FRICTION STIR OVERLAP WELDING OF 2124 ALUMINIUM PLATE

W. Van Haver[1], A. Geurten[2], B. de Meester[3] and J. Defrancq[4]

[1] Belgian Welding Institute, Belgium
[2] CEWAC, Belgium
[3] UCL-PRM, Belgium
[4] Ghent University, Belgium

Abstract In this ongoing investigation, experimental results of friction stir welding (FSW) applied to high-thickness 2124 aerospace aluminium alloy are discussed. Flanges of 30 mm high are produced onto a 44 mm thick plate by two consecutive overlap welds in this non-fusion weldable material, followed by a final milling step. This approach results in significant material savings compared to the conventional production route, which consists of milling out the entire part starting from a high-thickness plate. Furthermore, the flanges built up by FSW consist fully of fine-grained material. Due to the nature of the processing route, the nugget zone of the first weld pass is partially reheated by the second weld pass. The influence of parent material temper (i.e., T851 or T4) on friction stir welding characteristics is studied; it is noted that in T4 temper, a significant increase in welding speed can be obtained compared to T851. The softer T4 temper also causes less danger of tool fracture, which allows incorporating more features to the pin and shoulder of the tool. During this investigation, the emphasis is put on microstructural characterisation and microhardness testing of various zones in the weld.

Keywords Friction stir welding; Light metals; Aluminium alloys; High thickness; Lap joints; Microstructure; Weld defects; Hardness; Aerospace

1 INTRODUCTION

1.1 Background

It is well established that aluminium alloys have a large potential in many industrial sectors (automotive, aerospace, construction, general engineering, packaging) due to their interesting properties, e.g. low density, good mechanical properties, good corrosion resistance and high thermal/electrical conductivity. However, the industrial use of certain aluminium alloys was somewhat inhibited, since these are considered difficult to join with conventional fusion welding techniques.

In the case of the high-strength Al-Cu (2xxx series) and Al-ZnMgCu alloys (certain 7xxx series alloys, such as 7075), the high tendency to hot cracking is problematic when conventional fusion welding processes causing shrinkage and stresses in the welded zone are applied. Successfully welding these alloys with MIG or TIG would require the use of filler material with a lower melting range than the parent material, combined with a sufficiently high strength. Filler materials that meet both requirements are not commercially available (with the exception of 2319 for welding of alloy 2219 [1]).

Because of this, highly hot crack sensitive alloys are generally joined in a purely mechanical manner (such as bolting and riveting), or parts are produced by milling the entire structure from a high-thickness plate. For these alloys in particular, "Friction Stir Welding" (FSW), a fully mechanical solid phase welding process, provides a solution. This technique was invented and patented in the early nineties by The Welding Institute (TWI, UK) [2].

The basic principle of this process is to soften the material by frictional heat generated between the material surfaces and a rotating tool. In the classic butt joint set-up, the components to be joined are rigidly clamped on a backing plate. A rotating tool, consisting of a profiled pin and a shoulder, is forced down into the material until the shoulder meets the surface of the workpieces. The material in the close surrounding of the tool is thereby frictionally heated to temperatures where it is easily plasticized. As the tool moves forward, material is stirred from the leading to the trailing edge of the pin. Behind the pin, the joint is formed – see Figure 1 on the left. A distinction is made between the advancing side of the weld (side where the tool rotation direction is the same as the welding direction), and the retreating side (side where the tool rotation direction is opposite to the welding direction), as also indicated on Figure 1 on the left.

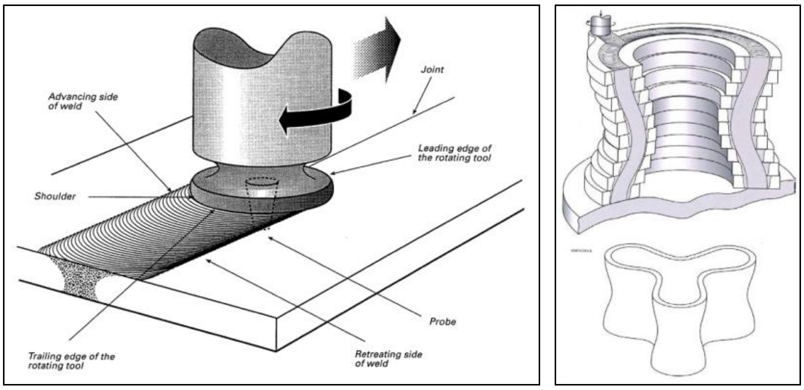


Figure 1. Schematic representation of (left) friction stir butt welding process [3], and (right) Pro-Stir™ technique [4]

By all means, an analogous approach as in friction stir butt welding can be used for the realization of lap joints. Pro-Stir™ is a near-net shape manufacturing technique using friction stir overlap joints, developed by The Welding Institute. It concerns the build-up of a structure by repeated lap welding of sheets or plates, followed by machining (Figure 1 on the right). This technique allows:

- the build-up of structures which would otherwise necessitate, using other techniques (fusion welding, machining, forging), a great degree of material loss in order to produce the desired structure;
- the manufacturing of complex structures which are difficult/impossible to produce with conventional techniques.

Only very little practical examples could be identified so far in literature, e.g. build up of flanges in Ti-6Al-4V alloy [5], and complex-finned aluminium heat exchangers, created by a combination of abrasive waterjet cutting, friction stir lap welding and CNC machining [6].

1.2 Application

The application envisaged for the current study concerns the production of complex aerospace wing elements, which are currently produced as deeply machined parts – see Figure 2.

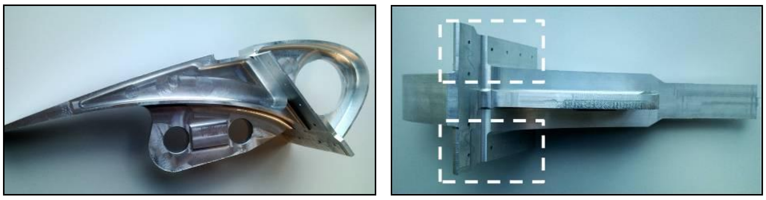


Figure 2. Photographs of the deeply machined aerospace part. Left: side view; right: top view (note the vertical flanges, indicated by the white rectangles)

In this investigation, the build-up of the 30 mm high flanges (Figure 2 on the right) is produced by FSW. Given the fact that overlap welding 30 mm 2124 material in one welding pass is not possible with the FSW equipment available at CEWAC (see §2.1), the flanges are built up by friction stir overlap welding two 17 mm thick 2124 material plates onto a 44 mm thick base plate (in order to make abstraction of the rest of the piece), as follows:

- the first 17 mm thick “flange plate” is overlap welded onto the base plate (Figure 3 – A);
- after welding, the top 2 mm of the weld is removed by milling;
- one week after realization of the first weld pass, a second 17 mm thick flange plate is overlap welded onto the previous weld pass (Figure 3 – B).

