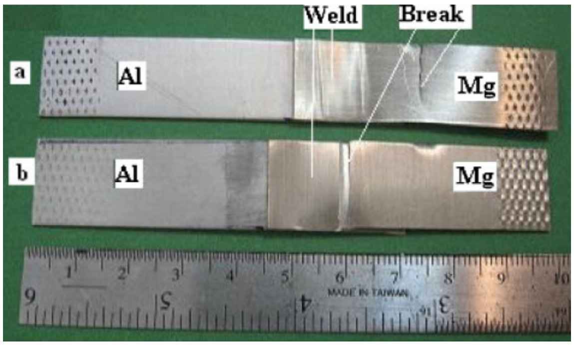

Figure 21: Joining of aluminium to magnesium [24,][25],[26],[27]

5.7 Laser beam welding (continuous or pulsed)

Laser beam welding (LBW) is based on the interaction between a light beam with a specific composition and the workpiece material. The beam is concentrated very locally, making this welding method a high power density process.

Different laser sources exist such as YAG, fibre, CO_2 etc. The fibre laser produces a beam of outstanding optical quality for precise cutting and welding actions. Due to the local heat input, deep welds can be produced at high heating and cooling rates. These process characteristics make it possible to produce precision joints with a narrow heat-affected zone (HAZ) and limited workpiece deformation after welding. The high heat exchange rates also have a positive effect when joining dissimilar metals [28],[29],[30],[31],[32],[33],[34],[35].

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[24]: S. D. Kore, J. Imbert, M. J. Worswick and Y. Zhou. Electromagnetic impact welding of Mg to Al sheets. Science and Technology of Welding and Joining 2009, Vol 14 No. 6, p. 549-553.

[25]: R. Schäfer, P. Pasquale. Material hybrid joining of sheet metals by electromagnetic pulse technology. PSTproducts GmbH; http://www.english.pstproducts.com/downloads.htm

[26]: S.D. Kore, P.P. Date, S.V. Kulkarni, S. Kumar, D. Rani, M.R. Kulkarni, S.V. Desai, R.K. Rajawat, K.V. Nagesh, D.P. Chakravarty. Application of electromagnetic impact technique for welding copper-to-stainless steel sheets. The International Journal of Advanced Manufacturing Technology, June 2011, Volume 54, Issue 9-12, p. 949-955.

[27]: S.D. Kore, P.P. Date, S.V. Kulkarni, Electromagnetic impact welding of aluminum to stainless steel sheets. Journal Of Materials Processing Technology, 208 (1-3), 486-493

[28]: Y. Shu-rong. Laser beam welding of dissimilar metals of aluminum alloy and galvanized steel sheet. Second International Conference on Mechanic Automation and Control Engineering (MACE), 2011.

Experiments and applications of heterogeneous welding include connections of bronze to stainless steel (watch mechanism), copper to aluminium (electronics) and copper to steel (power generation). Other combinations like titanium to aluminium etc. have been tried also with varying degrees of success.

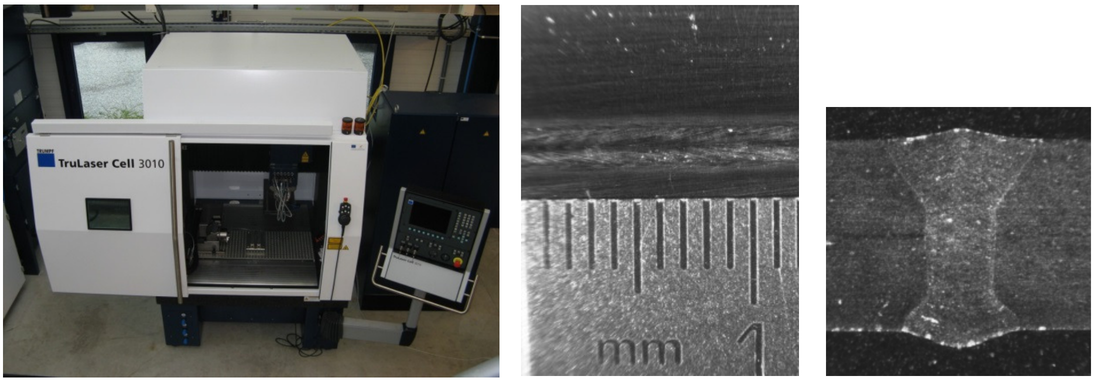

Figure 22: Laser welding cabin (left) and typical weldment (right) (Source: CEWAC)

The process often takes place in a closed chamber, so that the operator is protected from any harmful radiation, while using a shielding gas for the protection of the welding zone. Welding equipment using this robust laser technology is typically robot or CNC based so that important welding speeds and accurate movements are combined with a high and constant process quality.

The different parameters that can be set and controlled during the welding process for optimising the heat input and thus the penetration and weld quality for a specific application are:

- laser beam power and welding speed,
- in the case of pulsed laser welding: also the beam pulse frequency, duration and form,
- type and flow of the shielding gas.

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[29]: M. Naeem, R. Jessett, K. Withers. Fiber laser welding of dissimilar materials. Industrial Laser solutions for manufacturing Magazine, 03/30/2012.

[30]: G. Sierra, P. Peyre, F. Deschaux-Beaume, D. Stuart, G. Fras. Steel to aluminium keyhole laser welding. Material Science and Engineering A447, 197-208, 2007.

[31]: M. Naeem. Microjoining of dissimilar metals with pulsed Nd: YAG laser.PICALEO Conference Proceeding, Melbourne, Australia, March, 2006.

[32]: M. Jokiel, R. Holtz. Experiences with laser beam welding of dissimilar materials. The industrial Laser User No 43, 26-29, 2006.

[33]: F. Vollertsen, M. Grupp. Laser beam joining of dissimilar thin sheet materials. Steel research international 76 No 2/3, 240-244, 2005.

[34]: T.A. Mai, A.C. Spowage. Characterisation of dissimilar joints in laser welding of steel-kovar, copper-steel and copper-aluminium. Material Science and Engineering A374, 224-233, 2004.

[35]: K. Klages, C. Ruettimann, and A.M. Olowinsky. Laser beam micro welding of dissimilar metals. Proc. of ICALEO, Laser Institute of America, Jacksonville, 2003.

Additionally, the weld can be produced by moving the beam according to a certain geometrical path (circle ...) in order to mimic a spot weld and typically increase the mechanical characteristics.

Different methods in laser beam welding exist, such as continuous and pulsed welding. The continuous laser is typically standard, while the pulsed laser makes it possible to very accurately control the heat input and weld penetration. This means that the most appropriate method can be chosen for a specific application (thin workpiece, materials with high thermal conductivity, etc).

5.8 Arc element welding with an auxiliary joining part

In arc element welding (AEW), a short auxiliary joining part (the so-called element) is used. The top sheet must be perforated. There is no direct joint between the top sheet and the bottom sheet, but the auxiliary joining part guarantees the fixing of the top sheet onto the bottom sheet in a mainly form-fitting and partial force-fitting joint. In this respect, a welded joint is created only between the auxiliary joining part and the bottom sheet.

The existing welding process variants are drawn-arc stud welding and the process variants with initial-contact capacitor discharge. In this respect, the auxiliary joining part is a constituent of the development work [36],[37],[38],[39].

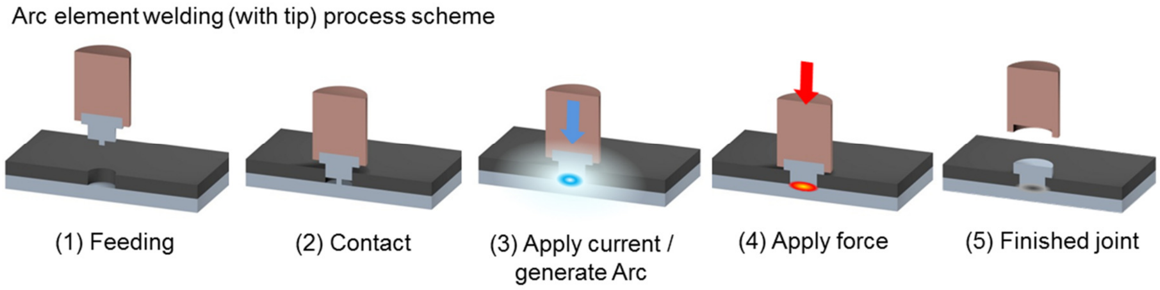

Figure 23: Process principle of arc element welding with an auxiliary joining part (Source : SLV)

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[36] : W. Welz, A. Jenicek, G. Yang: Bolzenschweißen mit hochlegierten Stählen. Schweißen und Schneiden 40 (1988), H. 5, S. 232 - 237.

[37]: Cramer, H., A. Jenicek: Hubzündungsbolzenschweißen – Neues Verfahren reduziert Fehler. Metallbau 09/2005.

[38]: Cramer, H., u.a.: Neue ”kalte” Verfahren in der Schweißtechnik – zukunftsweisende Neuerungen mit dem MSG-Lichtbogen, Vortrag Technologietransfer, SLV München 2005.

[39]: N.N.: Bewertung und Optimierung der Tragfähigkeit von Gewindebolzenschweißverbindungen unter Ermüdungsbeanspruchung. Forschungsbericht 5159/2011 der GSI mbH, NL68 SLV München (2011). AiF-Nr. 16.027N.

Figure 24: Arc element weld with an auxiliary joining part (Source : Soyer / SLV)

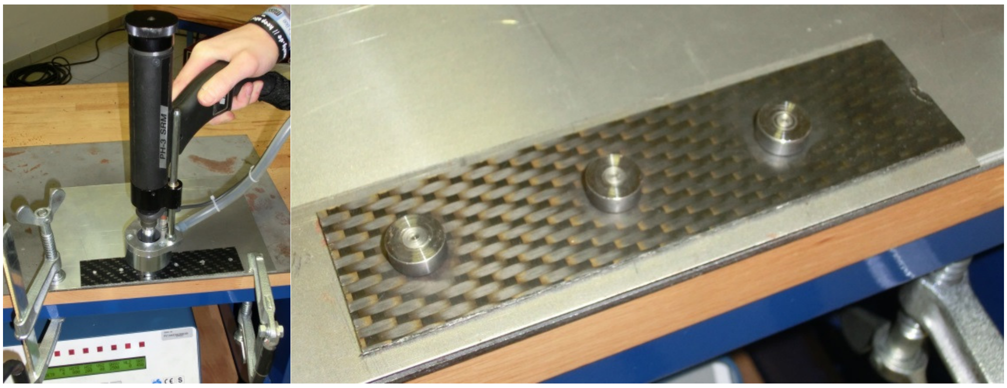

Figure 25: Arc element welding for the attachment of polymers

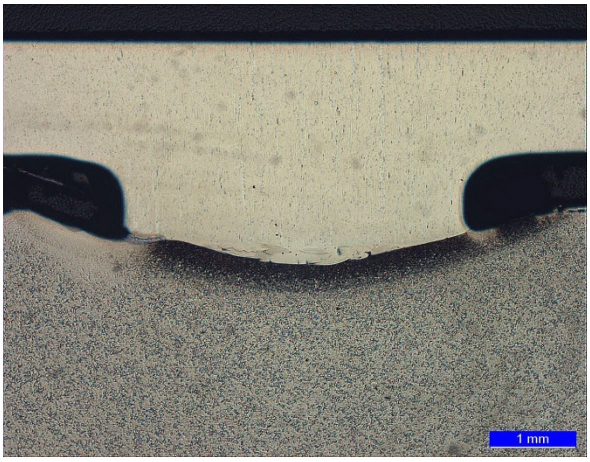

Figure 26: Cross section of the auxiliary joining part (element) welded onto the bottom sheet

6 Summary of scientific results

6.1 Introduction

The full technical report contains all results in detail and can be obtained by request (contact: Koen Faes - Koen.Faes@bil-ibs.be).

6.2 Investigated material combinations

The selection of the material combinations was done by regarding different market areas. Therefore, representative combinations were chosen from the sectors of automotive and truck, cooling applications, electronics, food, tank construction and façade engineering. The final choice of the materials was done after consultation of the user committee.

Material combination 1: Aluminium - Steel

- Aluminium: EN-AW 5182 (AlMg4,5Mn0,4) - Thickness : 2,0 mm
- Steel: MS-W1200 (HDT1200M) ZE50/50 - Thickness : 1,5 mm

Material combination 2: Non-ferrous alloy - Non-ferrous alloy

- Aluminium: EN-AW 1050 (H14/24) - Thickness: 1,0 mm
- Copper: Cu-ETP (R240) - Thickness: 1,0 mm

Material combination 3: High strength steel - Stainless steel

- High strength steel: HCT780X ZE50/50) - Thickness: 1,5 mm
- Stainless steel: H800 (1.4378) - Thickness: 1,5 mm

6.3 Welding equipment used in the project

6.3.1 Resistance spot welding with process tape (KU Leuven)

The Deltaspot resistance spot welding machine (manufacturer: Fronius) has been used in this project for resistance spot welding with process tape (Figure 27). The process tape, which controls the heat balance in the joint, is useful when welding dissimilar material combinations. The Deltaspot welding machine used in this project is the model X500 with a maximum force of 5 kN.

