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REPORT

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Qualification of the hybrid metal extrusion & bonding (HYB) process for welding of aluminium offshore structures

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Abstract
In the present investigation the aptness of the HYB process for butt welding of 4mm AA6082-T6 profiles is evaluated and benchmarked against one gas metal arc (GMA) weld and one friction stir (FS) weld, representing best practice for both methods. The tensile testing shows that the yield strength of the HYB weld exceeds that of the GMA weld and is comparable with that of the FS weld. When it comes to impact toughness the HYB weld is the superior one of the three. Since the subsequent transverse bend testing did not reveal any evidence of bonding defects or crack formation, it means that the 4mm AA6082-T6 HYB butt weld meets all acceptance criteria being specified by Equinor for offshore use.

KEYWORDS
hybrid metal extrusion & bonding, Al–Mg–Si alloys, solid-state joining, mechanical testing, qualification for offshore use

1 | INTRODUCTION

The hybrid metal extrusion & bonding (HYB) process is a patented solid-state joining method for metals and alloys being developed at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.[1–3] It is based on the principles of continuous extrusion, where the so-called PinPoint extruder is the core of the invention.[4,5] In the HYB case the best features of friction stir welding (FSW) and gas metal arc welding (GMAW) are combined by allowing solid-state joining to be performed through aluminium filler metal (FM) additions along with the use of an appropriate groove or joint design.[6–9] Over the years the method has evolved into a multifunctional joining process handling a wide range of joint configurations (butt, fillet, lap and slot welds) and base metal combinations (Al, Fe, Ti and Cu).[4,10–14]

However, in order to attract the attention of potential industry users, its superiority must first be documented through extensive benchmark testing against well-established commercial joining methods for aluminium such as GMAW and FSW. As far as technology readiness level (TRL) is concerned, the HYB process has already passed TRL 4 (validation of the technology in the laboratory) and is now at TRL 5. Entering this phase means that the technology needs to be qualified for industrial use under conditions which apply to testing of real aluminium structures. Therefore, qualification of HYB for offshore applications is a good case for highlighting the current status of the technology development, particularly when it is realized that the benchmarking is done against best practice for GMAW and FSW by a competent end-user as Equinor.

2 | QUALIFICATION TEST REGIME FOR WELDED ALUMINIUM OFFSHORE STRUCTURES

In offshore structures aluminium is sometimes used in replacement of steel to achieve weight reductions. However, because aluminium and in particular aluminium welds exhibit a low fatigue strength,[15–19] the material is only a realistic alternative to steel in cases where design against fatigue failure is not an issue. Living quarters in aluminium for offshore applications are examples of light-weight offshore structures that are not subjected to fatigue loading, where current practice implies that both GMAW and FSW are employed during the assembling stage.

The living quarter topside being installed on the Johan Sverdrup oil platform in the North Sea is partly made up of extruded profiles of the AA6082-T6 type. They have a nominal chemical composition of about 0.65 wt% Mg - 1.00 wt% Si - 0.50 wt% Mn - 0.20 wt% Fe - 0.03 wt% Cu - 0.02 wt% Ti - Al (balance) and display yield and ultimate tensile strength values in the range from 310-320 and 335-350 MPa, respectively in the T6 temper condition.[20] In the present study, one 4mmthick GMA butt weld (produced using AA5183 filler metal additions) and one 4mmthick FS butt weld, which stem from the production of the Johan Sverdrup living quarter topside structure, have been selected for the HYB benchmarking. They represent best practice for both methods in the sense that the applied welding procedures ensure weld properties that comply with the mandatory specifications listed in Table 1.