In actual production, machining would be carried out in order to obtain the final desired dimensions of the part (Figure 3 – C and D). This way, the flange will consist, after milling, fully of recrystallised material – see also weld *T8-2-0* in Figure 7.

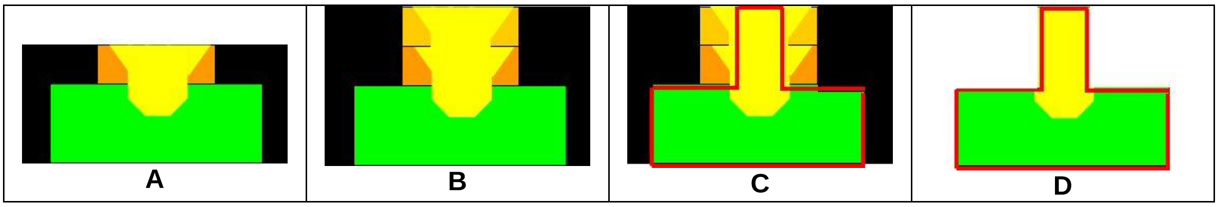


Figure 3. Schematic processing route for the production of flanges in 2124 material

It is clear that this production route can be considered an application of Pro-Stir™. The main potential advantages of the new processing route that can be recognized for this case are:

- Very significant material savings compared to the current production route (estimated to 40-50%);
- Time savings (hence economical benefits);
- Economic alternative for casting, forging or linear friction welding;
- No available alternative in fusion welding processes such as MIG, TIG, (hybrid) laser welding or electron beam welding given the aforementioned high proneness to hot cracking of 2124 alloy.

1.3 Parent material

EN AW-2124 aluminium alloy is in the EN 573-3 standard also indicated by means of chemical symbols as EN AW-Al Cu4Mg1(A). It is a heat treatable wrought alloy, with Al_2CuMg as the main precipitation hardening component. 2124 alloy was delivered as large rolled plates with a thickness of 44 mm (used as base plate) and 26 mm (used for the build-up of flanges), in the T851 temper according to EN 515. In Table 1, the chemical composition of the parent materials is given.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
EN 573-3	0.20 max.	0.30 max.	3.8 – 4.9	0.30 – 0.9	1.2 – 1.8	0.10 max.	0.25 max.	0.15 max.	0.15 max.
Certificate 26 mm	0.03	0.07	4.00	0.56	1.28	0.00	0.01	0.02	0.02
Certificate 44 mm	0.03	0.07	4.11	0.61	1.28	0.00	0.02	0.03	0.02

Table 1. Chemical composition of 26 and 44 mm 2124 material compared to EN 573-3

T851-temper is the state in which the 2124 alloy was originally supplied. This temper designation applies to material which has been solution heat treated, stress relieved by stretching to a controlled amount (permanent set 1.5 to 3% for plate) and then artificially aged. Products receive no further straightening after stretching. 2124 alloy is mostly used in this temper, as it then possesses good toughness and strength and optimum machinability.

Within the investigation, part of the 2124-T851 material was subjected to a T4 heat treatment, which corresponds to solution heat treating and water quenching (performed in accordance with the specifications in AMS 2772C), followed by natural ageing during at least 1 month. Tensile properties of both base plate and flange plate material in T851 and T4 material (executed according to EN 485-2) are given in Table 2. Clearly, the T4 heat treatment has a large influence in terms of yield strength and elongation after fracture; the tensile strength on the other hand is only marginally affected.

Material	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation A_{50} [%]
2124-T851 (26 mm, certificate)	449 ± 6	486 ± 5	11.2 ± 0.3
2124-T851 (26 mm, BWI)	454 ± 2	495 ± 1	12.8 ± 0.8
2124-T851 (44 mm, certificate)	448 ± 1	491 ± 1	10.8 ± 0.2
2124-T851 (44 mm, BWI)	450 ± 1	494 ± 2	10.6 ± 1.0
2124-T4 (26 mm, BWI)	291 ± 1	450 ± 1	28.5 ± 0.9
2124-T4 (44 mm, BWI)	306 ± 2	473 ± 2	24.5 ± 0.3

Table 2. Tensile test results of 2124-T851 and 2124-T4 parent material

The plates were sawn to appropriate dimensions, followed by milling down to the correct thickness. The final dimensions for welding are:

- for the base plate: 400 mm long (parallel with rolling direction), 155 mm wide and 44 mm thick;
- for the flange plates: 400 mm long (parallel with rolling direction), 65 mm wide and 17 mm thick.

2 FSW JOINT REALISATION

2.1 FSW equipment

The friction stir welding experiments were executed by CEWAC on an ESAB SuperStir™ FSW 53 STL machine. This equipment, capable of carrying out FSW both in position control or in force control, is suited for linear welding only. It allows to weld conventional (e.g. 6xxx series) aluminium alloys in thickness from 2 mm up to 30 mm. The clamping system which was used for the processing route (described in §1.2) is shown in Figure 4: the base plate (1) is bolted directly to the machine table with the clamping system (A), which assures a good clamping between the flange plate (2) and the base plate (1). After realization of the first weld pass and machining off the top 2 mm from the first flange plate, clamping system (A) is replaced by clamping system (B) for welding the second flange plate. In order to avoid generation of excessive heat in the parts, a water cooled clamping system was used. Furthermore, the tool holder was cooled with a mixture of 65% water and 35% glycol, with a maximum flow rate of 5.5 l/min.