6.3.2 Resistance element welding (LWF)

Investigations for resistance element welding were done with a conventional resistance spot welding system, consisting of a constant current control from Bosch Rexroth AG and a servo motor driven welding gun from Nimak GmbH (see Figure 28).

Figure 27: Deltaspot resistance welding machine at KULeuven

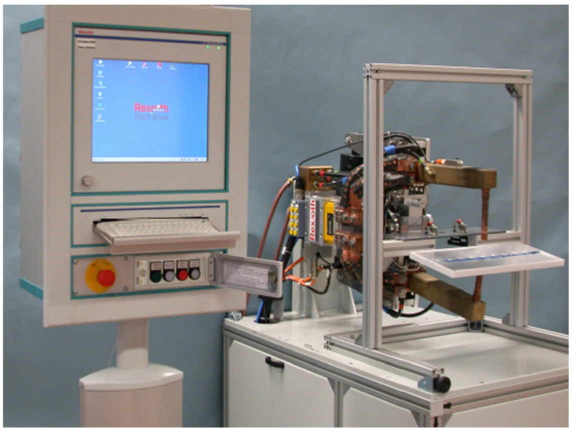

Figure 28: Resistance (spot) element welding equipment at LWF

6.3.3 Friction spot welding (BWI)

The FSpW welding machine is shown in Figure 29 (manufacturer: Harms & Wende GmbH). The most important component is the welding head. It consists of a clamping ring, a sleeve, a pin and all the required actuators. The welding head is provided with a hydraulic actuator, allowing the head to move in the vertical direction. This is required for the clamping ring to perform the clamping operation. The sleeve and the pin each have their own actuator allowing them to move independently in the vertical direction. Both are driven by the same motor for the rotational motion.

6.3.4 Friction stir spot welding (CEWAC)

The experiments have been performed according to the plunge method, by using an ESAB Legio FSW machine (see Figure 30). The characteristics of this machine are:

- very robust machine that can be used for 2.5D welding of up to 6 m long parts,
- max. 1500 rpm, max. 2 m/min welding speed, max. 100 kN forging force,
- can be used in position control or force control mode, incl. data acquisition of speeds, positions and forces (in X,Y,Z),
- the welding head is equipped with water cooling and can be combined with standard, retractable and bobbin tools.

6.3.5 Friction element welding (LWF)

The experiments for friction element welding were carried out with a friction welding machine from Harms & Wende GmbH, which is integrated in a C-frame and equipped with a blank holder, an element holder (bit-system) and a specimen fixation (see Figure 31).

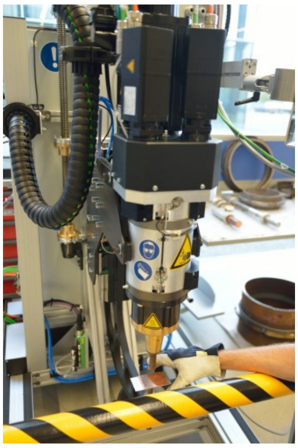

Figure 29: Friction spot welding machine at BWI

Figure 30: Friction stir welding machine at CEWAC

Figure 31: Friction element welding machine at LWF

6.3.6 Electromagnetic pulse sheet welding (BWI)

The electromagnetic pulse welding installation at BWI comprises four main parts as shown in Figure 33: the high-voltage cabinet containing the grid power supply, the energy storage bank containing the capacitors, the work table containing the coil and the operating panel, to set the required voltage.

6.3.7 Laser beam welding (CEWAC)

A laser head coupled to a 3kW source was used (Figure 32). The robot with positioning table enables easy and flexible positioning of the beam vs. the workpiece. Some characteristics of this equipment:

- up to 3kW laser power, min. focal spot of 0,6 mm, focal distance of 150 mm, camera,
- robot reach of approx. 2 m, welding speeds of up to 10 m/min.

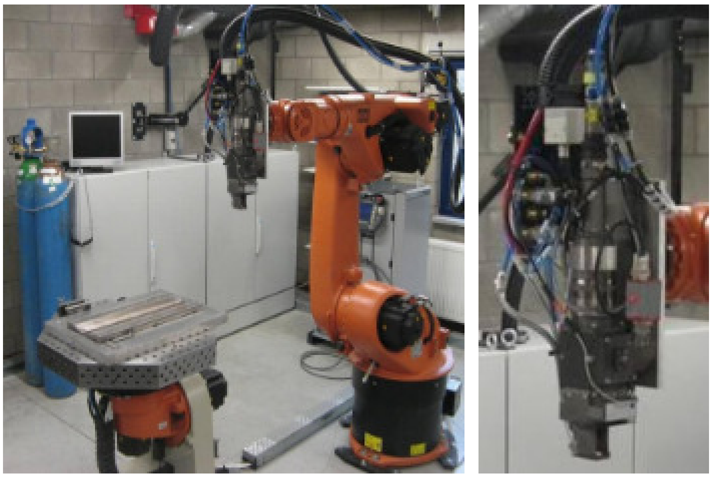

Figure 32: Laser beam welding equipment at CEWAC

6.3.8 Arc element welding (SLV Halle)

The tests were carried out with a stud welding machine with capacitor discharge "Soyer BMS 8-NV" and a gun "SOYER PS-1K" (see Figure 34). The gun was modified so that a penetration of the element of P = 2,0 mm was obtained. The variable setting was the charging voltage of the capacitor. The stud welding machine has two workpiece clamps to eliminate the magnetic arc blow.

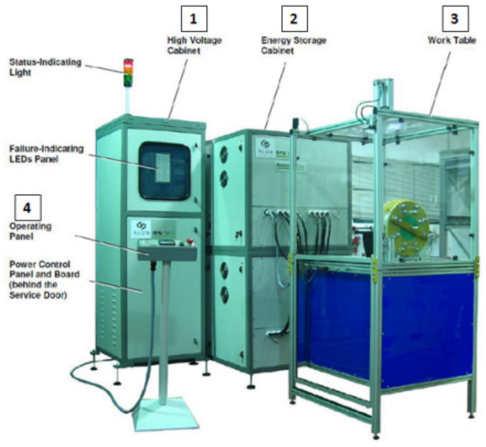

Figure 33: Electromagnetic pulse equipment at BWI

Figure 34: Stud weld device and weld gun at SLV Hälle

6.3.9 Specimen geometries

While for pre-investigations and process parameter studies different specimen geometries were used individually at each research institute, standard geometries were selected for quasi-static lap shear, cross tension and fatigue testing and testing with high strain rates to guarantee comparability. In the following illustrations, the different specimen geometries are shown. For optimal comparison of the results for the industrial applications, representative standards has been used (SEP1220/DIN EN 14273).

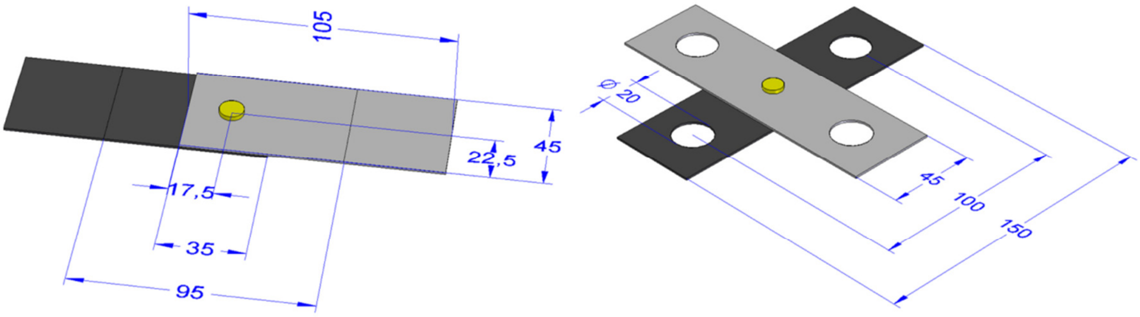

Figure 35: Lap shear (left) and cross tension (right) specimen geometries for quasi-static and high-strain rate testing according SEP 1220/DIN EN ISO 14273

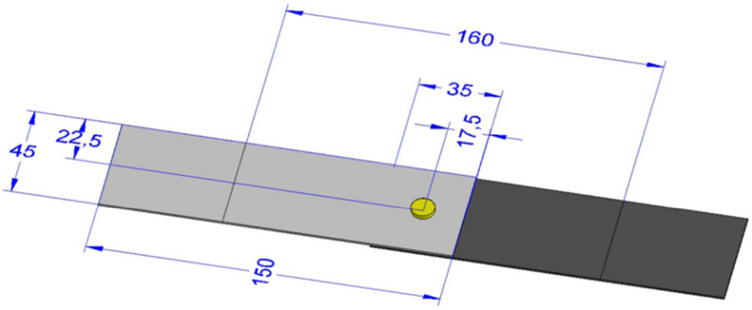

Figure 36: Lap shear specimen geometry for fatigue testing according DIN EN ISO 14273

6.4 Methods and tests for evaluation

Depending on the purpose and research partner, different kinds of methods for evaluation have been used.

- Chisel testing: to determine the nugget diameter or to define the boundaries of the weldability windows (according to DIN EN ISO 10447),
- Cross sections with different kinds of etching methods: for investigation of the welding nugget, welding zones and interlayers, the joints have been cut, polished, etched and investigated by optical microscopy. Each research partner has used his own equipment and methods for cross sections (micro-sections).
- Quasi-static lap shear and cross tension testing: performed with different universal testing machines.
- Impact testing: for high strain rate lap shear testing (displacement speed = 1 m/s).
- Fatigue testing (S-N curves) of lap shear specimens.

6.5 Results of the generic research

6.5.1 Feasibility investigation

The following table presents the results of the feasibility investigation of the different welding processes for the targeted material combinations. As can be seen in this overview, not all processes were suitable for all material combinations.

The results are further discussed in the following sections.

	Material combination 1: Aluminium - Steel EN-AW5182 (2,0 mm) + MS-W1200 (1,5 mm)	Material combination 2: Non-ferrous - non-ferrous EN-AW 1050 (1,0 mm) + Cu-ETP (1,0 mm)	Material combination 3: High strength - Stainless HCT600X (1,5 mm) + H800+ X (1,5 mm)
Resistance welding with process tape (KUL)	Feasible	Feasible	Feasible
Resistance element welding (LWF)	Feasible	Feasible	Feasible
Friction element welding (LWF)	Feasible	Feasible	Not feasible
Friction stir spot welding (CEWAC)	Not feasible	Feasible	Not feasible
Friction spot welding (BWI)	Feasible	Feasible	Not feasible
Electromagnetic pulse sheet welding (BWI)	Not feasible	Feasible	Not feasible
Laser (spot) welding (CEWAC)	Not feasible	Not feasible	Not feasible
Arc element welding (SLV)	Feasible	Feasible	Feasible

6.5.2 Material combination 1: Aluminium - Steel EN-AW5182 + MS-W1200

6.5.2.1 Resistance welding with process tape (KUL)

The experimental conditions have been varied (welding current, time and force) to investigate the influence of the process parameters on the weld quality, expressed by for example the lap shear strength. Metallographic examination was also used to examine the welds for porosities, cracks or other weld defects. The welding parameters used for this material combination were determined.

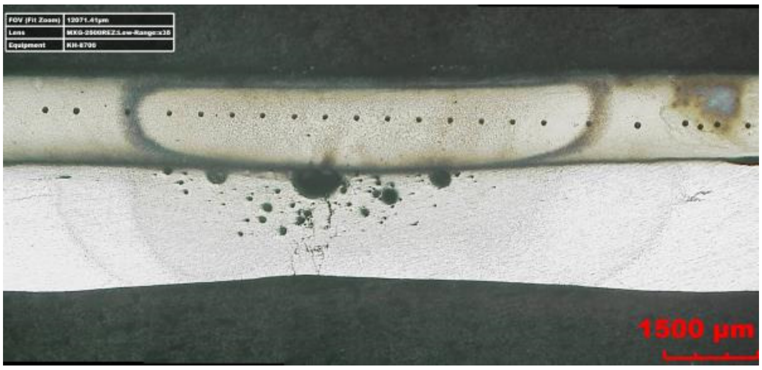

Figure 37: Resistance spot weld with process tape of aluminium to steel (Source: KULeuven)

6.5.2.2 Resistance element welding (LWF)

For determination of appropriate welding conditions and process parameters, following approach was used:

- Determination of the weldability window for the chosen boundary conditions and typical welding times (150 and 380 ms for welding steel, 60 ms for welding of aluminium) according to SEP 1220-part 2. The lower boundary in the current range was determined by chisel testing. The upper boarder (spatter) is defined by visual inspection of the welding process.
- Based on the weldability windows, suitable process parameters were chosen for further testing, for determining the load bearing capacity. By determining and comparing the joint performance by lap shear and cross tension testing, it was possible to specify the optimal parameter set.
- Finally, these parameter and boundary conditions were used to manufacture the specimens for NDT, impact and fatigue testing and the demonstrators.