In addition to the mechanical tests and the macro/microexaminations required by the ISO standards, Equinor as an end-user demands that the following supplementary tests are carried out for further documentation of the weld properties[20]:

- Hardness testing (HV_1) in transverse (T) direction (1kg load)
- Subsize Charpy V-notch (CVN) testing
  - Fusion zone (FZ)/thermomechanically affected zone (TMAZ)
  - Fusion line (FL)/TMAZ/HAZ interface
  - Base metal (BM)
- All-weld tensile testing in longitudinal (L) direction
- Longitudinal BM tensile testing

The same mandatory and supplementary test regimes have also been adopted in the present benchmark study, where the dual objective is to qualify the HYB process for butt welding of 4mm AA6082-T6 extruded profiles and rank its performance against GMAW and FSW under comparable experimental conditions.

TABLE 1 Mandatory qualification test regime for gas metal arc and friction stir welded aluminium offshore structures

Type of weld	Type of test	Test standard	Extent of testing
Butt weld	Visual examination	ISO 17637:2011	100%
	Radiography	ISO 17636:2013	100%
	Ultrasonic testing	ISO 17640:2010	100%
	Penetrant examination	ISO 3452-1:2013	100%
	Transverse tensile testing	ISO 4136:2012	2 specimens
	Transverse bend testing	ISO 5173:2010	2 root + 2 face
	Macro examination	ISO 17639:2013	1 section
	Micro examination	ISO 17639:2013	1 section

3 | HYB BENCHMARK TEST PROGRAMME

The HYB butt welding trial was carried out in HyBond's research laboratory at NTNU. The pilot HYB machine allows welds to be produced under controlled conditions, with full documentation of all relevant process parameters, e.g. temperature, torque, rotational speed, travel speed and wire feed rate as well as the main reaction forces acting on the extruder during welding.

3.1 | Welding conditions

Since a full description of the pilot HYB machine at NTNU and the working principles of the PinPoint extruder have been reported elsewhere,[3–5,20] only a brief summary of the experimental set-up and applied welding conditions is given below.

As shown in Figure 1, the two 1000mm long and 4mm thick Johan Sverdrup aluminium profiles were mounted upside down in a fixture so that a 2mm wide I-groove did form between them. Both start and stop plates were employed to ensure uniform weld properties along the entire length of the weld. In the present benchmark study, a stationary extruder housing with no separate die opening at the rear for partial outlet of the extrudate was selected. When this housing is used in combination with a bobbin pin, a slick weld surface and root face can be obtained also in the HYB case as in FSW. Moreover, in order to achieve a good match in the chemistry between the BM and the FM a ϕ1.4mm filler wire (FW) of the AA6082 type produced by HyBond AS was selected. The chemical composition of this specially designed FW is given in Table 2.

During the butt welding operation the upper bobbin pin shoulder faces the bottom side of profiles, while the lower bobbin pin shoulder faces the top side of the profiles. This is because the two aluminium profiles are mounted upside down in the fixture, as shown previously in Figure 1. Then, if the correct value of the drive spindle rotational speed (which controls the FM deposition rate) is employed for the chosen combination of groove width and welding speed,[5] the entire groove cross-sectional area of 8 mm^2 can be filled with solid aluminium in one pass without creating a large metal surplus and problems with flash formation.

Table 3 summarizes the welding parameters employed in the butt welding trial. They represent best practice for the HYB process at the time of completion of the benchmarking.

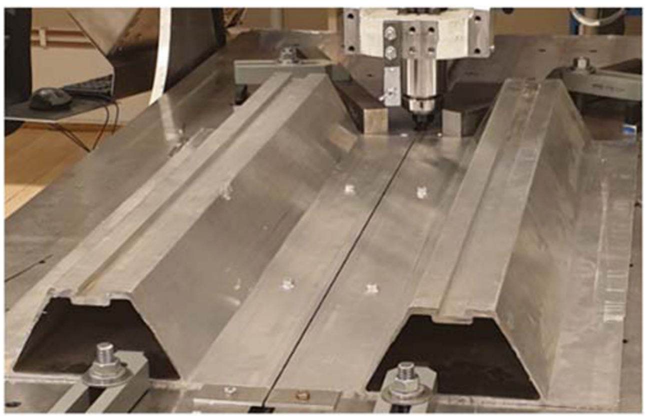

FIGURE 1 Photograph showing the experimental set-up employed in the HYB butt welding trial with the 4mm AA6082-T6 Johan Sverdrup profiles