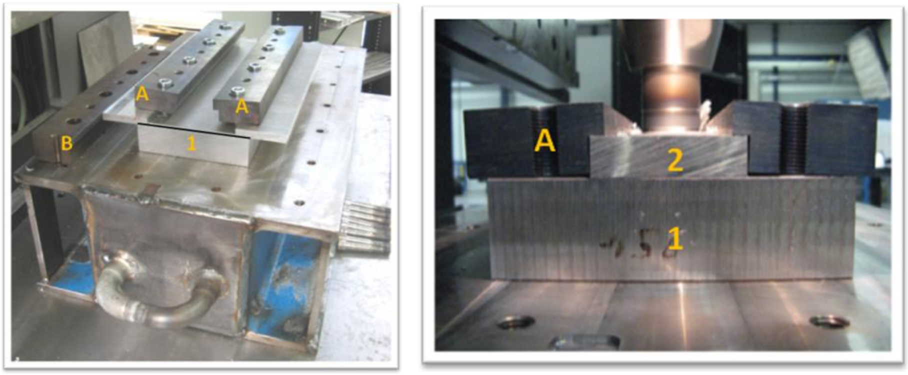


Figure 4. Experimental setup of the backing plate and clamping equipment

2.2 FSW parameters

Weld lengths of 320 mm were realized on the workpieces with dimensions already specified in §1.3. The welding parameters (in force control) used for this investigation are summarized in Table 3. Note that the first two digits of the designations indicate the temper of the parent material, the second digit mentions the number of weld passes, and finally the third digit gives the “tool number”.

Designation	Temper	# passes	Tool geometry (*)	Welding speed [mm/min]	Rotation speed [rev/min]	Plunge force [kN]	Tilt angle [°]
T8-1-0	T851	1	St. 1 (tool 0)	5	200	30-31	1.5
T8-2-0	T851	2	St. 1 (tool 0)	5	200	26	1.5
T4-2-08	T4	2	St. 1 (tool 0)	5	200	32.5-30	1.5
T4-1-0	T4	1	St. 1 (tool 0)	60	300	62.5	1.5
T4-2-0	T4	2	St. 1 (tool 0)	60	300	55-62.5	1.5
T4-2-1	T4	2	St. 2 (tool 1)	55	300	55-65 40-65	1.5
T4-2-2	T4	2	Triflat™ (tool 2)	55	300	55-65 40-55	0
T4-2-3	T4	2	Triflute™ (tool 3)	55	300	52.5-65 55-52.5	0

Table 3. Welding parameters of the current investigation; (*) see Table 4

All tools were made from “QRO 90 Supreme” Cr-Mo-V alloyed hot-work tool steel [7], hardened to HRC 55. Further data about the tool geometry are included in Table 4.
In 2124-T851 material, it was very hard to achieve welds without tool fracture (occurring at the base of the pin, near the shoulder). For that reason, the welding speed could not be increased above 5 mm/min. Moreover, it was not possible to include more tool features than an unprofiled concave tool shoulder and a conical threaded pin: other features such as shoulder spirals or pin flutes made the tool weaker, and fracture became more likely to occur.
Intentionally, one weld in 2124-T4 material (designated *T4-2-08*, with the “8” at the end indicating that the same welding parameters as for 2124-T851 were used) was performed with comparable parameters as those used for 2124-T851. In 2124-T4 parent material, the welding speed could be increased significantly

without tool fracture (by a factor of more than 10: e.g. compare *T4-2-0* with *T8-2-0*). This led to believe that it would become possible to use more advanced shoulder and pin geometries.

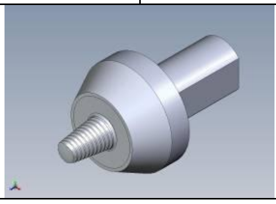
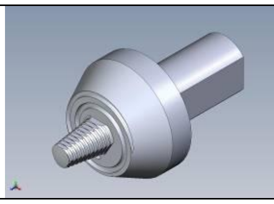
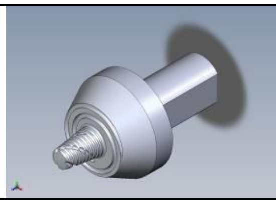
	"Standard" tools		**Triflat™ tool**	**Triflute™ tool**
	Tool 0	***Tool 1***	***Tool 2***	***Tool 3***
Drawing				
Ø shoulder [mm]	35			
Tool shoulder angle [°]	*St. 1:* 1.5 *(concave)*	*St. 2:* 1.5 *(concave)*	0	0
Shoulder features	/		spiral machined with Ø 2.5 mm ball-shaped tool	spiral machined with Ø 2.5 mm ball-shaped tool
Ø pin [mm]	15 *(shoulder)* 10 *(extremity)*			
Pitch of thread [mm]	1.5	2	2	2
Pin features	/		3 flats @ 120° 0.75 mm below pin surface	3 threads with 35 mm pitch
Pin length [mm]	20			

Table 4. FSW tool geometry data

It should be noted that for the welds *T4-2-1*, *T4-2-2* and *T4-2-3* the welding speed and rotation speed were intentionally kept the same, in order to allow for a comparison between three different tool geometries.
Welds *T8-1-0* and *T4-1-0* were performed for comparison with *T8-2-0* and *T4-2-0*, respectively – this was done in order to check whether the realization of a second weld pass had an influence on the base plate characteristics (more precisely: on the microhardness). For all double-pass welds, the second weld pass was realized at least one week after performing the first weld pass.

3 PARENT MATERIAL AND JOINT CHARACTERISATION

3.1 Methods of characterisation

All parent materials and welds were subjected to metallography and microhardness testing. No test specimens were extracted from the first or the last 50 mm of weld length, in accordance with ISO/DIS 25239-4. Two metallographic samples were extracted from each weld, which were examined microscopically after etching with Keller's modified (consisting of 1 ml 38-40% HF, 1.5 ml 37% HCl, 10 ml 70% HNO_3 and 100 ml water) etchant using a Zeiss-Axioskop 2 optical microscope, equipped with an AxioCam Mrc5 digital colour camera and the AxioVision image processing programme. The metallographic samples were 65 mm wide – the width of the flange plates – and 61 mm or 76 mm high, which corresponds with the thickness of the base plate and 1 or 2 weld passes, respectively. It should be noted here that etching was very difficult for the welds *T8-1-0*, *T8-2-0* and *T4-2-08* (all executed with a very high input): a strong attack of the parent material occurred, whereas the weld nugget was hardly affected. For that reason, the nugget area was embedded separately and re-etched, which did make grain boundaries visible.
HV0.2 microhardness profiles were performed on all metallographic samples, using a Struers Duramin A300-D automatic hardness indenter, with a 27 s indentation time and 0.3 mm spacing between individual indentations. A horizontal microhardness profile was made 1.5 mm below the base plate upper surface (see path *H* in *T4-2-0* in Figure 7), while a vertical microhardness profile was carried out through the weld middle (path *V* in *T4-2-0* in Figure 7). The hardness profile extended through the entire metallographic sample, in order to measure unaffected parent material hardness as well.
In all weld macro- and micrographs as well as in all microhardness profiles, the advancing side (AS) is displayed on the left, and the retreating side (RS) on the right.