1. No Gaps between the sheets detected (melted material)
2. Escape of Al-material out of the joining area in each examination
3. Spatter (material out of the welding nugget and melted Al-material) for I>5.0kA
4. Big deformations of the elements for I>4.5kA
5. Deformations of the head proportional to the welding current

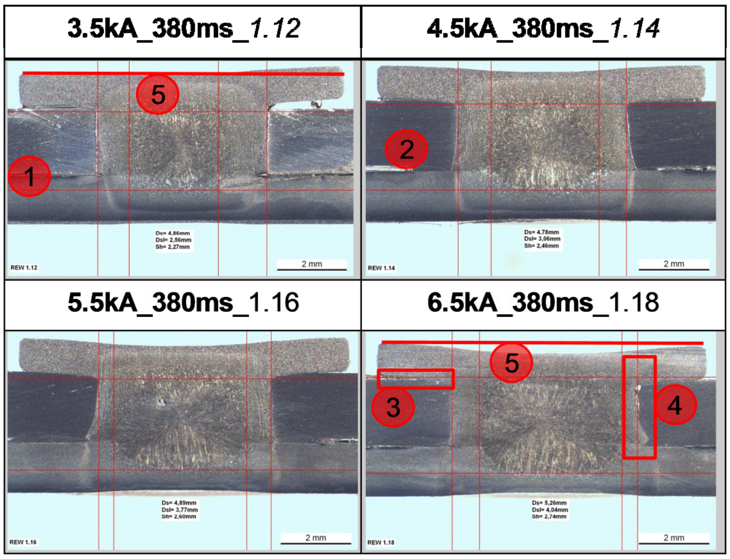

Figure 38: General phenomena of resistance element welded joints by varying the welding current for the combination aluminium-steel (Source: LWF)

6.5.2.3 Friction element welding (LWF)

Determination of suitable parameters was initiated, based on previous experience and the process parameters were incrementally optimised by the following steps:

- metallographic investigations and evaluation of the cross-sections,
- determination of the load-bearing capacity under lap shear and tension loads,

- finally, the best parameter and boundary conditions were used for manufacturing the specimens for NDT, impact and fatigue testing and the demonstrators.

Figure 39 shows exemplary the resulting joint formation by varying the rotation speed and the axial force, while keeping the switching point constant. The following mechanisms were identified:

- increasing the axial force and decreasing the rotation speed, leads to a bigger friction weld diameter,
- a flat and less curved upset is generated by a lower rotation speed, a later switching point and a higher axial force,
- the switching point has no recognisable influence for the friction weld diameter.

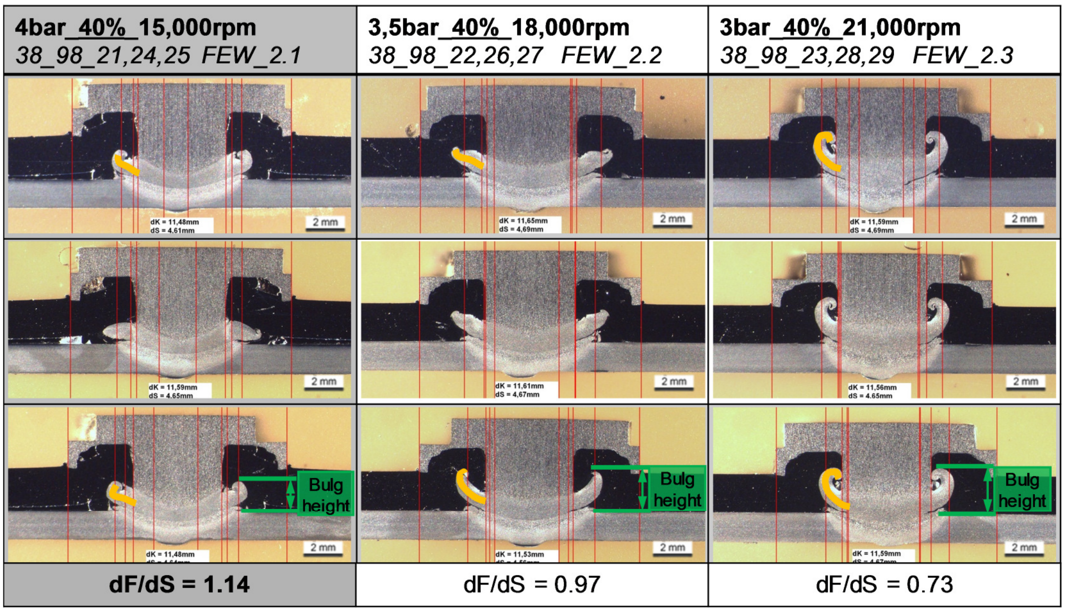

Figure 39: Microsections of friction element welded joints by keeping the switching point constant and varying the turning speed and axial force (Source: LWF)

6.5.2.4 Friction stir spot welding (CEWAC)

Because of practical reasons, only the configuration using aluminium on top of steel has been investigated. During the development of potentially suitable parameters, it has been observed that only “hot” welding conditions with the hardened steel tool pin passing just above the steel sheet surface produced joints with at least some adherence at the interface. However, in general, the obtained results were too bad for defining a functional parameter window (brittle detachment at the Zn-layer with only little adhesion). Also, the pin sometimes made contact with the steel sheet, leading to immediate wear, because neither with position- or force control mode, the small gap between tool pin and steel surface could be stabilised.

In a second testing phase, a WC type tool has been used, so that the pin entering into the steel surface would no longer damage the tool. It was also tried to slightly plastically deform (plough into) the steel surface, to obtain an additional mechanical interlock with the plasticised aluminium. No good results have been achieved, probably because the welding parameters for the aluminium grade and the steel were totally incompatible. The tool was often just ripping through the aluminium without any weld formation.

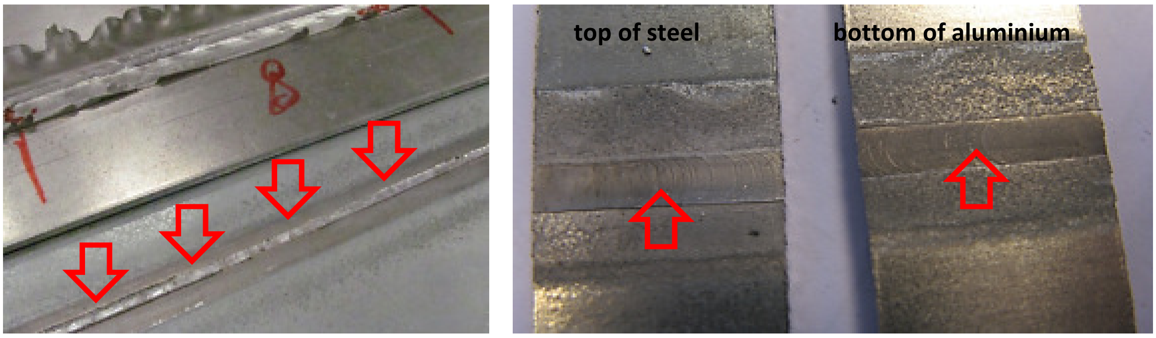

Figure 40: Left: Very local adherence (only where the pin passed) between aluminium and steel Right: Brittle detachment of the Zn layer at the steel interface (Source: CEWAC)

6.5.2.5 Friction spot welding (BWI)

It was possible to obtain welds with high quality, without welding defects. The creation and development of the aluminium-zinc microstructure at the weld interface has also been investigated:

The different welding parameters each have an effect on the microstructure created:

- A maximum plunge depth of 1,8 mm is allowed to avoid breaking of the sleeve (top sheet thickness: 2 mm).
- A rotation speed of approximately 2700 rpm should be maintained to obtain a smooth weld appearance.
- On the one hand, an insufficient clamping pressure of 4 bar resulted in incomplete filling of the stirring zone. On the other hand, a sufficiently high clamping pressure of 5 bar allowed for complete filling of the stirring zone, but resulted in a reduction of the aluminium sheet thickness.
- A sufficiently long holding time should be maintained, in order to cool down the resulting weld and hence resist the forces induced during removal of the clamping ring.

A typical cross-section is shown in Figure 41.

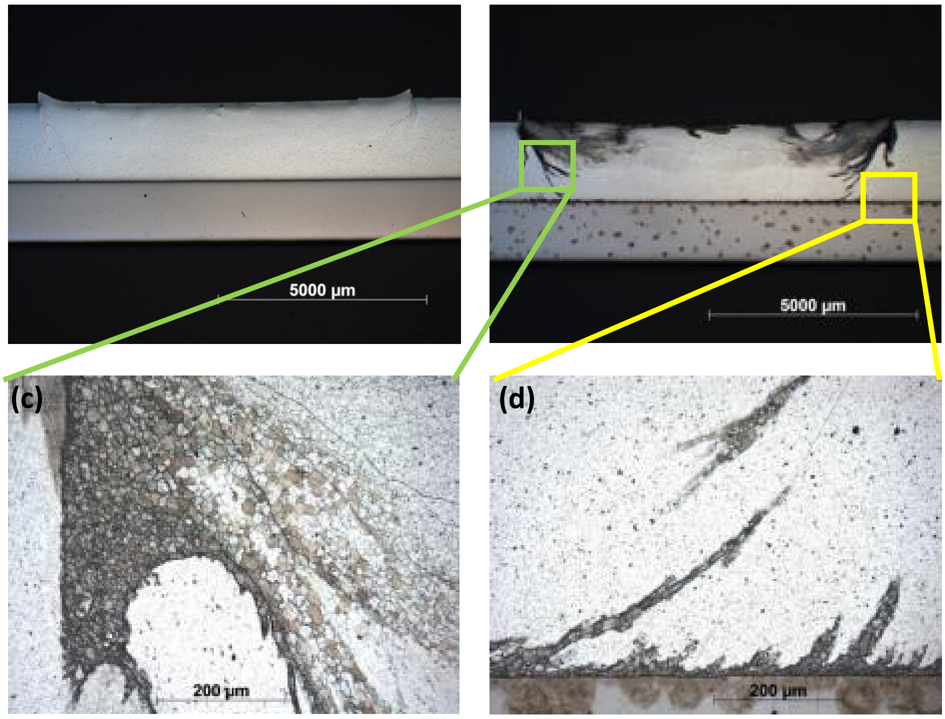

Figure 41: Cross section of a EN AW-5182/MS-W1200+ZE50/50 weld (specimen nr. 4.3)
a) Cross-sectional overview in unetched condition b) Cross-sectional overview in etched condition
c) Green box: microstructure with enlarged grains
d) Yellow box: microstructure with lines of refined grains (Source: BWI)

6.5.2.6 Electromagnetic pulse sheet welding (BWI)

Although the material combination aluminium-steel is feasible using the electromagnetic pulse sheet welding process, this particular material combination was not possible with the used coil system. This can possibly be attributed to the high mass (sheet thickness of 2 mm) and the high yield strength of EN-AW 5182 (145 MPa), which requires a high magnetic pressure for bonding to occur. Substantial modifications to the equipment were required to achieve a good result.

6.5.2.7 Laser (spot) welding (CEWAC)

During the preliminary experiments, no parameter window could be identified where a weld with consistent quality could be obtained. Various parameters and other settings have been varied in order to optimise the joint characteristics:

- main welding parameters (beam power, welding speed and focus position),
- steel vs aluminium on top, in the overlap configuration,
- welding with a penetration equal to the interface thickness (to avoid dilution).

None of the measures above has given sufficient improvement and the joints typically failed due to brittle behaviour (intermetallic layer too thick in case of steel on top) or lack of fusion (adhesion in case of aluminium on top).

6.5.2.8 Arc element welding (SLV)

The capacitor charging voltage was the only parameter that could be varied. In ISO 14555, recommendations for setting the parameters are presented. The capacitor charging voltage was increased until the welding result was satisfactory. A too high charging charge voltage led to strong partial melting of the cover plate. The found welding parameters were selected for welding the specimens for non-destructive and destructive testing.

Figure 43 shows a micro-section of the material combination aluminium - steel. In all joints, the element head never applies a force fit on the sheets; there is always a gap. Also between the neck and cover plate, there is a gap, which is filled with the insulation. Despite this gap, the arc of the joining process melts the cover plate in the area of the hole.

Porosities were found in all joints, which cannot be excluded because of the nature of the joining process. The chosen parameters are a compromise of the energy: the energy needs to be high enough to create a joint (however with pores), but should not be too high, otherwise the cover sheet melts. More energy could prevent the porosities, but would melt the cover plate even more.

