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A techno-economic evaluation of friction stir welding of DH36 steel

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ABSTRACT

Friction stir welding of steel presents an array of advantages across many industrial sectors such as shipbuilding when compared to conventional fusion welding techniques. However, there seems to be very limited techno-economic assessment studies on its potential introduction in industry, and particularly in shipbuilding. A microstructure and property evaluation of friction stir welded low alloy steel grade DH36 plate, commonly used in ship and marine applications has been undertaken. In this comprehensive study, steel plates were butt welded together at increasing traverse speeds in order to improve the technical competitiveness of the process. Samples were examined microscopically and by transverse tensile testing, Charpy impact testing and micro-hardness testing in various regions of the weld. The study has examined a wide range of traverse speeds; from this, initial process parameter data have been established that are able to produce commercially attractive excellent quality welds through a substantial increase in the conventionally recognised welding traverse speed. In parallel, a comparative economic evaluation between friction stir welding and submerged arc welding has revealed a number of areas where the former is superior. However, the cost of the friction stir welding tool for steel has been exposed as the dominant obstacle for the wider commercial acceptance of the process on steel.

Keywords: Friction stir welding; Techno-economic evaluation; Low alloy steel.

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1. Introduction

Many industrial sectors have incorporated friction stir welding (FSW) of aluminium in various joining applications; it is expected however that transferring the technology and its advantages to steel will benefit equally many industries. FSW of steel is potentially applicable and appealing to several sectors, such as shipbuilding, automotive, train manufacturing, and the offshore industry. The highly beneficial properties of friction stir welds may also enable its use for structural assemblies subjected to cyclic or high magnitude static loads. An application already implemented is the joining of piping for special purposes like in the deep-sea industry.

Clearly, it is essential that FSW becomes both technically capable and economically viable to be transferred to steel. On the former, studies have demonstrated the feasibility of FSW of steel [1,2] and have shown that there are several positive effects on the properties of friction stir welded steel plates such as considerable grain refinement, excellent fatigue properties and minimised distortion [3]. Reynolds *et al.* [2] examine friction stir single sided welds of hot rolled, 6.4 mm thick DH36 steel, produced by four different welding speeds to assess the relationship between varying weld parameters and resultant weld properties. A bainitic and martensitic microstructure is observed in the bulk of the thermo-mechanically affected zone (weld nugget) of the fast weld (450 mm/min). However, only this weld's microstructural features are reported therefore no comparison can be made to slower traverse speed welds examined herein. Weld hardness demonstrates a continuous increase from parent material to nugget, with a variation of approximately 190 HV up to the peak hardness of the fast weld. The tensile tests reveal significant overmatching of all welds; longitudinal tensile tests show that the yield strength of all welds is higher than the parent material's ultimate tensile strength (UTS), and this is attributed to the weld nugget microstructure being very different from the original ferrite / pearlite microstructure. In all, weld hardness and strength is seen to increase with increasing welding speed [2].

A separate publication [3] is evaluating the technical potential of FSW as a shipbuilding welding process and how it compares to submerged arc welding (SAW), a well-established technique in the shipbuilding sector. The research [3] is based on the same grade of steel, DH36 and assesses the mechanical properties of FSW and SAW plates. An important finding is that the SAW plates present substantially more distortion than the FSW plates of the same thickness. Furthermore, an analysis of the chemical composition of all welds revealed that SAW produces considerably different composition than the parent metal due to the addition of filler material, while FSW essentially results in no change to the chemical composition of the parent metal. An acicular shaped ferrite microstructure is observed in the thermo-mechanically affected zone, consistent over the mid-thickness of all FSW samples, and a finer unspecified structure seemingly increasing with decreasing plate thickness. SAW samples present a typical acicular ferrite microstructure defined around proeutectoid ferrite grains. A comprehensive fatigue testing programme demonstrated that FSW samples exhibit better fatigue performance than the SAW samples of equivalent thickness. Variations in hardness distribution are considered minor and certainly not expected to produce adverse effects. Likewise, impact toughness levels for FSW and SAW samples at $-20^{o}C$ are reported to be similar and within classification society impact requirements. In conclusion, this study [3] supports sufficiently the argument for the capability of FSW to match shipbuilding requirements.

The process's technical capability and competitiveness to fusion welding methods has therefore been established; in the context of shipbuilding however, there is a critical requirement for high welding speeds (in millimetres per minute) which produce welded joints of acceptable quality to be addressed. Concentrating on the potential introduction of FSW in this sector, the current study is investigating the FSW of steel grade DH36 which is a low alloy steel widely utilised in European shipbuilding by examining welds of gradually increasing welding traverse speed.

The development of faster traverse welding speeds commenced with a parameter set (tool traverse speed of 100 mm/min and tool rotational speed of 200 rpm) recommended by the FSW tool manufacturer, which is known to deliver acceptable quality welds on steel. A number of welds were produced using these process parameters and this provided a baseline data set of the resultant forces, torques and heat inputs. As an initial understanding of the welding process was achieved, the tool traverse speed was increased to the region of 350 mm/min where FSW would commence to be competitive to fusion welding processes in terms of acceptable quality production speed. Since faster welding speeds are desirable to improve the competitiveness of FSW, the traverse speed was further increased to 500 mm/min.

It is desirable to develop welding speeds that produce acceptable quality welds in terms of microstructure and mechanical properties. Although many parameters such as tool rotational speed, tool traverse speed, tool tilt, plunge depth, backing bar characteristics and clamping arrangements affect the welding process, the FSW tool represents a crucial factor in the development of high welding speeds. The current tool technology for FSW of steel is still relatively immature, thus it is important to protect and prolong the tool's service life as it operates in an aggressive welding environment. Attention must be paid into employing parameters which deliver good weld properties but equally extend the life of the tool and thereby improve the economic viability of the FSW process in steel. One example is the need to ensure that the steel ahead of the tool is sufficiently plasticised so that the forces experienced by the tool do not rise excessively as traverse speed is increased.