3.2 Parent material observations

The result of optical microscopy on the 2124-T851 and 2124-T4 parent materials, as well as microhardness values, are shown in Figure 5. The displayed microhardness values are based on at least 20 individual microhardness measurements performed throughout the thickness of each parent material sample. The standard deviation is also mentioned. It can be derived that the T4 heat treatment has only a minor effect on the microhardness when compared to the original T851 temper, which indicates that the microhardness follows the same tendency as the tensile strength of the parent materials (Table 2). Furthermore, the base plate material and the flange plate material of the same temper have the same microhardness.

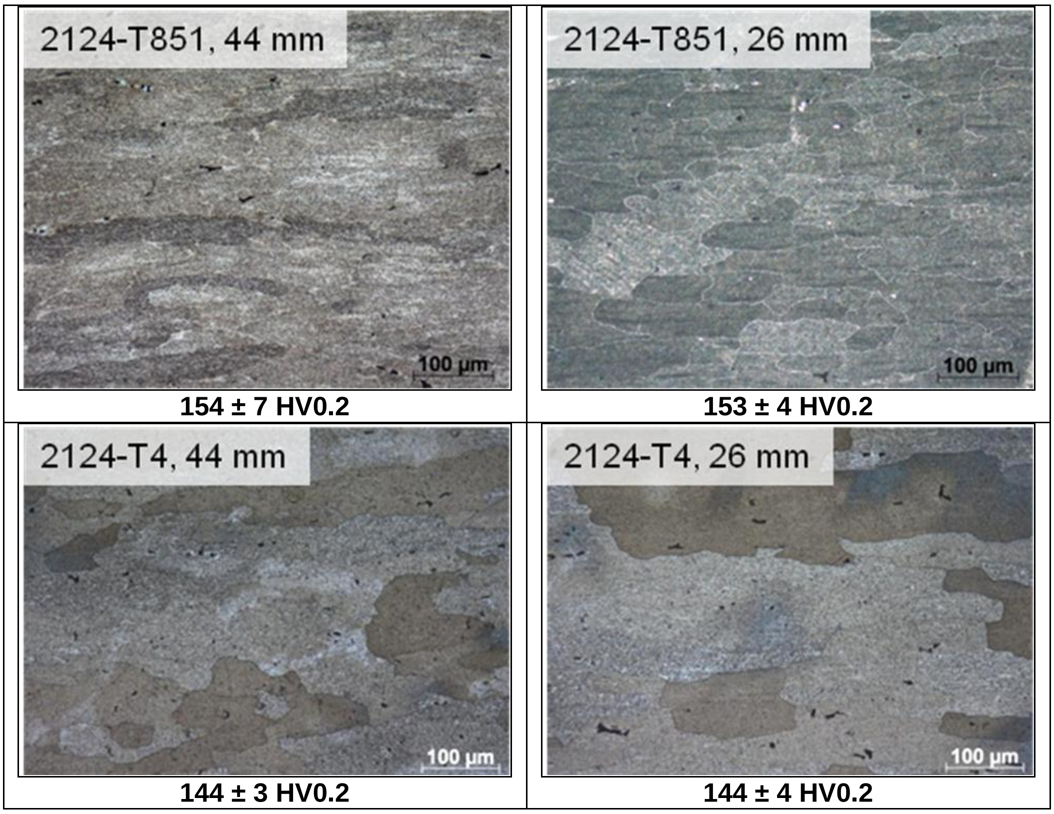


Figure 5. 2124 parent materials microstructure and HV0.2 microhardness

3.3 Weld microstructure observations

Macrographs of the various welds included in this investigation (see Table 3) are shown in Figure 7. No voids (tunnel defects or other) were found in the two welds in 2124-T851. In weld *T4-2-08* on the other hand, small voids were visible on the advancing side near the face of the second pass – this is the region where defects, assuming that they are present, tend to appear. An example of these voids – which are sometimes surface-breaking near the start of the weld – is shown in Figure 6.

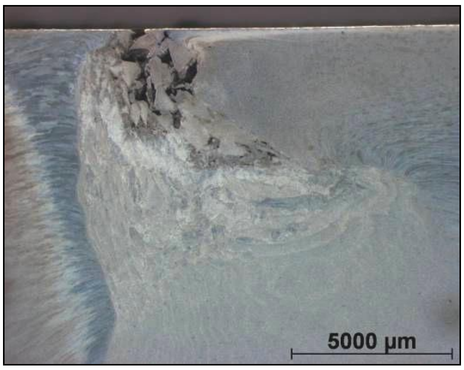


Figure 6. Macrograph of voids on AS of second pass in weld *T4-2-0* (as an example)

The only weld in 2124-T4 where these voids were not observed in either of the two metallographic samples extracted from each was *T4-2-2* (in other words: the weld realised with the Triflat™ tool). Furthermore, the nugget shape of that weld is somewhat different: it has a more of a “chalice”-like shape with relatively straight edges, whereas the nugget shape of the other welds is more rounded-off.