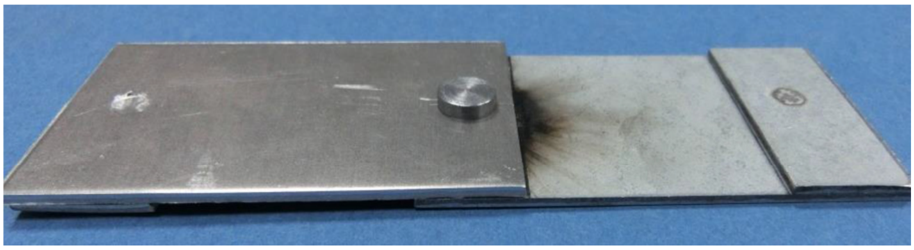

Figure 42: Arc element weld of aluminium to steel (Source: SLV)

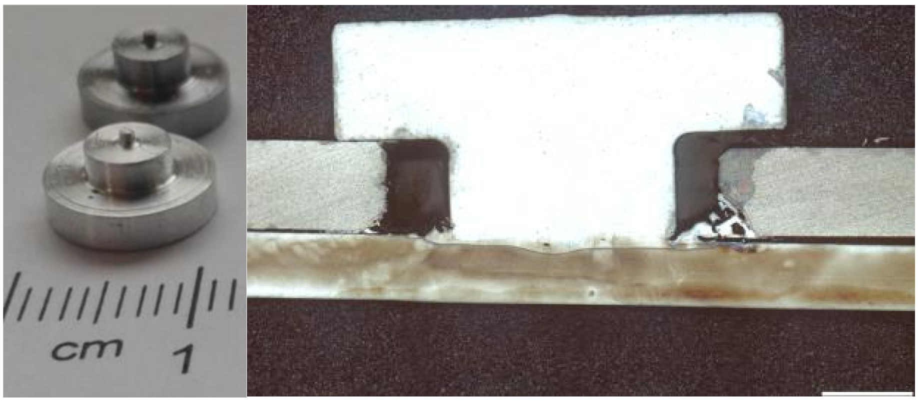

Figure 43: Left: Elements used - Right: Arc element weld of aluminium to steel (Source: SLV)

6.5.3 Material combination 2: Non-ferrous - Non-ferrous : EN-AW 1050 + Cu-ETP

6.5.3.1 Resistance welding with process tape (KUL)

The experimental conditions have been varied to investigate the influence of the parameters on the weld quality. Metallographic examination was also used to examine the welds for porosities, cracks or other weld defects. The most suitable welding parameters for this material combination were determined.

Figure 44: Resistance welding with process tape of copper to aluminium (Source: KULeuven)

6.5.3.2 Resistance element welding (LWF)

For material combination 2 (aluminium-copper), an investigation to determine the relationships between the parameters and the joint properties has been performed. The two best joining conditions (according to chisel testing and metallographic investigation) were determined:

- element: 1,4 mm (sharp tip); 2 bar; 10.000rpm; 120%,
- element: 1,6 mm (sharp tip); 2bar; 10.000rpm; 100%.

As REW is based on resistance spot welding, the SEP1220-2 [40] procedure for determination of the weldability window can be adapted. According to the specification, all boundary conditions are fixed, while the welding current is varied and the current time is constant at 380 ms. The resulting nugget diameter is measured in the cross section. In Figure 46, the weldability window for uncoated (green) and ZnNi-coated (red) fasteners are displayed. It was observed that bonding (failure of the nugget during chisel testing) and spatter (visible spatter of melted material) occurs for both fastener types at similar current ranges. Furthermore, joints with uncoated elements have always bigger nugget diameters at equal currents than joints with coated elements.

The best parameter set was identified with a current of 5,5 kA for both types of elements. Therefore, it can be stated that welding parameters for uncoated elements can be transferred to zinc-nickel-coated elements.

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[40] : Stahl-Eisen-Prüfblatt (SEP) 1220 Part 2: Testing and Documentation Guide-line for the Joinability of thin sheet of steel – Part 2: Resistance Spot Welding. Stahlinstitut, VDEh, 08/2011

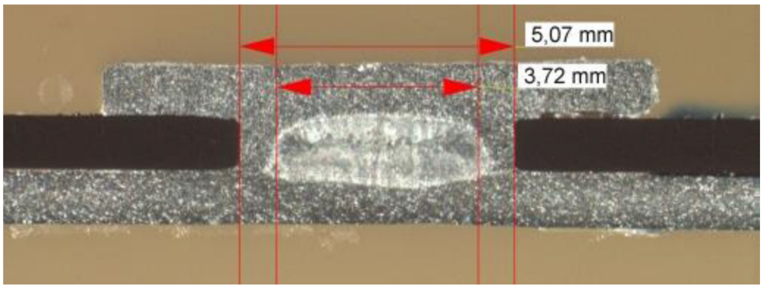

Figure 45: Resistance element welding of copper to aluminium (Source: LWF)

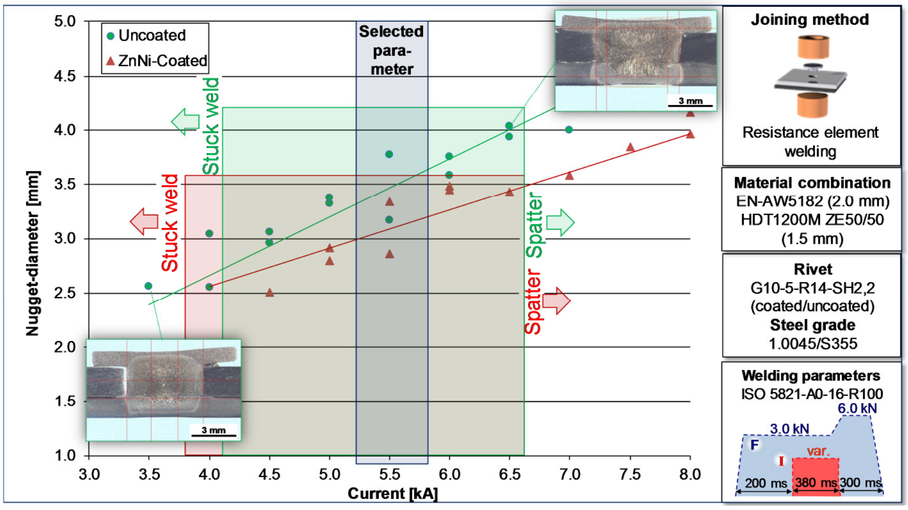

Figure 46: Weldability window for resistance element welding with uncoated and coated fastener elements (Source: LWF)

6.5.3.3 Friction element welding (LWF)

For friction element welding, the low material strength of the sheet members leads to a reduced formation of the upset. The typical procedure is that the friction element penetrates through the upper sheet and is joined with the bottom sheet by friction welding. To avoid a complete penetration of the element through both sheets, the shaft length was reduced in a first step. In a second step, the volume of the ring groove was decreased and the tip geometry was varied (radius, sharp).

Concerning the element material, the joining directing was chosen in a first step. Copper-ETP (R240), which has a higher strength than aluminium EN AW-1050 (H24/20), was selected as the base sheet.

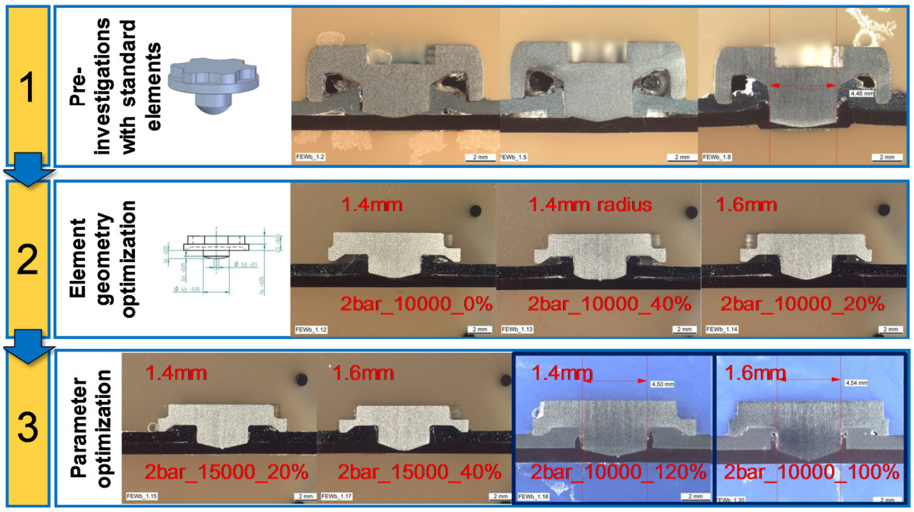

Figure 47: Steps of friction element optimization for joining EN AW-1050 and Cu-ETP (Source: LWF)

6.5.3.4 Friction stir spot welding (CEWAC)

Screening tests have indicated that repetitive qualitative joints could only be obtained in case the copper sheet is placed on top. Based on this info, all subsequent spot welding experiments have been performed in this configuration. The screening tests have shown that a tool with a shoulder diameter of 12 mm and a pin diameter of 6 mm (0,5 mm long and without thread) provides the best results. Therefore, development of suitable welding parameters has been performed with this tool geometry and configuration. In order to obtain acceptable joints, the main parameters have been optimised (rotation speed, dwell time and penetration depth).

Figure 48: Increasing strength of the Cu-Al FSSW joints, obtained during experiments with copper on top (from left to right), going from Cu & Al deformation without any adhesion up to tearing out of the weld nugget (Source: CEWAC)

6.5.3.5 Friction spot welding (BWI)

Refill friction spot welding of EN AW-1050 to Cu-ETP R240 was investigated by varying the rotation speed, the plunge depth and welding time. The aluminium sheet was welded on top of the copper sheet.

The effect of the rotation speed, plunge depth and welding time on the occurrence of a keyhole defect, the weld quality and the transferable force and corresponding failure modes were investigated:

- The highest average transferable force of 2,8 kN was attained for welds produced with at a rotation speed of 500 rpm, a plunge depth of 0,9 mm and welding time of 6 sec.
- Three different failure modes were observed: interfacial debonding (or weld nugget debonding), tearing-off the nugget from the upper aluminium sheet, and shearing of the aluminium base material. The highest transferable forces were recorded for welds which failed according to shearing of the aluminium base material.
- Due to the large scatter in the tensile test results, no correlation between the transferable force and the weld quality was observed.

Figure 49: Friction spot weld of copper to aluminium EN-AW 1050 + Cu-ETP (Source: BWI)

6.5.3.6 Electromagnetic pulse sheet welding (BWI)

The material combination EN AW-1050 (1 mm) to Cu ETP-R240 sheet (1 mm) was welded using 2 different coils. The interfacial morphology, structural characteristics (weld shape, weld length, weld width, interfacial layer thickness) and mechanical characteristics (transferable force, hardness) were characterised and related to the welding parameters.

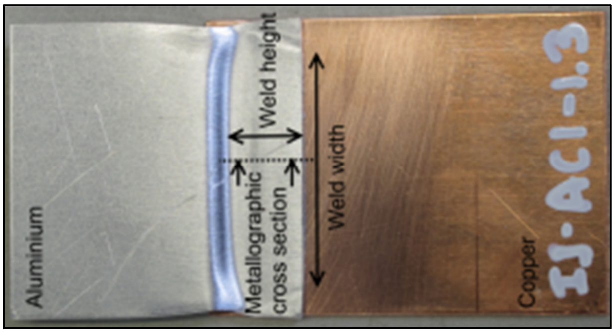

Figure 50: Electromagnetic pulse sheet weld of copper to aluminium EN-AW 1050 + Cu-ETP (Source: BWI)

Figure 51 shows a typical metallographic cross-section obtained at the centre of the weld, as indicated Figure 50. The first impact was at the right extremity of the aluminium flyer sheet, after which the bonding process advances to the left. In general, all metallographic cross-sections showed that aluminium/copper sheet welds evolved from a non-welded zone to a welded zone. The weld length corresponds to the length of the welded zone.

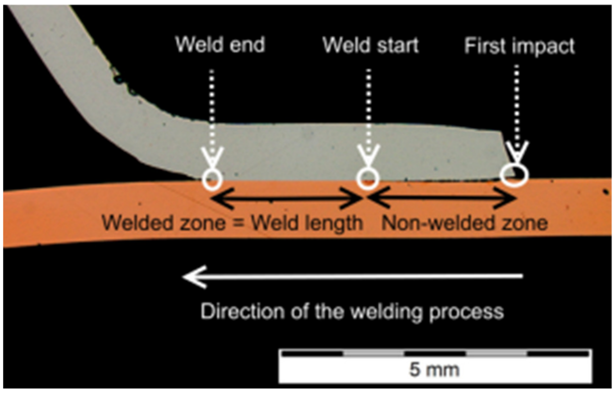

Figure 51: Typical metallographic cross-section at the centre of the welded sample (discharge energy: 10 kJ, stand-off distance: 3 mm, overlap: 10 mm, free length: 15 mm) (Source: BWI)

6.5.3.7 Laser (spot) welding (CEWAC)

Already during the preliminary testing phase, it was clear that laser welding of this material combination is difficult with the current available equipment. With a laser power of 3 kW, the copper sheet could be penetrated, but it was not possible to obtain a repeatable process.

In order to achieve reproducible results, higher as well as lower welding speeds have been tried. Also the keyhole mode as well as the conduction mode was tried. The latter is only possible in a limited manner, since the copper sheet acts as an important heatsink, thus requiring a substantial amount of heat input. Joints typically failed due to brittle behaviour and weld defects (hot cracking).