TABLE 2 Chemical composition of the ϕ1.4mm AA6082 filler wire (in wt%)

Si	Mg	Cu	Fe	Mn	Cr	Ti	Zr	B	Other	Al
1.11	0.61	0.002	0.20	0.51	0.14	0.043	0.13	0.006	0.029	Balance

TABLE 3 Operational conditions employed in the HYB butt welding trial with the 4mm AA6082-T6 Johan Sverdrup profiles

Groove width (mm)	Pin rotation (RPM)	Welding speed (mm/s)	Wire feed rate (mm/s)	Gross heat input (kJ/mm)
2	350	18	125	0.11

3.2 | Mechanical testing

Table 4 provides a summary of the HYB benchmark test programme. Included in the table are an overview of the different tests conducted and the number of parallel tests being specified for the BM and the weldments along with references to the pertinent test standards and their acceptance criteria. Moreover, the sketch in Figure 2 illustrates the location of the different specimens being extracted from the HYB butt weld, whereas their dimensions are shown in Figure 3. Further details can be found in Equinor's documentation report.[20]

4 | RESULTS AND DISCUSSION

In the following the main results from the HYB benchmark testing against GMAW and FSW are presented.

4.1 | Macrographs of weld cross sections

Figure 4A shows macrographs of the different weld cross-sections. Whereas the solid-state FS and HYB welds are made in one pass, the GMA fusion weld is a double-sided three-pass (1 + 2) butt joint. The applied welding procedures are in accordance with best practice for the different methods. The extrusion zone (EZ) in the HYB weld consists of a mixture of consolidated FM and thermally softened BM, where the BM is brought into the groove from the retreating side

TABLE 4 Summary of the HYB benchmark test programme

Test type	Welds or BM HYB/FSW/GMAW	Test standard	Acceptance criteria
Tensile testing (T)	2/2/2	NS-EN ISO 4136	Welds: $\sigma_{UTS} \geq 174$ MPa
Bend testing	3/2/2	NS-EN ISO 5173	No crack >3 mm in any direction
Macro examination	1/1/1	NS-EN ISO 17639	See standard for details
Micro examination	1/1/1	NS-EN ISO 17639	See standard for details
All-weld tensile testing (L)	1/1/1	For information only	
Sub-size CVN–Weld centre line	3/3/3	For information only	
Sub-size CVN–HAZ	3/3/3	For information only	
Subsize CVN–BM	3	For information only	
Tensile testing (L & T)–BM	2 + 2	ISO 6892-1	$\sigma_{YS} \geq 250$ MPa $\sigma_{UTS} \geq 290$ MPa $A_{50} \geq 6\%$

Abbreviations: BM, base metal; HYB, Hybrid metal extrusion & bonding; FSW, Friction stir welding; GMAW, Gas metal arc welding; T, transverse direction; L, longitudinal direction; CVN, Charpy V-notch; HAZ, heat-affected zone; σ_{YS}, yield strength; σ_{UTS}, ultimate tensile strength; A_{50}, fracture elongation (50 mm gauge length).