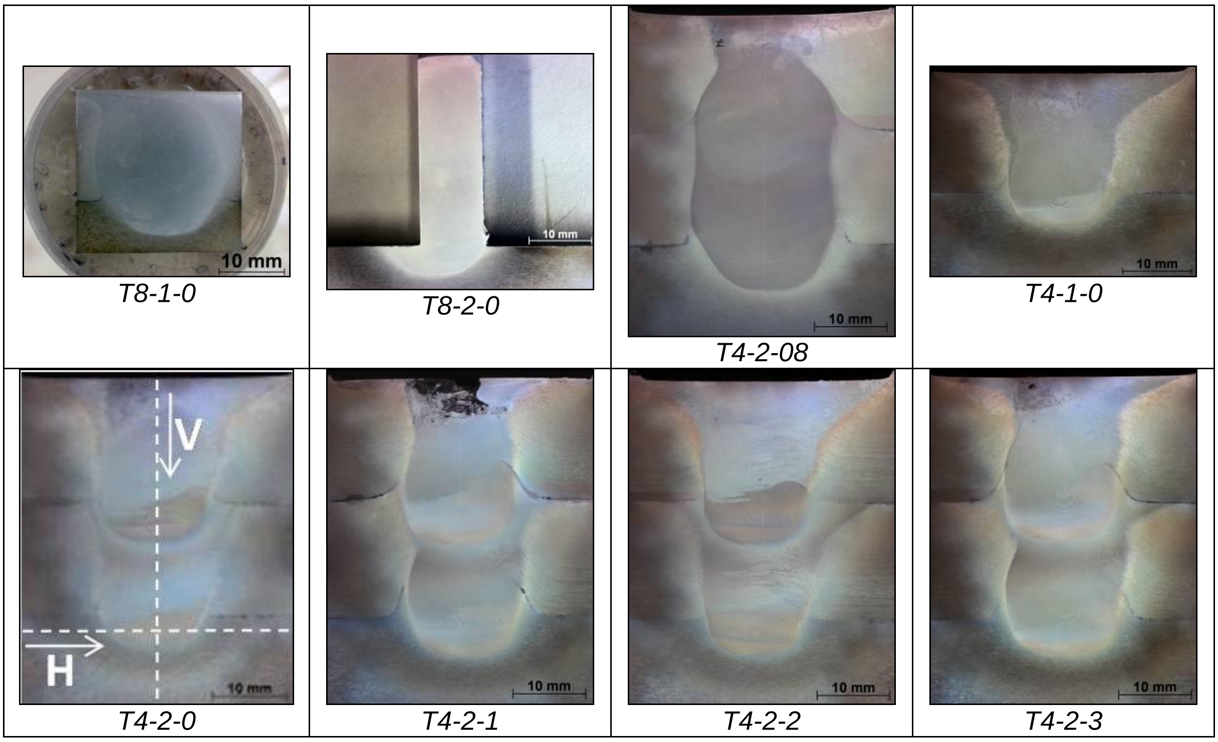


Figure 7. Etched macrographs of the joints included in this investigation

Furthermore, the metallographic samples were subjected to microstructural investigation. Some details are shown in Figure 8. Despite large differences in welding speed, hence heat input (*T8-2-0* and *T4-2-08* compared to e.g. *T4-2-2*), the nugget grain size is very fine compared to the parent material grain size (see Figure 5) and of the same order of magnitude in all cases, namely around 2-5 µm (see Figure 8). Due to the heat treatment that the first weld pass has undergone during the realisation of the second weld pass, grain boundaries become hard to distinguish. However, no significant coarsening seems to have taken place in the nugget of the first weld pass.

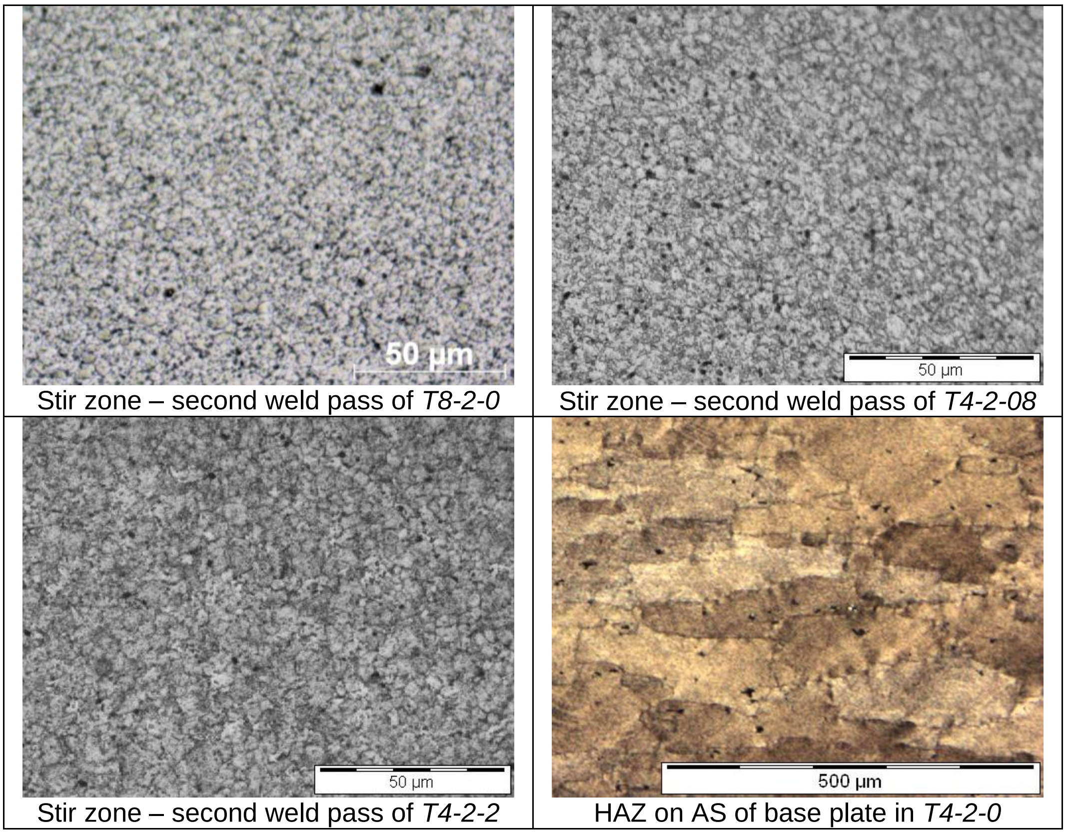
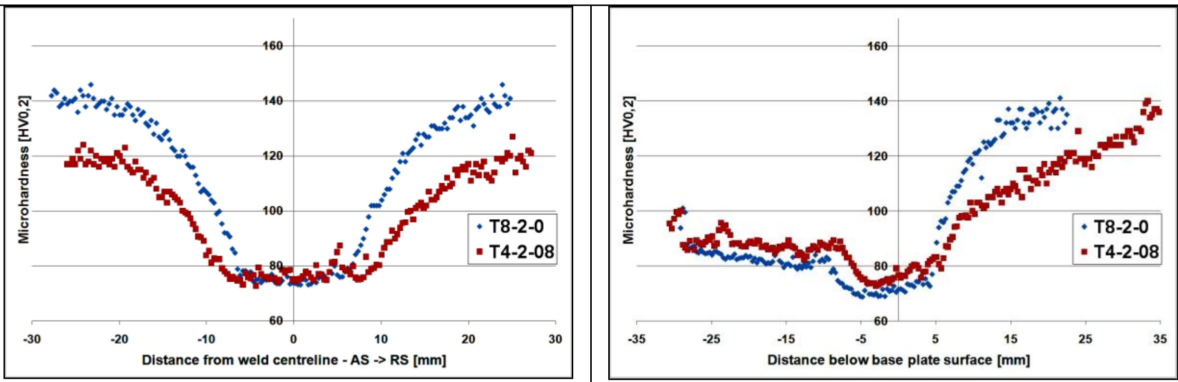


Figure 8. Selected etched microscopic details

3.4 Microhardness results

3.4.1 Microhardness results: welding with very high heat input

Figure 9 gives the horizontal and vertical hardness traverses (refer to *H* and *V* in Figure 7, sample *T4-2-0*) for the 2 two-pass welds carried out with a very low welding speed.