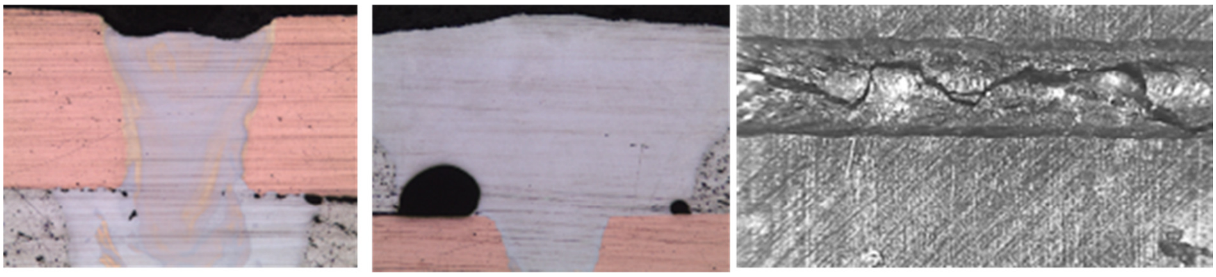

Figure 52: Welding with a high energy density beam of Cu on top of Al (left) and Al on top of Cu (middle) with the same parameters lead to very different dilution and joint geometry but in most cases hot cracking occurs in the weldment (right) (Source: CEWAC)

6.5.3.8 Arc element welding (SLV)

Figure 53 shows a cross section of the material combination copper - aluminium. Again, porosities have been observed at the weld interface. In all joints, the element head never applies a force fit on the sheets.

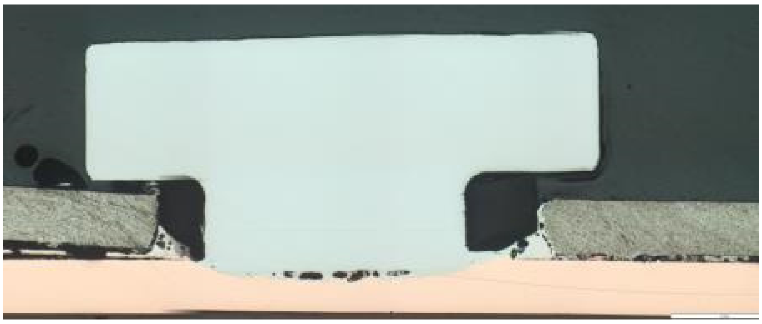

Figure 53: Arc element weld of copper to aluminium (Source: SLV)

6.5.4 Material combination 3: High strength - Stainless HCT600X + H800+X

6.5.4.1 Resistance welding with process tape (KUL)

The experimental conditions have been varied to investigate the influence of the parameters on the weld quality. Metallographic examination was also used to examine the welds for porosities, cracks or other weld defects. The most suitable welding parameters for this material combination were determined.

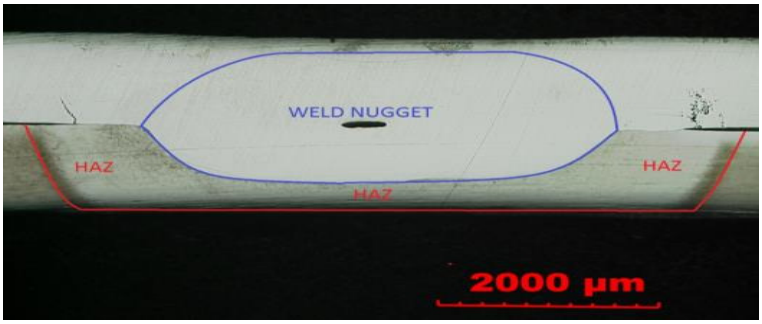

Figure 54: Resistance welding with process tape of high strength steel to stainless steel (Source: KULeuven)

6.5.4.2 Resistance element welding (LWF)

Two different joint setups were investigated for this material combination:

- positioning of HCT780 as base sheet, welding with a “standard” S355-element,
- positioning of H800 as base sheet, welding with resistance elements of 1.4305 (danger of hot cracks) and 1.4301 (optimized element material).

According to the first setup with S355 elements, the resulting weldability window for a welding time of 150 and 380 ms is shown in Figure 56. The resulting nugget diameter as well as the current ranges between bonding and spatter were quite different for both welding times, but applicable for further investigations. For this setup, parameter sets were determined for the investigation of the load-bearing capacity.

For the second setup with elements made of 1.4305 and 1.4301, the resulting weldability windows were also determined.

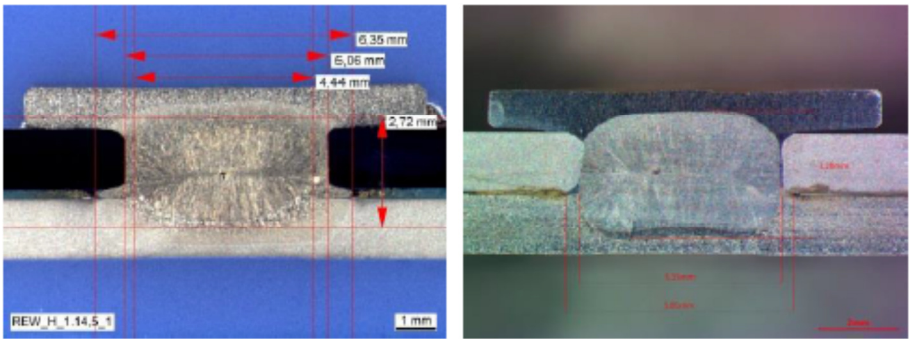

Figure 55: Resistance element welding of high strength steel to stainless steel (Source: LWF)

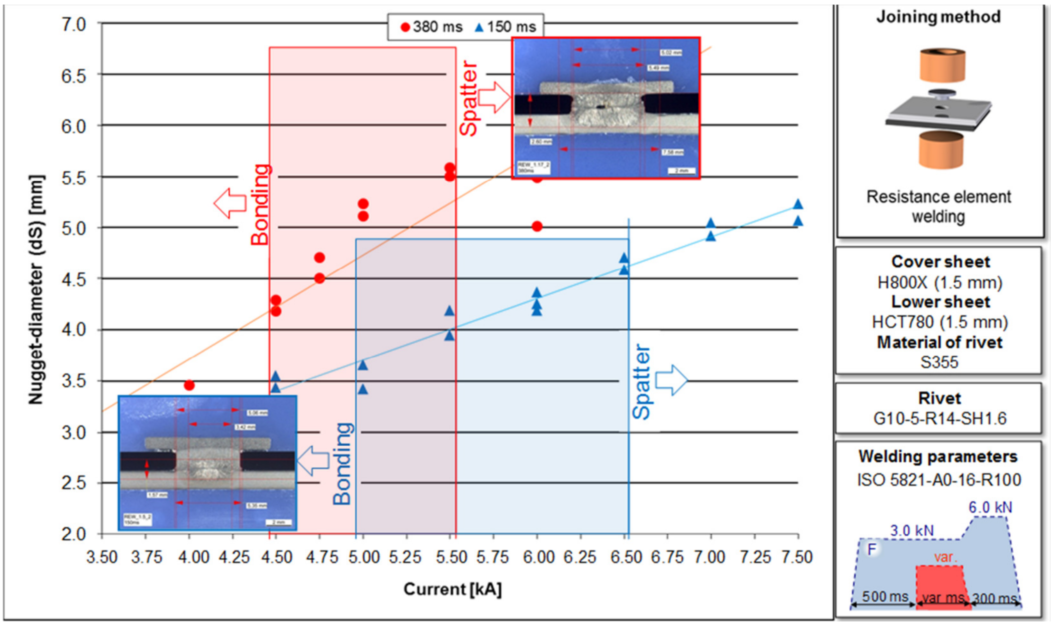

Figure 56: Weldability window for resistance element welding of the material combination high strength steel-stainless steel with a welding time of 150 and 380 ms and a steel element (S355) (Source: LWF)

6.5.4.3 Friction element welding (LWF)

For this material combination, it is not possible to apply FEW. For more details, see the full technical report.

6.5.4.4 Friction stir spot welding (CEWAC)

This combination has not been investigated, because it is uneconomical for this type of application. The cycle times and tool cost are too high to achieve a beneficial result.

6.5.4.5 Friction spot welding (BWI)

This material combination is not possible using this process.

6.5.4.6 Electromagnetic pulse sheet welding (BWI)

This material combination was not possible due to the high yield strength and low thermal conductivity of both steel sheets.

6.5.4.7 Laser (spot) welding (CEWAC)

Various parameters and other settings have been investigated in order to obtain optimised welds regarding:

- load bearing capacity (increasing the width at the interface without degrading any other aspect),
- minimisation of the influence of the Zn-coating on the joint quality (cracking, projections and entrapped vapours),
- acceptable hardness in the weld HAZ.

The load bearing capacity of an overlap weld, in absence of any weld defects, is mainly dependant on the width of the interface. When modifying the parameters in order to obtain wider joints, either the process efficiency will decrease (too low welding speed) or overheating of the material will occur. It is therefore important to look for a compromise between these aspects. The main laser welding parameters (power, speed, focal position) have been varied within acceptable limits to analyse the effect on the lap shear strength of the joint. During the development of optimised parameters, the power was varied between 1500 and 3000 W, the welding speed between 1 and 5 m/min and the focal positions between -5 and +5 mm (Ar shielding gas at 20 l/min). Welding experiments have been performed for linear welds as well as for spot welds in various forms. The lap shear and cross tension tests for joint validation have only be performed on C-shaped spot welds.

Based on the experience obtained during the testing phases, the lap shear and cross tensions testing samples have been produced at 2000 W, 0,04m/sec and a focus of 0 mm. These settings provided the best compromise between the weld width and the joint quality.

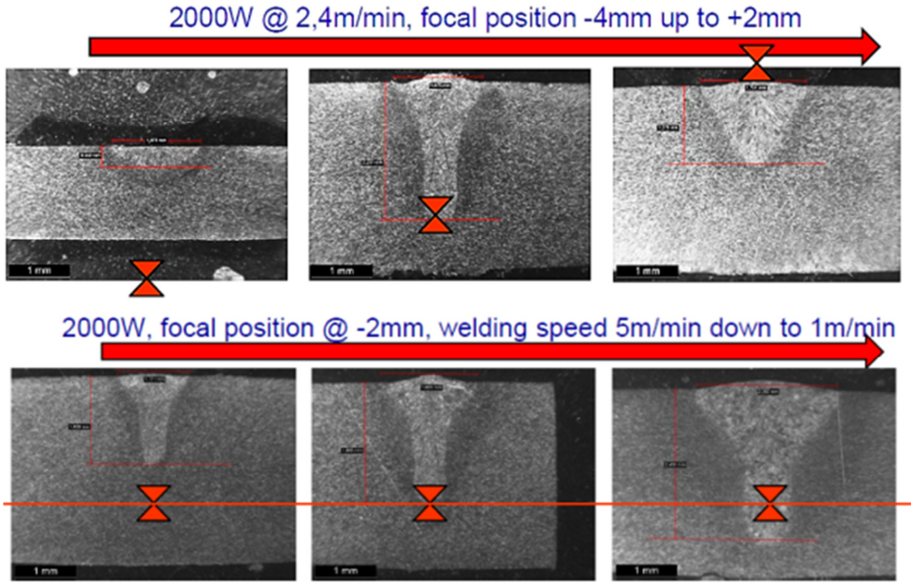

Figure 57: Results of preliminary experiments on 3 mm thick steel in order to demonstrate the influence of the main welding parameters on the joint geometry (to be used for joint width optimisation afterwards (Source: CEWAC)

6.5.4.8 Arc element welding (SLV)

Figure 58 shows a cross-section of a weld of high strength steel to stainless steel. Porosities are observed at the weld interface. As in the previous material combinations, these porosities can't be avoided.

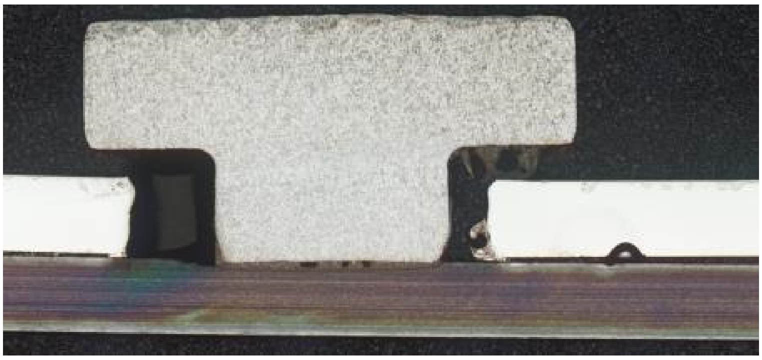

Figure 58: Arc element weld of high strength steel to stainless steel (Source: SLV)

6.6 Benchmarking of the joining technologies

Based on the experimental investigations and joint characterisation, a comparison was made of the different joining technologies, based on benchmark criteria defined by the consortium. In addition, an external benchmark comparing the investigated welding technologies with mechanical joining methods was performed.