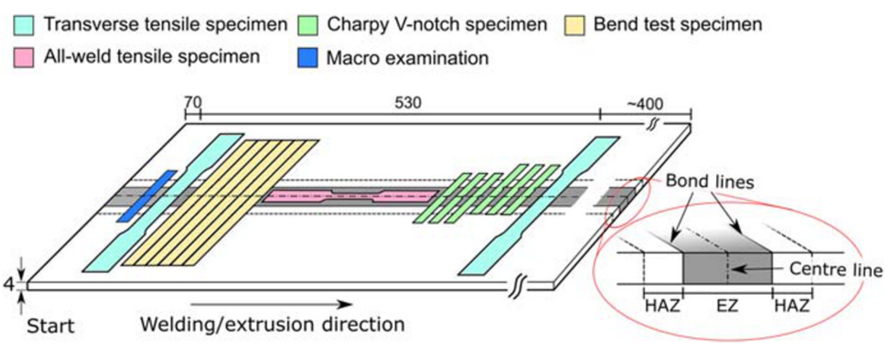

FIGURE 2 Sketch showing the approximate location of the different test specimens extracted from the 4mm HYB butt weld referred to the position of the extrusion zone (EZ) and the heat-affected zone (HAZ)

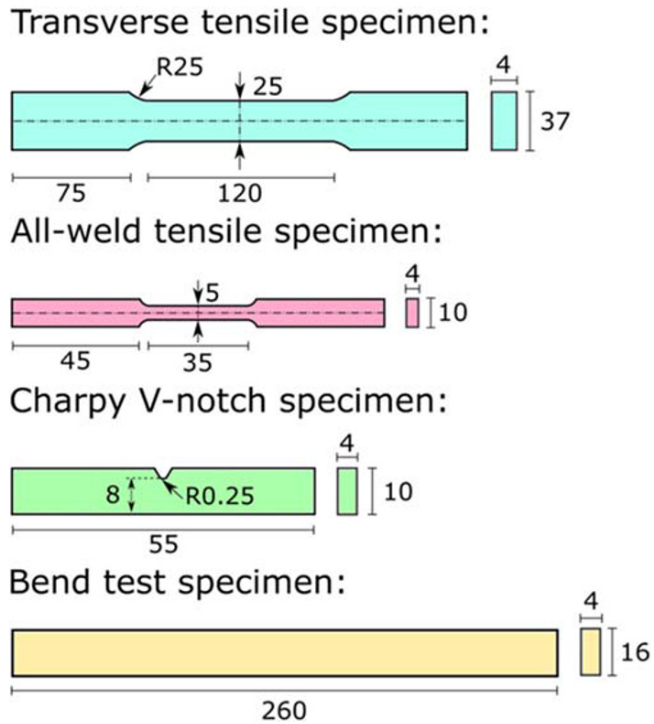

FIGURE 3 Dimensions (in millimetres) of the different specimens used in the benchmark testing of the HYB process against GMAW and FSW

(RS) of the joint due to the sweeping action of the rotating pin.[8,9] It has therefore completely different metallurgical and mechanical properties compared to the TMAZ of the FS weld, which only consists of reheated and plastically deformed BM.

4.2 | Hardness testing

The results from the hardness measurements are shown graphically in Figure 4B. As expected, the extent of HAZ softening is seen to be most predominant in the GMA fusion weld, where the total width of the HAZ is between 12-15 mm. In contrast, the two solid-state welds display much smaller HAZ widths, ranging from 3-4 mm in the HYB case and up to 5 mm for the FS weld. However, the FS weld reveals the smallest hardness reduction of the three. This follows from a comparison of the minimum hardness levels. Obviously, the boundary between the EZ and the HAZ is the weakest part of the HYB joint, where the properties achieved are determined by those of the thermally softened BM. This material has not undergone subsequent plastic deformation as in FSW and is therefore softer than the BM inside the TMAZ.

4.3 | Tensile testing

The results from the transverse (T) cross-weld and the longitudinal (L) all-weld tensile testing are presented in Figure 5A and B, respectively. It follows that the HYB tensile properties surpass those of the GMA weld and approach the strength level of the FS weld, both in the T and the L directions. Still, the HYB weld is the weaker of the two, as documented by a transverse joint efficiency of 69% compared to 81% for the FS weld. However, if the comparison instead is based on the yield strength data in Figure 5A, the corresponding strength reduction factors become 61% and 63%, respectively. The latter values are the ones being incorporated in current design codes for welded aluminium structures and used for calculating the maximum allowable design stress.[21] Because the observed difference between the FS and the HYB strength reduction factors is rather smaller, both welds are deemed to exhibit approximately the same load-bearing capacity.