Horizontal profiles | Vertical profiles

Figure 9. HV0.2 microhardness profiles for welds *T8-2-0* and *T4-2-08*

The following general tendencies are noted:

- Horizontal profiles:
  - For both welds, the nugget hardness in the base plate is more or less comparable, namely around 75 to 80 HV0.2. This could signify that, due to the very high heat input, the nugget material is put in more or less the same metallurgical state in terms of precipitation; moreover it was already indicated in §3.3 that the nugget grain size is more or less comparable.
  - In *T8-2-0*, the minimum is reached in the stir zone (located between -7 mm and +7 mm from the weld centreline). Moving out of the stir zone, towards the HAZ goes along with a hardness increase. The 2124-T851 parent material hardness (around 154 HV0.2) is still not reached at 30 mm from the weld centreline.
  - In *T4-2-08* on the other hand, the width of the hardness minimum is wider than the nugget width, indicating that the hardness of the HAZ immediately next to the nugget is comparable to that of the nugget itself. At 30 mm away from the weld centreline, the hardness is still significantly lower than that of 2124-T4 parent material (which was equal to 144 HV0.2). The hardness increase in the HAZ moving away from the nugget of *T4-2-08* is slower than in *T8-2-0*.
  - Some asymmetry can be noticed in both cases: the hardness increase moving away from the nugget is somewhat steeper on the advancing side than on the retreating side of the joint.
- Vertical profiles:
  - The nugget hardness of weld *T4-2-08* is consistently some 5-10 HV0.2 higher than that of weld *T8-2-0*. In both cases, the absolute hardness minimum occurs in the first weld pass, namely in the HAZ of the second weld pass (which lies in the first weld pass). In both cases, the nugget hardness in the second weld pass increases slightly towards the face of the weld.
  - As in the horizontal hardness profile, the hardness increase in the HAZ moving away from the nugget of *T4-2-08* is slower than in *T8-2-0*.

3.4.2 Microhardness results: influence of tool geometry in 2124-T4

In Figure 10, the hardness profiles are given of all four double-pass friction stir welds in 2124-T4, executed with more or less the same welding speed and rotation speed but with different tool designs.
The following can be noted:

- Horizontal profiles:
  - First of all, the attention should already be drawn to the significantly different shape of the horizontal hardness profiles. In the current case, the nugget hardness (between 115 and 125 HV0.2) lies between the minimum hardness, noted in the HAZ close to the nugget (of which a micrograph is shown in Figure 8 on the lower right) with a value around 95-100 HV0.2 for the different profiles, and that of the parent material with values between 140 and 160 HV0.2.
  - Only small, possibly insignificant differences can be noted for the different tool in terms of nugget hardness (within the order of 10 HV0.2), with sometimes a rather high scatter.
  - The width of the HAZ is more or less the same for all four welding tools: the parent material hardness is reached at some 20 mm away from the weld centreline.

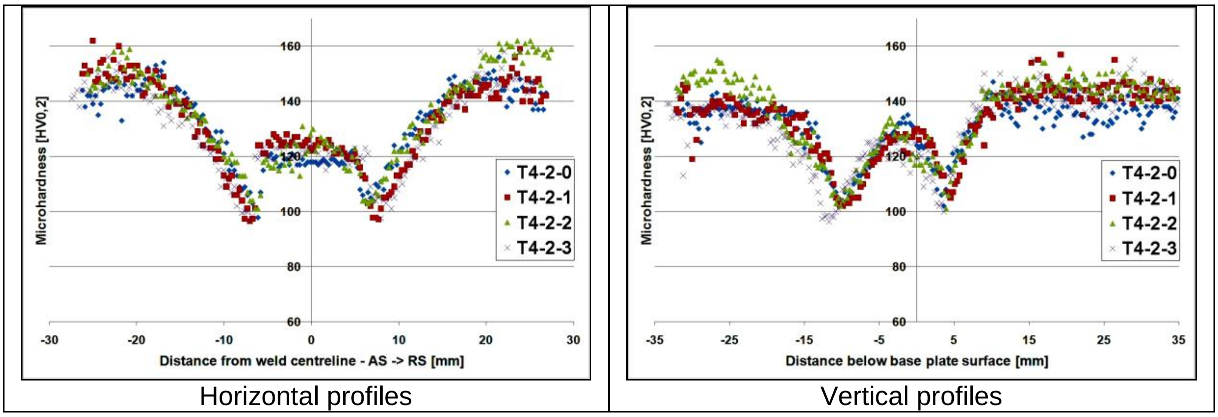


Figure 10. HV0.2 microhardness profiles for the four different FSW tools on 2124-T4

- Vertical profiles:
  - The steep hardness drops near the weld face (around -30 mm in the graph) can be explained by the fact that in three of the four welds, areas with voids occurred, as shown in Figure 6 – this was only not the case for weld *T4-2-2*. In the latter weld, high nugget hardness values of the same order as 2124-T4 parent material are found near the weld face.
  - Starting from 20 mm above the base place and moving "inward", the four profiles share the same tendencies: a significant hardness drop occurs in the HAZ of the second weld pass, which is also more or less comparable as the hardness drop occurring in the HAZ of the first weld pass – i.e., in the base plate. This minimum hardness is around 100 HV0.2 which is 25 HV0.2 higher than the minimum value found in *T4-2-08* (Figure 9). Between the HAZ hardness minima, a local maximum occurs in the nugget of the first weld pass which corresponds to a hardness value between 130 to 135 HV0.2. A hardness value of 140 HV0.2 is already reached at some 10 mm below the base plate surface.