6.6.1 Benchmark criteria

The following benchmark criteria were used to evaluate the joint performance for each joining technology:

- quasi-static lap shear strength,
- quasi-static cross tension strength,
- lap shear strength under high strain rates,
- fatigue strength,
- corrosion resistance: visual qualification and quasi-static lap shear strength after corrosion testing.

6.6.2 Results of the benchmark

The results of the main benchmark for the 3 material combinations are shown in Table 65, Table 66 and Table 67. In addition, also the results of the external benchmark are presented for comparison.

Table 1: Benchmark for material combination 1
(Aluminium: EN-AW 5182 (AlMg4,5Mn0,4) - Thickness : 2,0 mm + Steel: MS-W1200 ZE50/50 - Thickness : 1,5 mm

Criteria	**Unit**	**Resistance spot welding with process tape**	**Resistance element welding**	**Friction spot welding**	**Friction stir spot welding**	**Friction element welding**	**Electromagnetic pulse sheet welding**	**Laser beam welding**	**Arc element welding**	**External benchmark: semi-tubular riveting**
		RSW	**REW**	**FSpW**	**FSSW**	**FEW**	**EMPS**	**LBW**	**AEW**	**STR**
Applicability for this material combination	-/0/+	+	+	+	-	+	-	-	+	+
Quasi-static lap shear strength	kN	5,66	5	5,6	/	8,5	/	/	4	7,56
Repeatability of quasi-st. lap shear results	kN (scatter)	+0,81 / -0,95	+0,2 / -0,1	N/A	/	+0,4 / -0,6	/	/	N/A	+0,2 / -0,1
Quasi-static cross tension strength	kN	1,46	4,37	N/A	/	6,13	/	/	6	2,79
Repeatability of quasi-st. cross tens test results	kN (scatter)	+0,17 / -0,21	+0,1 / -0,1	N/A	/	+0,3 / -0,1	/	/	N/A	+0,25 / -0,25
Lap shear strength under high strain rates [kN]	kN	7,36	5,25	7,92	/	9,81	/	/	3,8	N/A
Repeatability of high strain lap shear results	kN (scatter)	+0,91 / -1,8	+0,13 / - 0,1	+5,51 / -2,56	/	+0,45 / -0,55	/	/	+0,36 / -0,51	N/A
Fatigue testing (lap shear) 2Mio. Cycles, 90% survival probability, R=0,1	kN	1,05	1,54	2,29	/	1,10	/	/	1,16	N/A
Visual qualification of corrosion resistance	'--/-/0/+/++	-	--	-	/	--	/	/	--	N/A

Criteria	Unit	Resistance spot welding with process tape	Resistance element welding	Friction spot welding	Friction stir spot welding	Friction element welding	Electromagnetic pulse sheet welding	Laser beam welding	Arc element welding	External benchmark: semi-tubular riveting
		RSW	**REW**	**FSpW**	**FSSW**	**FEW**	**EMPS**	**LBW**	**AEW**	**STR**
Quasi-static lap shear strength after corrosion test (immersion/salt spray)	kN	6,1 / 3,2	5,0 / 4,4	0	/	8,9 / 8,2	/	/	3,1 / 3,0	N/A
Repeatability of quasi-st. lap shear strength after corrosion test (immersion/salt spray)	kN (scatter)	± 0,2 / ± 0,4	± 0,1 / ± 0,2	N/A	/	± 0,4 / ± 0,3	/	/	± 0,9 / ± 0,2	N/A
Lap shear strength reduction after corrosion test, compared to blank specimen (immersion/salt spray)	%	20,8 / 59,1	0 / 9,4	100 / 100	/	6,0 / 13,5	/	/	23,4 / 28,0	N/A
Overall ranking for corrosion resistance: based on lap shear strength after corrosion test	1 : low; 5: high	4	3	1	/	5	/	/	2	N/A
Overall ranking for corrosion resistance: based on corrosion sensitivity	1: low; 5: high	3	5	1	/	4	/	/	2	N/A
Process time	s	2,5	0,15 & 0,38	5	/	5	/	/	0,003	N/A
Material thickness flexibility	'--/-/0/+/++’	‘-‘	0	0	/	0	/	/	‘-‘	N/A
Joint Quality Indicator		**116**	**142**	**87**		**168**			**112**	
Final ranking		**3**	**2**	**5**		**1**			**4**	

Table 2: Benchmark for material combination 2
(Aluminium: EN-AW 1050 (H14/24) - Thickness: 1,0 mm + Copper: Cu-ETP (R240) - Thickness: 1,0 mm)

Criteria	**Unit**	**Resistance spot welding with process tape**	**Resistance element welding**	**Friction spot welding**	**Friction stir spot welding**	**Friction element welding**	**Electromagnetic pulse sheet welding**	**Laser beam welding**	**Arc element welding**	**External benchmark: Clinching**
		RSW	**REW**	**FSpW**	**FSSW**	**FEW**	**EMPS**	**LBW**	**AEW**	**CL**
Applicability for this material combination	-/0/+	+	+	+	+	+	+	-	+	-
Quasi-static lap shear strength	kN	2,85	0,89	2	3,5	2,04	5,1	/	1	1,1
Repeatability of quasi-st. lap shear results	kN (scatter)	0,27 / - 0,346	0,1 / - 0,1	N/A	0 / - 0,1	0,1 / - 0,1	N/A	/	N/A	N/A
Quasi-static cross tension strength	kN	0,18	0,59	N/A	1,4	1,28	N/A	/	1,2	0,37
Repeatability of quasi-st. cross tens test results	kN (scatter)	0,03 / - 0,02	0,3 / - 0,3	N/A	0,3 / - 0,2	0,1 / - 0,1	N/A	/	N/A	N/A
Lap shear strength under high strain rates [kN]	kN	3,1	1,3	2,1	3,29	2,7	5,9	/	1,2	N/A
Repeatability of high strain lap shear results	kN (scatter)	1 / - 0,6	0,2 / - 0,1	0,8 / - 0,7	0,7 / - 0,9	0,4 / - 0,3	0,1 / - 0,1	/	0,03 / - 0,04	N/A
Fatigue testing (lap shear) 2Mio. Cycles, 90% survival probability, R=0,1	kN	0,49	0,38	0,55	0,58	0,84	1,62	/	0,42	N/A
Visual qualification of corrosion resistance	'--/-/0/+/++	´--`	´-`	´-`	´--`	´--`	´-`	/	´--`	N/A
Quasi-static lap shear strength after corrosion test (immersion/salt	kN	2,0 / 0,6	0,7 / 0,9	0,9 / 0,8	2,6 / 1,9	1,7 / 1,3	4,2 / 2,3	/	0,7 / 0,7	N/A

Criteria	Unit	Resistance spot welding with process tape	Resistance element welding	Friction spot welding	Friction stir spot welding	Friction element welding	Electromagnetic pulse sheet welding	Laser beam welding	Arc element welding	External benchmark: Clinching
		RSW	**REW**	**FSpW**	**FSSW**	**FEW**	**EMPS**	**LBW**	**AEW**	**CL**
spray)										
Repeatability of quasi-st. lap shear strength after corrosion test (immersion/salt spray)	kN (scatter)	± 0,4 / ± 0,2	NA / ± 0,1	± 0,1 / NA	± 0,6 / ± 1,2	± 0,3 / ± 0,1	± 0,1 / ± 0,4	/	± 0,2 / ± 0,1	N/A
Lap shear strength reduction after corrosion test, compared to blank specimen (immersion/salt spray)	%	29,5/ 80,0	40,0 /17,3	53,6 / 57,7	0 / 48,3	18,0 / 37,0	17,0 / 55,6	/	84,1 / 82,2	N/A
Overall ranking for corrosion resistance: based on lap shear strength after corrosion test	1 : low; 5: high	4	1	3	6	5	7	/	2	N/A
Overall ranking for corrosion resistance: based on corrosion sensitivity	1 : low; 5: high	3	5	3	7	6	4	/	1	N/A
Process time	s	1,4	0,06	5	20,5	5	1-1,5 x 10^{-5}	/	0,003	N/A
Material thickness flexibility	'--/-/0/+/++’	-	0	0	-	0	- or +	/	-	
Joint Quality Indicator		**95**	**93**	**89**	**137**	**131**	**191**		**80**	
Final ranking		**4**	**5**	**6**	**2**	**3**	**1**		**7**	

Table 3: Benchmark for material combination 3
(High strength steel: HCT780X ZE50/50) - Thickness: 1,5 mm + Stainless steel: H800 (1.4378) - Thickness: 1,5 mm)

Criteria	**Unit**	**Resistance spot welding with process tape**	**Resistance element welding**	**Friction spot welding**	**Friction stir spot welding**	**Friction element welding**	**Electromag netic pulse sheet welding**	**Laser beam welding**	**Arc element welding**	**External benchmark**
		RSW	**REW**	**FSpW**	**FSSW**	**FEW**	**EMPS**	**LBW**	**AEW**	**none**
Applicability for this material combination	-/0/+	+	+	-	-	-	-	-	+	/
Quasi-static lap shear strength	kN	15,8	12,9	/	/	/	/	34,9	5,8	/
Repeatability of quasist. lap shear results	kN (scatter)	+1,44 / -1,54	+1 / -1	/	/	/	/	0,6 / -0,8	N/A	/
Quasi-static cross tension strength	kN	9,04	8,5	/	/	/	/	6	7,6	/
Repeatability of quasist. cross tens test results	kN (scatter)	+1,28 / -1,33	+0,6 / -0,5	/	/	/	/	0,4 / -0,4	N/A	/
Lap shear strength under high strain rates [kN]	kN	19,38	14,1	/	/	/	/	/	7,63	/
Repeatability of high strain lap shear results	kN (scatter)	+0.64 / -1.12	+0.84 / -1.38	/	/	/	/	/	+0.88 / -0.69	/
Fatigue testing (lap shear) 2Mio. Cycles, 90% survival probability, R=0,1	kN	1,42	1,29	/	/	/	/	N/A	1,3	/
Visual qualification of corrosion resistance	'--/-/0/+/++	´--`	´-`	/	/	/	/	/	´--`	/
Quasi-static lap shear strength after corrosion test (immersion/salt	kN	16,5 / 15,8	9,9 / 9,3	/	/	/	/	/	6,4 / 5,3	/

Criteria	Unit	Resistance spot welding with process tape	Resistance element welding	Friction spot welding	Friction stir spot welding	Friction element welding	Electromagnetic pulse sheet welding	Laser beam welding	Arc element welding	External benchmark
		RSW	REW	FSpW	FSSW	FEW	EMPS	LBW	AEW	none
spray)										
Repeatability of quasist. lap shear strength after corrosion test (immersion/salt spray)	kN (scatter)	± 0,3 / ± 0,8	± 1,1 / ± 1,1	/	/	/	/	/	± 0,3 / ± 0,3	/
Lap shear strength reduction after corrosion test, compared to blank specimen (immersion/salt spray)	%	3,1 / 7,2	15,1 / 20,1	/	/	/	/	/	0 / 0,74	/
Overall ranking for corrosion resistance: based on lap shear strength after corrosion test	1 : low; 3: high	1	2	/	/	/	/	/	3	/
Overall ranking for corrosion resistance: based on corrosion sensitivity	1 : low; 3: high	3	2	/	/	/	/	/	1	/
Process time	s	2,2	0,15 & 0,38	/	/	/	/	1,8	0,003	/
Material thickness flexibility	--/-/0/+/++	-	0	/	/	/	/	-	-	/
Joint Quality Indicator		**162**	**124**						**105**	
Final ranking		**1**	**2**						**3**	

Based on the benchmark for each material combination in Table 1, Table 2 and Table 3, a final ranking of the different joining processes was obtained. This ranking was based on an arbitrarily defined ”joint quality indicator”. For this purpose, the range of each weld property was assigned a specific value, which was subsequently multiplied by a weight factor that indicated the relative importance of the specific joint property. In this way, the joint quality indicator was calculated for each joining process and for each material combination. In summary, the joint quality indicator was defined as:

> Joint quality indicator for each joining process and each material combination = ∑(specific value × weight factor) for each joint property

The weight factors for the different joint properties are shown in Table 4.

Table 4: Joint property and corresponding weight factor

Joint property	Weight factor
Applicability for this material combination [-/0/+]	3
Quasi-static lap shear strength [kN]	3
Quasi-static cross tension strength [kN]	2
Lap shear strength under high strain rates [kN]	2
Fatigue testing (lap shear) 2 mill. cycles, 90% survival probability, R=0,1 [kN]	3
Visual qualification of corrosion resistance [--/-//0/+/++]	1
Quasi-static lap shear strength after corrosion test (immersion/salt spray) [kN]	3
Lap shear strength reduction after corrosion test, compared to blank specimen (immersion/salt spray) [kN]	2
Process time [s]	2
Material thickness flexibility [-/0/+]	1

The following conclusions can be drawn based on the main benchmark criteria.