Moreover, the subsequent visual examination of the broken tensile specimens revealed a good correspondence between the fracture location and the minimum HAZ hardness level in all three welds (see Figure 4B for details). Hence, during tensile testing of the GMA weld necking and final fracture occurred 6–8 mm outside the FZ, whereas the

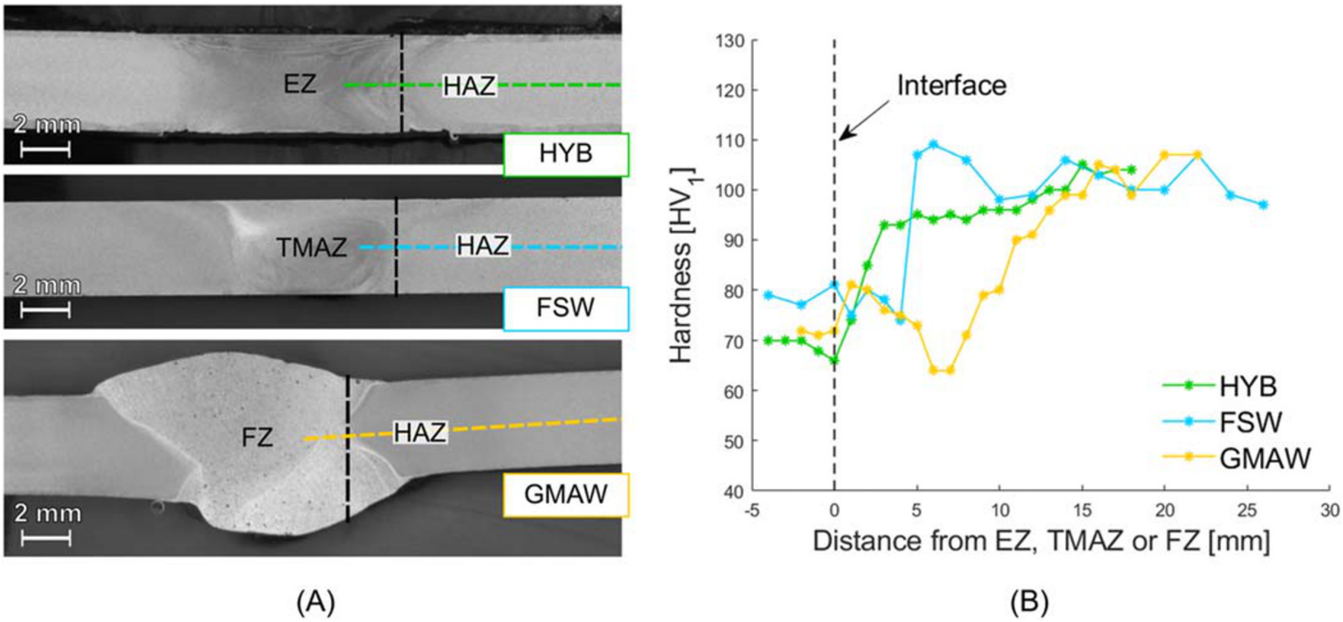

FIGURE 4 A, Optical macrographs of the HYB, FS and GMA weld cross-sections. The black vertical lines indicate the inmost position of the HAZ, whereas the coloured horizontal lines display the hardness indentation paths. B, Measured transverse hardness profiles in the mid-section of the HYB, the FS and the GMA welds