3.4.3 Microhardness results: influence of second weld pass

It was found interesting to check the influence of the realisation of the second weld pass on the hardness of the first weld pass, and also to see whether the realisation of the second weld pass had an influence on the base plate hardness evolution. For that cause, Figure 11 gives the horizontal and vertical hardness traverses of *T8-1-0*, *T8-2-0*, *T4-1-0* and *T4-2-0*. As shown in Table 3, these welds were performed using a tool with the same geometry, but with significantly different welding parameters and a different parent material temper. The influence of these significantly different welding parameters on the hardness evolution in the joint has already been mentioned in §3.4.2, and the same observations can be made in the present paragraph.

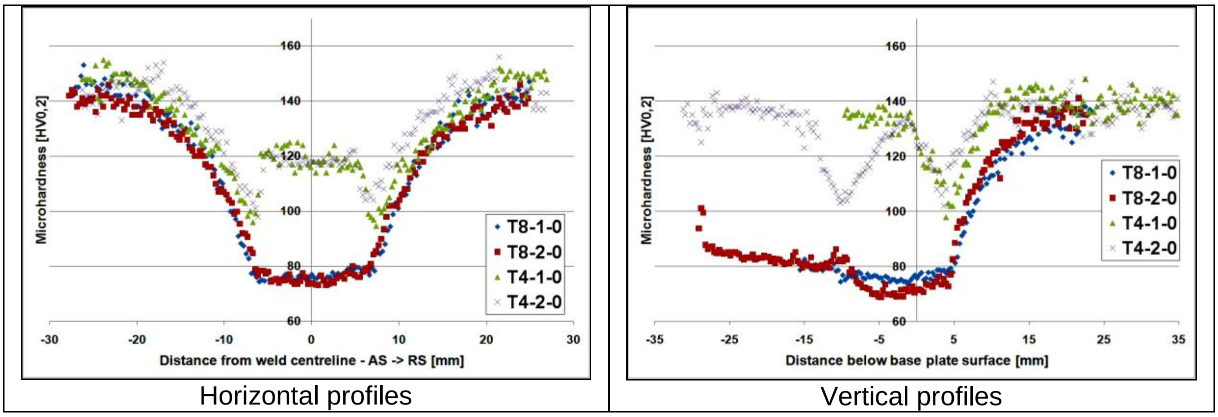


Figure 11. HV0.2 microhardness profiles: influence of second weld pass

The main observations that can be made by comparing *T8-1-0* with *T8-2-0* on the one hand, and *T4-1-0* with *T4-2-0* on the other hand are the following:

- Horizontal profiles:
  - In the 2124-T851 welds, the hardness profiles are very comparable. For that reason, it can be stated that the realisation of the second weld pass has no notable influence on the hardness evolution in the base plate.
  - The same reasoning seems valid for the 2124-T4 welds in the nugget region; however, the base material hardness is more readily reached in the two-pass weld compared to the single-pass weld.

This might indicate that in the HAZ of the base plate, there is still a potential for artificial ageing during the short thermal cycle due to the realisation of the second weld pass.

- Vertical profiles:
  - In the 2124-T851 welds, the realisation of the second weld pass seems to soften even more the part of the first weld pass nugget which lies in the HAZ of the second weld pass: the minimum hardness decreases from 75 HV 0.2 to 70 HV0.2 due to the realisation of the second weld pass. It can be noted that the nugget hardness of the second weld pass in *T8-2-0* is higher than the nugget hardness of the first weld pass in *T8-1-0*. The HAZ hardness in the base plate evolves more or less in the same way for the two welds.
  - For the 2124-T4 welds, the nugget hardness in the first weld pass of *T4-1-0* is more or less comparable to the 2124-T4 parent material. The realisation of a second weld pass (*T4-2-0*) creates a HAZ with comparable hardness development (i.e. rate of hardness decrease, value of hardness minimum and rate of hardness increase) as that already created in the base plate. The nugget hardness of the second pass in *T4-2-0* is very comparable to that of first pass in *T4-1-0*.
    The same tendency in terms of HAZ hardness development in the base plate (i.e. the somewhat faster attainment of the parent material hardness in *T4-2-0* compared to *T4-1-0*) can be noted as for the horizontal hardness profiles in these welds.

3.5 Interface properties and depth of penetration as a function of tool geometry

Specifically for the friction stir welds in 2124-T4, the depth of penetration as well as the dimensional “interface properties” were measured, based on the macrographs – see Figure 12. The way these distances were measured is indicated in the top left figure of Figure 12. All data indicated in the graphs are based on measurements of two separate metallographic samples. The following observations were made:

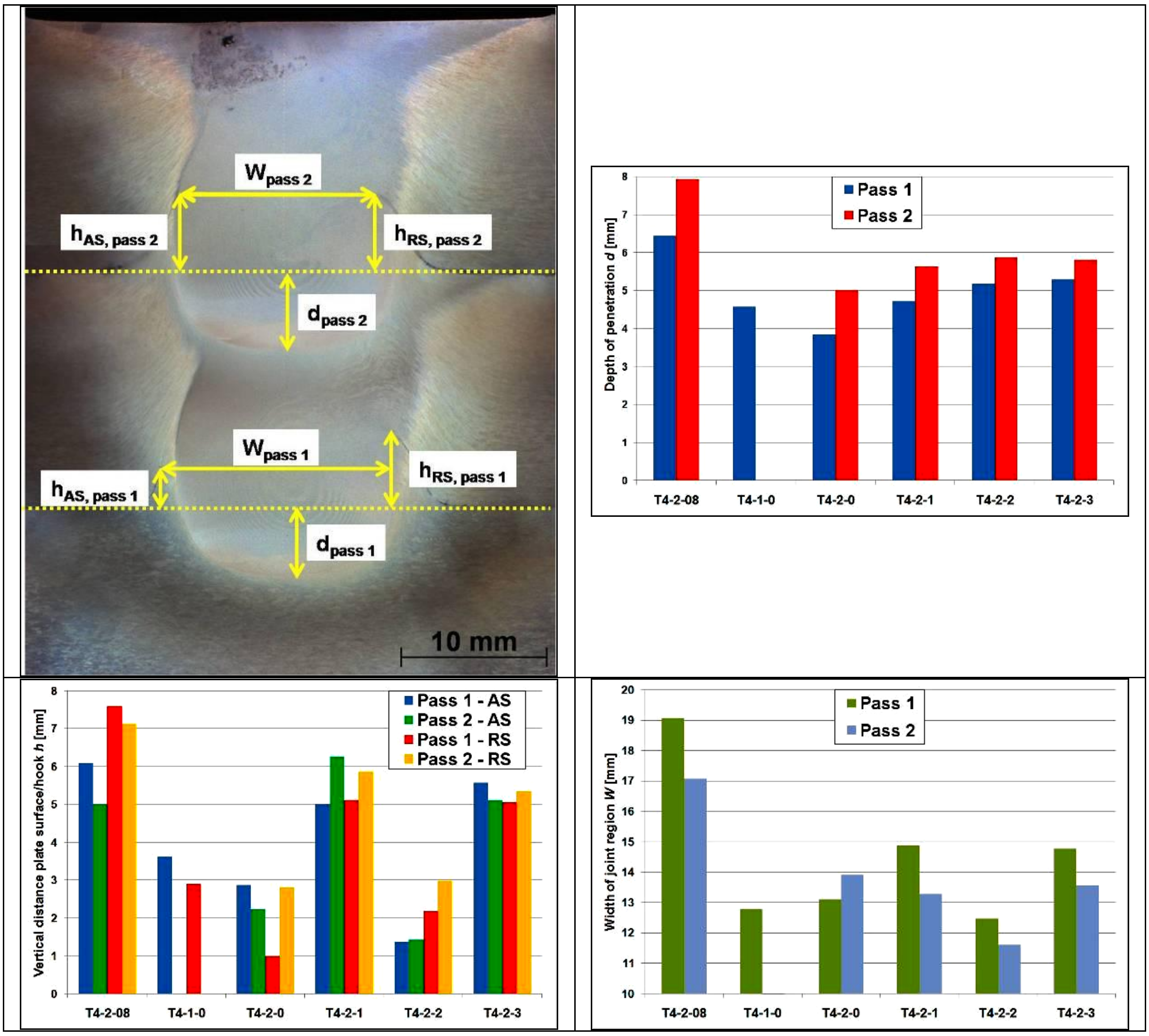


Figure 12. Depth of penetration and interface properties in 2124-T4 welds

- *d* (maximum depth under the surface of the underlying plate where recrystallised material is found)
  - The penetration depth is clearly the highest for the weld realised with the lowest welding speed (*T4-2-08*), which is most likely due to the much higher heat generation, causing easier penetration.
  - More or less comparable penetration depths are found for the welds performed with the four different tool geometries and comparable welding parameters.
  - In all cases, the penetration depth of the first weld pass is lower than that of the second weld pass. Most probably, this is due to the fact that the heat can escape much more easily in the massive base plate during the realisation of the first pass, while during the second weld pass the heat will mainly escape through the lower thickness flange plates. Additionally, the base plate possesses a higher hardness during the realisation of the first weld pass than the first flange plate during the realisation of the second weld pass.
- *h* (distance that the hook extends in the flange material in vertical direction)
  - The highest *h*-values are found for *T4-2-08*, which must be related to the much lower welding speed. This assumption is justified when comparing these with *T4-2-0*, executed with the same tool geometry but at a 12 times higher welding speed.
  - For the welds executed with different tool geometries but comparable welding parameters, the the h-value is the lowest for both tool 0 (standard tool 1) and tool 2 (Triflat™), and the highest for both tool 1 (standard tool 2) and tool 3 (Triflute™).
  - No consistent tendencies could be found in terms of *h*-value for the first and second weld pass, nor for the advancing or retreating side.
- *W* (width of the joint region)
  - The highest heat input condition resulted in the largest joint width.
  - The narrowest joint width is found for weld *T4-2-2*; this is due to the fact that in this Triflat™ weld, hooking on the retreating side extends quite deeply in the horizontal direction.
  - With the exception of weld *T4-2-0*, the largest joint width is noticed in the first weld pass.
  - In all conditions, the joint width is higher than 10 mm, which means that a flange of 10 mm can easily be machined out of the structure without exposing cracks to the surrounding.

4 CONCLUSIONS

By the present work, which is part of an ongoing investigation, the authors have indicated the possibilities for the realisation of flanges in high thickness EN AW-2124 aerospace aluminium alloy by means of consecutive friction stir overlap welds. At this stage of the investigation, especially the importance of parent material temper becomes clear: the use of an appropriate “welding temper” allows a higher productivity on the one hand, and the use of more advanced tool geometries without risking tool pin fracture on the other hand. These more advanced tool geometries might lead to a further increase in productivity, but they have especially an influence in the generation (or avoidance) of joining defects. An optimum tool geometry at this point seems to be the Triflat™ tool: this tool allows to achieve sound welds in this material without the creation of voids. For the current application, the disadvantage of significant hooking on the retreating side in the horizontal direction encountered with this tool is of less significance, as a flange of 10 mm can still easily be machined out of the structure without exposure of this hooking to the surrounding.
In this ongoing investigation, future attention will go out to post-weld heat treatments, corrosion properties, microtensile tests and fracture mechanical testing of flanges.

5 ACKNOWLEDGEMENTS

The authors wish to thank the Belgian Science Policy, which funded the research of the TAP2 project "Innovative joining of critical aluminium structures with the friction stir welding technique" (CASSTIR – P2/00/02) within the "Programme to stimulate knowledge transfer in areas of strategic importance". Furthermore, they are grateful to Aleris Aluminum Koblenz GmbH, Corus RD&T and Sonaca S.A., and all colleagues from the BWI, CEWAC, UCL-PRM and UGent which have contributed in the experimental work.

6 REFERENCES

[1] G. Mathers, The welding of aluminium and its alloys, Woodhead Publishing ISBN 1 85573 567 9, September 2002, 248 pages
[2] W.M. Thomas et al., Friction Stir Butt Welding, International Patent Application PCT/GB92/02203, GB Patent Application 9125978.8, 6 Dec. 1991
[3] W. M. Thomas et al., Friction stir welding for the transportation industries, Materials & Design 1997, Vol. 18, Nos. 4 6, pp. 269-273
[4] W.M. Thomas et al., Developments in Friction Stir Welding, ASM Materials Solutions 2003 Conference & Exposition, 13-15 October 2003 Pittsburgh, Pennsylvania, USA

[5] C. Wiesner et al., Joining and Near-Net Shape Manufacturing processes, presentation at www.specialmetalsforum.com/doc/download/7
[6] http://lyle.smu.edu/rcam/rcamweb/fswrp.htm
[7] http://www.uddeholm.be/french/files/Uddeholm_QRO_90_Supreme_E2.pdf
[8]