Material combination 1 (EN-AW5182 (2,0 mm) + MS-W1200 ZE50/50 (1,5 mm)

- Friction element welding is the best joining technology as joints with the highest mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, and quasi-static cross tension strength) were achieved. Furthermore, it provided the highest corrosion resistance, since the highest lap shear strength after corrosion testing and the lowest corrosion sensitivity were obtained. However, poor visual qualification of the corroded joint was observed.
- Friction spot welding provided the poorest joints, especially in terms of corrosion resistance, as the corroded joints failed during lap shear testing.

- Resistance spot welding with process tape, resistance element welding and arc element welding can be considered as ‘medium’ joining technologies.

Material combination 2 EN-AW 1050 (1,0 mm) + Cu-ETP (1,0 mm)

- Electromagnetic pulse sheet welding is the best joining technology as joints with the highest mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, quasi-static cross tension strength, fatigue) were achieved. In addition, it provided the highest corrosion resistance (in terms of lap shear strength after corrosion). However, it exhibited a higher corrosion sensitivity compared to friction stir spot welding.
- Arc element welding provided the poorest joints, both in terms of mechanical properties and corrosion resistance.
- Resistance spot welding with process tape, resistance element welding, friction spot welding, friction stir spot welding and friction element welding can be considered as ‘medium’ joining technologies.

Material combination 3 (HCT600X (1,5mm) + H800+ X (1,5mm)

- Resistance spot welding with process tape is the best joining technology as joints with the highest mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, quasi-static cross tension strength and fatigue) were achieved. However, it exhibited a higher corrosion sensitivity, compared to arc element welding.
- Arc element welding provided joints with the lowest mechanical properties, but at the same time it also exhibited the lowest corrosion sensitivity.
- Resistance element welding can be regarded as a ‘medium’ joining technology.
- Although laser beam welding provided a significantly higher quasi-static lap shear strength compared to the other joining technologies, it is not applicable for this material combination as hot cracking was observed. It was therefore not taken into consideration for the benchmark.

7 Dissemination of results

7.1 Manufacturing of demonstrators

As a result of the Innojoin-project, demonstrators were manufactured at the end of the project. For exhibitions and public demonstrator presentations, the corresponding micro-section pictures and related lap shear test forces were placed on the respective specimen parts.

A simplified design was chosen by the project team, in agreement with the user committee, which shows the treated and applicable joining methods for each of the material combinations. In the following figures, the three demonstrators for the material combinations can be seen.

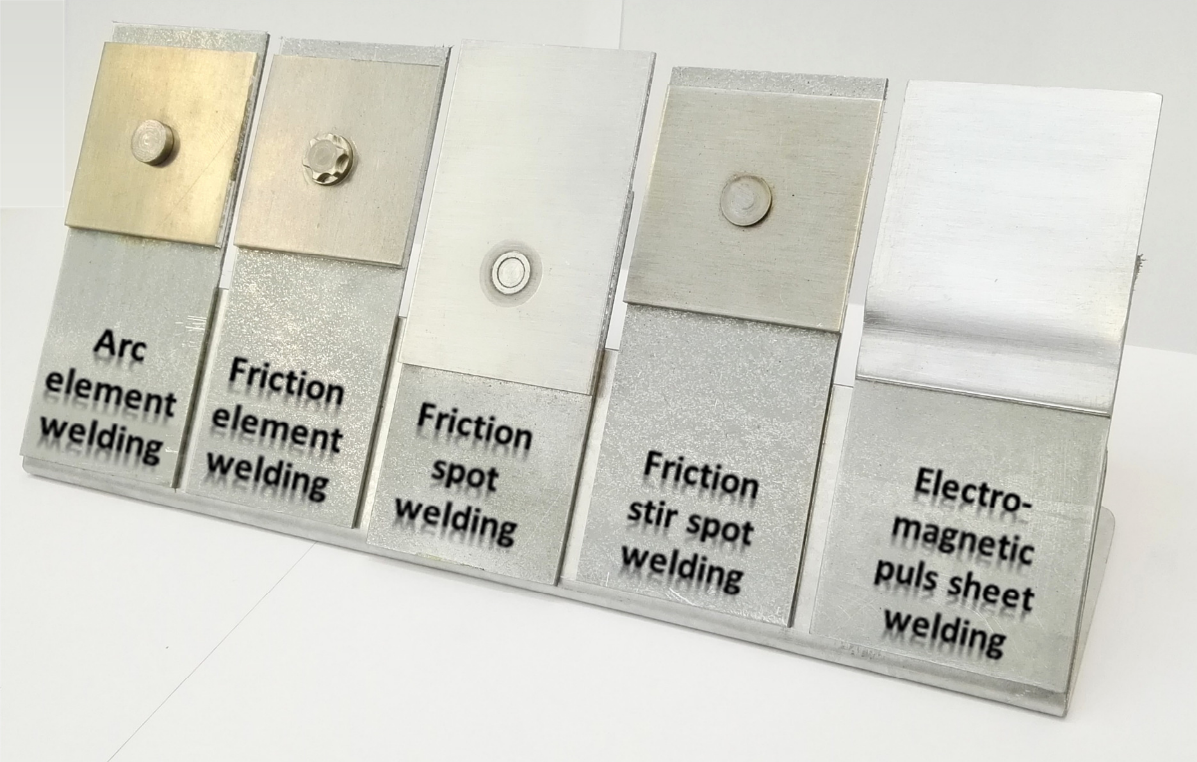

Figure 59: Demonstrators of material combination 1: Aluminium/steel

Figure 60: Demonstrators of material combination 2: Copper/Aluminium

Figure 61: Demonstrators of material combination 3: high strength steel/stainless steel

7.2 Publications, presentations and other dissemination activities

See Table 5 for all dissemination activities performed during the project.

Table 5: Overview of dissemination activities of the consortium

No.	Date	Activity	Type	Objective	Responsible
1	15/02/2013	K Faes, P. Van Rymenant, F. Hendrickx. Thermisch verbinden van ongelijksoortige plaatmaterialen. Metallerie 168, p. 26-29, 15 febr. 2013.	Publication in magazine	Article in magazine "Metallerie" (in Dutch) Purpose: Project presentation	BWI
2	15/02/2013	K Faes, P. Van Rymenant, F. Hendrickx. Assemblage thermique de toles en materiaux dissemblables. Metallerie 168, p. 26-29, 15 febr. 2013.	Publication in magazine	Article in magazine "Metallerie" (in French) Purpose: Project presentation	BWI
3	8/10/2013	AGORIA Advanced welding and micro welding presentation at CEWAC	Presentation	Project presentation	CEWAC
4	14/11/2013	User committee meeting 1 (organised in BWI, Ghent)	UC Meeting	Project presentation	BWI
5	12/12/2013	Non-conventional welding technologies. Student course for students of the Ghent University, Dec. 12, 2013, Zwijnaarde, Belgium.	Student course		BWI
6	1/03/2014	InnoJoin webpage on the BWI website: http://www.bil-ibs.be/onderzoeksproject/innojoin-verbinden-van-ongelijksoortige-materialen-plaatvorm (3 languages)	Website	Project presentation	BWI
7	31/03/2014	News on CEWAC website http://www.cewac.be/fr/news/40-projet-cornet-innojoin.aspx	Publication on website	Project presentation	CEWAC
8	01/04.-30/09/2014	publication of selected results within the student course "Thermische Fügeverfahren"	Student course	Implementation of the project contents in teaching	LWF
9	29/04/2014	K. Faes, T. Baaten. Nieuwe ontwikkelingen in de lastechniek. Postacademic formation, April 29, 2014, KU Leuven, Kortrijk, Belgium.	Student course		BWI
10	6/05/2014	Report at the DVS-Fachausschuss No. 5	DVS-Report/Expert Meeting	Report of the project progress and results	LWF, SLV
11	12/05/2014	LWF newsletter announcing the user committee meeting on 02/07/2014	Newsletter	Invitation for participation at the user committee	LWF

No.	Date	Activity	Type	Objective	Responsible
12	1/06/2014	Hans Costermans. Research of the weldability of dissimilar metals with ultrasonic welding and electromagnetic pulse welding Master Thesis submitted to obtain the degree of Master of Science in Engineering Technology: Electromechanics specialization: electromechanics, June 2014. supervisor: Dr. Ing. P. Van Rymenant, EWE mentor: Dr. Ir. Koen Faes, EWE	Student thesis		KWI, KUL
13	1/06/2014	Seppe Rymen. Magnetic pulse welding: Experimental research on the process parameters Master Thesis submitted to obtain the degree of Master of Science in Engineering Technology: Electromechanics specialization: electromechanics, June 2014. supervisor: Dr. Ing. P. Van Rymenant, EWE mentor: Dr. Ir. Koen Faes, EWE	Student thesis		KWI, KUL
14	1/07/2014	Student thesis on development of an FSSW machine	Student thesis	Development of FSSW machine for laboratory use	CEWAC
15	2/07/2014	User committee meeting 2 (organised in LWF, Paderborn)	UC Meeting	Project presentation & progress	LWF
16	30/07/2014	Yan-Yin Huynh. Welding of dissimilar materials Al-Cu Using Magnetic Pulse Welding Internship in the 4th year in the Engineering school of Ecole polytechnique de Nantes Supervisor: Professor Pascal Paillard Mentor: Dr. Ir. Koen Faes	Student thesis		BWI
17	1/09/2014	K. Faes, I. Kwee. Verbinden van ongelijksoortige materialen. Metallerie sept. 2014, p. 66--71.	Publication in magazine	Article in magazine "Metallerie" (in Dutch) Purpose: Project presentation & first results	BWI
18	1/09/2014	K. Faes, I. Kwee. Assembler des métaux dissemblables. Metallerie aug. 2014, p. 66--71.	Publication in magazine	Article in magazine "Metallerie" (in French) Purpose: Project presentation & first results	BWI

No.	Date	Activity	Type	Objective	Responsible
19	21-25/10/2014	Presentation of selected results at the trade fair EUROBLECH2014	Publication on trade fair	Reaching a wide range of possible interested companies	SLV
20	5/11/2014	K. Faes, I. Kwee. Verbinden van ongelijksoortige metalen in plaatvorm: koper - aluminium. Proceedings of the NIL BIL Lassymposium, 4 - 5 november 2014, Gorinchem, the Netherlands.	Conference presentation and publication in proceedings	Sensitisation of companies	BWI
21	13/10/2014	BWI newsletter announcing the user committee meeting on 13/11/2014	Newsletter	Invitation for participation at the user committee	BWI
22	13/11/2014	User committee meeting 3 (organised in KU Leuven, Sint-Katelijne-Waver)	UC Meeting	Project progress and results	KUL
23	3/12/2014	Report at the DVS-Fachausschuss No. 5	DVS-Report/Expert Meeting	Report of the project progress and results	LWF, SLV
24	1/01/2015	BWI annual report of 2014	Report	Project presentation and results	BWI
25	8/12/2015	LWF newsletter announcing the user committee meeting on 24/02/2015	Newsletter	Invitation for participation at the user committee	LWF
26	24/02/2015	User committee meeting 4 (organised in SLV Hälle)	UC Meeting		SLV
27	10/03/2015	K. Faes. Friction spot joining of the high strength aluminium alloy EN AW-2024 T3. Proceedings of the 21ste Erfahrungsaustausch Reibschweissen, 10 March 2015, SLV, Munchen.	Conference presentation and publication in proceedings	Publication of results on friction spot welding.	BWI
28	10/03/2015	C. Schmal. „Fügen artverschiedener metallischer Blechwerkstoffe durch Reibelementschweißen“ Proceedings of the 21ste Erfahrungsaustausch Reibschweissen, 10 March 2015, SLV, Munchen.	Conference presentation and publication in proceedings	Publication of results on friction element welding.	LWF
29	1/04/2015	I. Kwee, K. Faes. Elektromagnetisch puls lassen van aluminium-koper plaatverbindingen. Metallerie april. 2015, p. 11-15.	Publication in magazine	Publication of results (electromagnetic pulse welding of copper to aluminium)	BWI