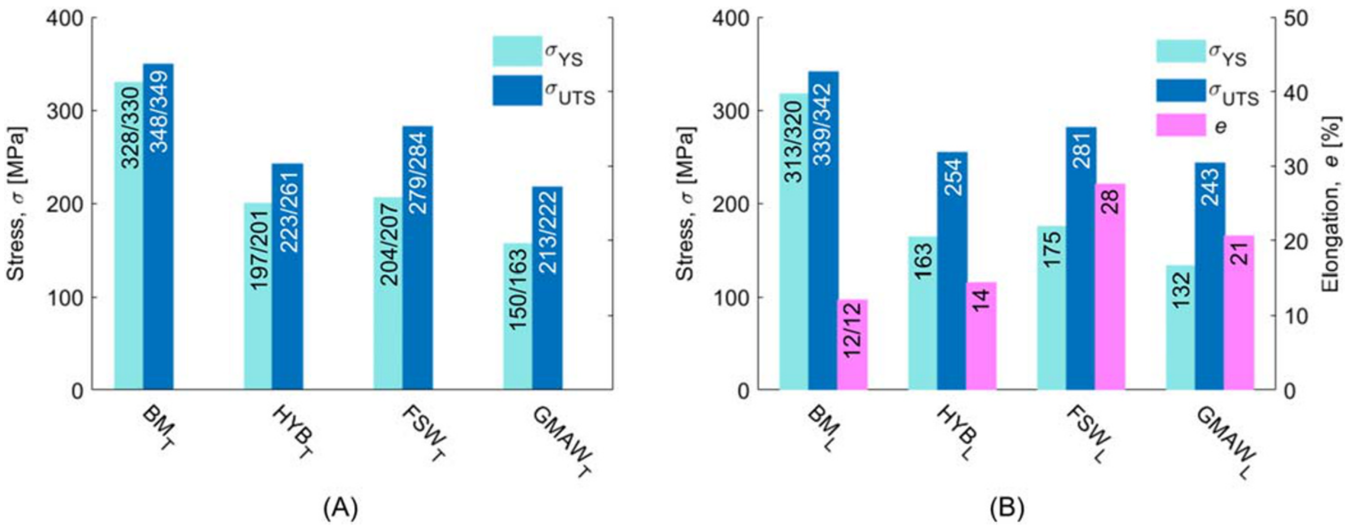

FIGURE 5 Summary of tensile test results for the BM and the HYB, the FS and the GMA welds (σ_{YS}: yield strength, σ_{UTS}: ultimate tensile strength, e: elongation at fracture). A, Transverse (T) tensile specimens. B, Longitudinal (L) tensile specimens. Testing conditions as in Table 4

transverse FS tensile specimens necked and fractured 1–3 mm outside the TMAZ. Similarly, in the HYB case necking and final fracture occurred at the boundary between the EZ and the HAZ. This is the weakest part of the HYB joint.

4.4 | Bend testing

The bend testing was done using the so-called wrap-around method and a roller diameter of 40 mm.[20] This testing did not reveal any evidence of bonding defects or crack formation in either of the weldments, which makes all of them qualified for offshore use.

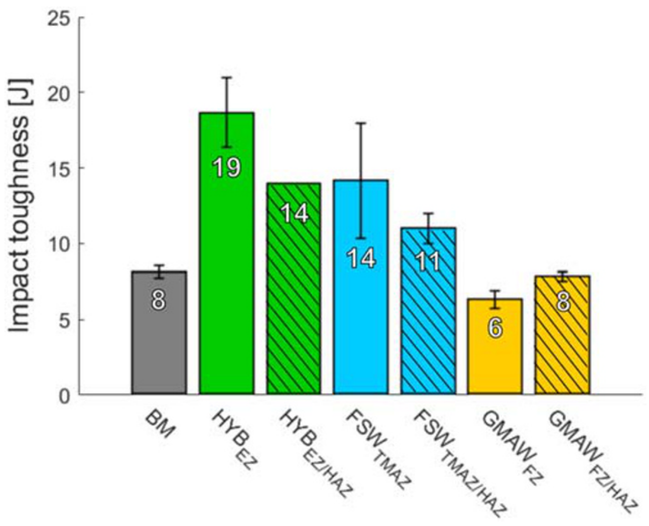

FIGURE 6 Summary of impact test results for the BM and the HYB, the FS and the GMA welds. In the latter case two sets of Charpy V-notch specimens were tested; one set where the V-notch is located at the weld centre line (EZ, TMAZ or FZ) and one set where the V-notch is located either at the EZ/HAZ interface, the TMAZ/HAZ interface or the FZ/HAZ interface. In these plots the superimposed error bars represent the standard deviation of three independent measurements

TABLE 5 Converted values for energy absorption per unit area in the hypothetical case where impact testing is done using full-size CVN specimens (in J/cm^2)

	GMAW (J/cm^2)		FSW (J/cm^2)		HYB (J/cm^2)	
BM (J/cm^2)	FZ	FZ/HAZ	TMAZ	TMAZ/HAZ	EZ	EZ/HAZ
26	20	25	44	34	58	44

4.5 | Impact testing

Finally, the results from the Charpy V-notch impact testing are presented in Figure 6. These data refer back to the specimen dimensions and notch locations shown preciously in Figure 2. Note that all CVN testing is done at room temperature (RT). It is evident from Figure 6 that the HYB weld exhibits the highest impact toughness for both notch locations. On the average it is about 20–30% higher compared to the CVN toughness of the FS weld and considerably higher than the measured values for the GMA weld and the peak-aged BM. If the recorded impact toughness values instead are reported as energy absorption per unit area (i.e. J/cm^2 as for full-size CVN specimens), the values listed in Table 5 are obtained. Although CVN testing is not included in the mandatory qualification test programme for welded aluminium offshore structure, an impact toughness of 58 J/cm^2 for the EZ and 44 J/cm^2 for the HAZ in the HYB case is impressing, also compared to steel weldments, where the acceptance criterion for offshore use is 35 J/cm^2 or higher.

5 | CONCLUSIONS

The main conclusions that can be drawn from this investigation are as follows:

- It is documented that the HYB process has reached a technology readiness level that makes it suitable for offshore applications. Specifically, the HYB process qualification applies to butt welding of 4mm AA6082-T6 profiles for use in living quarters, where both GMAW and FSW are currently employed during the assembling stage and design against fatigue failure is not an issue.
- The macro- and microexaminations together with the mandatory bend testing confirm that the single pass HYB butt joint is free from defects like internal pores and cavities and kissing bonds. However, the subsequent transverse hardness testing reveals evidence of weld softening. This reduces the yield strength and tensile strength joint efficiencies to values well below those of the base material (61% and 69%, respectively). On the other hand, the weld softening has a positive effect on the CVN impact toughness by contributing to an increase in the energy absorption by approximately a factor of two compared to that observed for the peak-aged base metal.

- Finally, the benchmark testing against GMAW and FSW shows that the yield strength of the HYB weld exceeds that of the corresponding GMA weld and is comparable to that of the FS weld. When it comes to impact toughness the HYB weld is the superior one of the three. These results represent best practice for all three methods at the time of completion of the benchmarking.

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CONFLICT OF INTEREST

The authors declare that there are no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

AUTHOR CONTRIBUTIONS

Lise Sandnes has prepared the draft manuscript and the illustrations used in the paper. She is also responsible for all communication between the co-authors. Gisle Rørvik has supervised the benchmark testing done at Equinor. He has also together with Inge Morten Kulbotten prepared the documentation report from Equinor. Inge Morten Kulbotten has performed the benchmark testing at Equinor. He has also together with Gisle Rørvik prepared the documentation report from Equinor. Øystein Grong is the inventor of the HYB process and the leader of the HYB development project at NTNU. He has also co-supervised PhD student Lise Sandnes and proof-read the final manuscript. Filippo Berto has co-supervised PhD student Lise Sandnes and provided funding for her work at NTNU. In addition, he has also proof-read the final manuscript.

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