No.	Date	Activity	Type	Objective	Responsible
30	1/04/2015	I. Kwee, K. Faes. Soudage par impulsion magnétique d'assemblages alu-cuivre. Métallerie avril. 2015, p. 11-15.	Publication in magazine	Publication of results (electromagnetic pulse welding of copper to aluminium)	BWI
31	1/04/2015	K. Faes. Wrijvingspuntlassen van hoogsterkte aluminium legeringen. Metallerie april. 2015, p. 20-25.	Publication in magazine	Publication of results	BWI
32	1/04/2015	K. Faes. Soudage par points par friction d'alliages d'alu haute resistance. Métallerie, Avril. 2015, p. 20-25.	Publication in magazine	Publication of results	BWI
33	1/04/2015	K. Faes, N. Vandermeieren. Moderne hoogsterkte stalen vragen nieuwe verbindingstechnieken. Metallerie april. 2015, p. 17.	Publication in magazine	Publication of results	BWI
34	1/04/2015	K. Faes, N. Vandermeieren. Les aciers à haute resistance exigent de nouvelles techniques d'assemblage. Métallerie avril. 2015, p. 17.	Publication in magazine	Publication of results	BWI
35	01/04.-30/09/2015	Publication of selected results within the student course "Thermische Fügeverfahren"	Student course	Implementation of the project contents in teaching	LWF
36	13-17/04/2015	Demonstration parts at the fair "Hannover Messe 2015"	Fair	Project presentation &illustration of technology	BWI
37	13-17/04/2015	Hannover Messe 2015 - presentation of FSSW welded samples	Publication on trade fair	Project presentation	CEWAC
38	15/04/2015	Report at the DVS-Fachausschuss No. 5	DVS-Report/Expert Meeting	Report of the project progress and results	LWF, SLV
39	5/05/2015	LWF newsletter announcing the user committee meeting on 30/09/2015	Newsletter	Invitation for participation at the user committee	LWF
40	10/05/2015	Open house at CEWAC - presentation of welding technology and related research	Open house	Project presentation	CEWAC
41	1/06/2015	W. Elegeert. The friction spot welding of high-strength Al alloys. Thesis submitted to obtain the degree of Master of Science in Engineering Technology. Thomas Moore high school, Campus De Nayer. Academic year 2014-2015. Promotor: Prof. dr. ir. Frans Vos Master Co-promotor: dr. ir. Koen Faes, BIL Welding Engineering	Student thesis		BWI/KUL

No.	Date	Activity	Type	Objective	Responsible
42	1/06/2015	O. Bilouet. Corrélation entre les paramètres de soudage à l'état solide, la microstructure et les caractéristiques mécaniques de soudures en alliages d'aluminium des séries 2000 et 7000. Travail de fin d'études présenté en vue de l'obtention du grade de Master Ingénieur civil en Chimie – Science des Matériaux. En collaboration avec la SONACA et IBS. Année académique 2014-2015.	Student thesis		BWI
43	24/06/2015	W. Hermans, W. Van Houcke. Resistance welding Aluminium to Copper using Process tapes. MSc thesis Master of Science in Welding Engineering, KULeuven, academic year 2014-2015.	Student thesis		KUL
44	30/09/2015	User committee meeting (organised in LWF, Paderborn)	UC Meeting	Project presentation & progress	LWF
45	1/10/2015	I. Kwee, N. Vandermeiren, K. Faes, S. Coppieters, D. Debruyne. Innovatieve verbindingstechnieken voor ongelijksoortige plaatmaterialen. Metallerie Nr. 194, october 2015, p. 29 - 32.	Publication in magazine	Publication of results	BWI
46	1/10/2015	I. Kwee, N. Vandermeiren, K. Faes, S. Coppieters, D. Debruyne. Techniques d'assemblage innovantes pour tôles heterogenes. Metallerie Nr. 194, octobre 2015, p. 29 - 32.	Publication in magazine	Publication of results	BWI
47	9/10/2015	User committee meeting (organised in BWI Gent)	UC Meeting	Project presentation & progress	BWI
48	14/10/2015	Schmal. C.; Broda, T. „Mechanisch-technologische Eigenschaften von Mischverbindungen mit geschweißtem Hilfsfügeelement" Proceedings of the 17. Kolloquium "Widerstandsschweißen und alternative Verfahren", 14 October 2015, SLV Halle.	Conference presentation and publication in proceedings	Publication of results on friction element welding.	LWF, SLV
49	20-22/10/2015	Flyers and demonstration parts at the fair "Welding Week", Antwerp, Belgium	Fair	Project presentation &illustration of technology	BWI
50	1/11/2015	I. Kwee, K. Faes. Innovatieve verbindingstechnieken voor het verbinden van ongelijksoortige plaatmaterialen. Lastechniek, nr. 11, November 2015, p. 14 - 18.	Publication in magazine	Publication of results	BWI
51	11/11/2015	LWF newsletter announcing the user committee meeting on 03/02/2016	Newsletter	Invitation for participation at the user committee	LWF, SLV
52	12/11/2015	Report at the DVS-Fachausschuss No. 5	DVS-	Report of the project progress and	LWF, SLV

No.	Date	Activity	Type	Objective	Responsible
			Report/Expert Meeting	results	
53	24-25/11/2015	Flyers and demonstration parts at the BWI Welding Symposium, Antwerp, Belgium	Symposium	Project presentation &illustration of technology	BWI
54	25/11/2015	M. Smits. Weerstandlassen van aluminium aan verzinkt martensitisch staal met behulp van processtape. BWI Welding Symposium.	Conference presentation and publication in proceedings	Publication of results on welding of aluminium to steel using resistance welding with process tape.	KUL
55	08-09/12/2015	Presentation of selected specimen on the EFB-Gemeinschaftskolloquium in Paderborn	Expert Meeting	Publication of selected results	LWF
56	9/12/2015	INNOVATECH breakfast workshop on Friction Stir Welding	Workshop incl. presentation and demos	Project presentation and general overview of results, demonstration of Friction Stir Spot Welding	CEWAC
57	1/01/2016	BWI annual report of 2015	Report	Project presentation and results	BWI
58	1/02/2016	K. Faes. BIL onderzoekt nieuwe puntlastechniek voor het lassen van aluminium. Metallerie Febr 2016.	Publication in magazine	Article in magazine "Metallerie" (in Dutch). General presentation of results about friction spot welding of aluminium alloys and dissimilar aluminium-steel combinations.	BWI
59	1/02/2016	K. Faes. L'IBS etudie un nouveau processus de soudage a l'état solide. Metallerie Febr 2016.	Publication in magazine	Article in magazine "Metallerie" (in French) General presentation of results about friction spot welding of aluminium alloys and dissimilar aluminium-steel combinations.	BWI
60	8/02/2016	Schmal. C. „Process characteristics and load bearing capacities of joints welded with elements for the application in multi-material-design“ Proceedings of the IIW COM-III Intermediate Meeting, 08.-10.	Conference presentation and publication in	Publication of results on friction element welding.	LWF, SLV

No.	Date	Activity	Type	Objective	Responsible
		February 2016, Helmholtz-Zentrum Geesthacht.	proceedings		
61	2/03/2016	INNOVATECH breakfast workshop on Friction Stir Welding	Workshop incl. presentation and demos	Project presentation and general overview of results, demonstration of Friction Stir Spot Welding	CEWAC
62	12/04/2016, 19/04/2016, 26/04/2016	Student lecture on "Non-conventional welding processes" for MSc. Engineering students at the Ghent University, Belgium	University lecture	Implementation of the project contents in teaching	BWI
63	20-21/04/2016	Flyers and demonstration parts at the fair "Pumps & Valves 2016", Antwerp, Belgium	Fair	Project presentation &illustration of technology	BWI
64	2/02/2016	S. Jacobs, Resistance welding of Steel to Stainless Steel using Process Tapes. MSc thesis Master of Science in Welding Engineering, KULeuven, academic year 2015-2016.	Student thesis		KUL
65	3/02/2016	User committee meeting (organised in SLV, Halle (Saale))	UC Meeting	Project presentation & progress	SLV
66	13-15/04/2016	P. Van Rymenant, S. Jacobs. Development of a welding procedure on a Fronius Deltaspot to avoid Liquid Metal Embrittlement in welding Zinc-Coated High Strength Steel. Presentation on AWS, RWMA, EWI & Swantec 9th International Seminar & Conference on Advances in Resistance Welding, Miami, Florida, USA.	Conference presentation and publication in proceedings	Publication of results on Deltaspot welding of steel to stainless steel and related LME issues.	KUL
67	26/04/2016	Workshop for Wallonia Design	Workshop incl. presentation and demos	Presentation of various welding technologies and current research projects to visitors active in product design	CEWAC
68	27/04/2016	K. Faes, I. Kwee. Morphological and mechanical characteristics of aluminium-copper sheet joints by electromagnetic pulse welding. Proceedings of the International Conference of High Speed Forming (ICHSF), Dortmund, Germany, 27-28 April 2016	Conference presentation and publication in proceedings	Publication of results on magnetic pulse welding of copper to aluminium	BWI
69	24/05/2016	Report at the DVS-Fachausschuss No. 5	DVS-Report/Expert Meeting	Report of the project progress and results	LWF

No.	Date	Activity	Type	Objective	Responsible
70	31/05/2016	Tom Kolba. Experimental investigation of the weldability of aluminium alloys using friction spot welding Master Thesis submitted to obtain the academic degree of Master of Science in Electromechanical Engineering, May 2016. supervisor: Prof.dr.ir. Wim De Waele mentor: Dr. Ir. Koen Faes, EWE	Student thesis		BWI
71	31/05/2016	T. Kolba, W. De Waele, K. Faes. Experimental investigation of the weldability of high strength aluminium EN AW-7475-T761 using friction spot welding. International Journal of Sustainable Construction and Design	Publication in magazine	Publication of results on friction spot welding.	BWI
72	31/05/2016	W. Demonie, K. Faes, W. De Waele. Influence of process parameters on the weld quality of dissimilar Cu-Al magnetic pulse welded sheets. International Journal of Sustainable Construction & Design. Vol. 7, No. 1, 2016.	Publication in journal	Publication of results on electromagnetic pulse welding of Copper-aluminium	BWI
73	31/05/2016	Report at the DVS AG-V11.1 (Workgroup for friction based joining processes) Meeting in Paderborn (Germany)	DVS-Report/Expert Meeting	Report of the project progress and results	LWF
74	Sept. 2016	I. Kwee, K. Faes. Structural, morphological and mechanical features of aluminium to copper sheet joints by electromagnetic pulse welding. Key Engineering Materials, Vol. 710, p. 109-114. DOI: 10.4028/www.scientific.net/KEM.710.109	Publication in journal		BWI
75	2014 - 2016	Visits and courses for university students and IWE/IWS/IWT students at CEWAC (2 groups per semester)	Student course	Project presentation and general overview of results incl. demonstration of various welding technologies	CEWAC
76	end 2016	Article in AIHE (magazine dedicated to Walloon technological SMEs)	Publication in magazine	Publication on joining technologies for dissimilar materials incl. presentation of the Innojoin project	CEWAC
77	end 2016	Technical and summary report of the project	Report	Final summary of the project	BWI

8 Summary

The INNOJOIN project has opened a window of new opportunities for manufacturing hybrid components, by validating the proposed technologies for joining dissimilar sheet metals. Eight joining technologies were selected, classified into three types of welding processes:

- Resistance welding processes: resistance spot welding with process tape and resistance element welding.
- Friction welding processes: friction spot welding, friction stir spot welding and friction element welding.
- Other welding processes: electromagnetic pulse sheet welding, laser beam welding and arc element welding.

The proposed processes were examined in a structured way for three representative industrial dissimilar material combinations. For each joining technology and material combination, determination of the appropriate boundary conditions and process parameters and the evaluation of the advantages and disadvantages of the techniques were examined. This was done by means of destructive and non-destructive testing and corrosion analysis. Moreover, the joining processes were further developed in order to adapt the process to the selected material combinations.

Systematic and reliable knowledge and data has been created about the applicability of these promising new joining processes for industrial material combinations and applications. This allowed to compare the different joining processes and proposed a final ranking for each material combination, based on main benchmark criteria defined by the consortium.

The following joining processes exhibited the highest ranking for the investigated material combinations, based on the measured joint properties.

- Material combination 1 (aluminium EN AW 5182 - steel MS-W1200): friction element welding provided joints with the best mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, and quasi-static cross tension strength) and the highest corrosion resistance (in terms of lap shear strength after corrosion testing and corrosion sensitivity). However, poor visual appearance of the corroded joints was observed.
- Material combination 2 (aluminium EN AW 1050 - copper Cu-ETP R240): electromagnetic pulse sheet welding provided joints with the best mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, quasi-static cross tension strength, fatigue). In addition, it provided the highest corrosion resistance (in terms of lap shear strength after corrosion). However, it exhibited a higher corrosion sensitivity, compared to friction stir spot welding.
- Material combination 3 (high strength steel HCT780X - stainless steel H800): resistance spot welding with process tape provided joints with the best mechanical properties (in terms of quasi-static lap shear strength, lap shear strength under high strain rates, quasi-static cross tension strength and fatigue). However, it showed a higher corrosion sensitivity, compared to arc element welding.

In addition, a benchmark compared the used welding technologies with the following mechanical joining methods:

- Material combination 1 (aluminium EN AW 5182 - steel MS-W1200): Semi-tubular riveting provided joints with a high quasi-static lap shear strength. However, the joints had a low quasi-static cross tension strength, compared to resistance element welding, friction element welding and arc element welding.
- Material combination 2 (aluminium EN AW 1050 - copper Cu-ETP R240): Clinching resulted in joints with a low quasi-static lap shear strength and a low quasi-static cross tension strength, compared to resistance element welding, friction element welding and arc element welding.

Finally, demonstrators were manufactured at the end of the project, which demonstrated the investigated and applicable joining methods for each material combination. This project therefore aimed at enabling the individual companies to make a technically and economically justified decision on whether or not to implement one of the processes in their production. This research project was application-oriented, resulting in a better understanding of the process flexibility and allowing a rapid and fluent industrial introduction.