Parameter selection is therefore a complex process with many interdependent variables, many of which are currently poorly understood, and requiring extensive welding and considerable testing over a very large data set. Through the welding traverse speed development undertaken in this extensive work, the state of the art has been increased from conventionally adopted welding speeds in the region of 100 mm/min to a more commercially attractive speed of 400 mm/min. Although a step change in the welding speed has been identified, the purpose of the present study is to assess the impact of this increase on the microstructural evolution and mechanical properties of each friction stir weld.

The current state of the art in FSW of steel allows for butt welding in the down-hand or flat position. This welding position is typically used in the shipbuilding industry for joining plates to larger plate-fields before these are stiffened with profiles. Automated processes join base plates to larger fields in widths of 25 – 40 m. Considering the demand for continuously decreasing plate thickness in ship structures, it is expected that new, low-energy input joining methods like FSW are needed. For this application of friction stir butt welding, it is not sufficient for the process to be technically efficient; the economic viability of FSW is equally important. In terms of current shipbuilding practice, shipyards have mainly been utilising FSW on aluminium structures mainly due to the process being economically competitive to fusion welding [4]. No corresponding comparative analysis is currently available with respect to fusion welding techniques in steel for welding large plate fields in shipyards. Therefore, an economic assessment and comparison of SAW to FSW is reported to demonstrate the economic aspects of the latter on steel within the context of the maritime industry.

2. Experimental procedures

The nominal chemical composition of steel grade DH36 is presented in Table 1. Rolled plates of 2000 x 200 x 6mm were welded in the as received condition without prior surface preparation. Single sided friction stir butt welds with final dimensions of 2000 x 400 mm were produced using a PowerStir FSW machine and WRe-pcBN Q70 FSW tools.

Table 1. Chemical composition of 6 mm thick DH36 steel (wt%).

C	**Si**	**Mn**	**P**	**S**	**Al**	**Nb**	**N**
0.11	0.37	1.48	0.014	0.004	0.02	0.02	0.002

The following testing programmes were conducted towards the objectives of this study:

- Microstructural characterisation: to relate to expected mechanical properties of the weld zone, and to identify possible undesirable process induced defects or flaws that may compromise the integrity of the weld.
- Transverse tensile testing: to determine the yield strength and UTS of each weld in accordance with ISO Standards, and the position of the fracture (parent material or weld metal) hence further support the observations on the weld quality
- Micro-hardness measurements: taken through the weld zone using a grid spacing of 1 mm for both x and y directions and 200 gf load.
- Charpy impact testing: to evaluate the impact toughness of the weld region as a function of welding parameters using standard V-notch, reduced-section samples of 5 mm width sectioned perpendicular to the weld centreline and transverse to the weld direction. To examine the full width of the weld region, one sample was sectioned with the notch axis of symmetry on the weld centreline and three more samples were sectioned towards both sides of the weld in 1.5 mm increments (Figure 1).

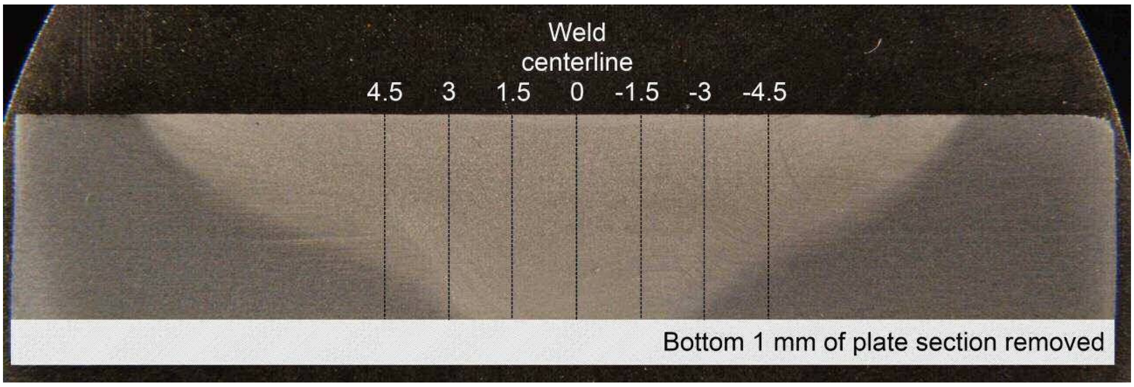


Fig. 1. Typical macro-graph showing the position of the notch axis of symmetry of the seven Charpy samples examined from each weld.

3. Results and discussion

3.1. Microstructural observations

The following nomenclature is adopted in the present study and the main regions of the weld zone are illustrated in Figure 2, where:

- AD: Advancing side, the side where the rotating FSW tool pushes the metal towards the weld direction, i.e. forwards. The convention employed herein is that samples are prepared so that the advancing side is presented on the left side of all images.
- RT: Retreating side, the side where the rotating tool pushes the metal in a direction opposite to the weld direction, i.e. backwards.
- TMAZ: Thermo-mechanically affected zone in which the material has been thermo-mechanically stirred by the FSW tool.
- Weld root: part of TMAZ, around and below the tip of the FSW tool's pin.
- HAZ: Heat affected zone, where the metal has been affected by heat as it dissipates from the TMAZ, but not mechanically stirred.
- PM: Parent material, metal not affected by the process.

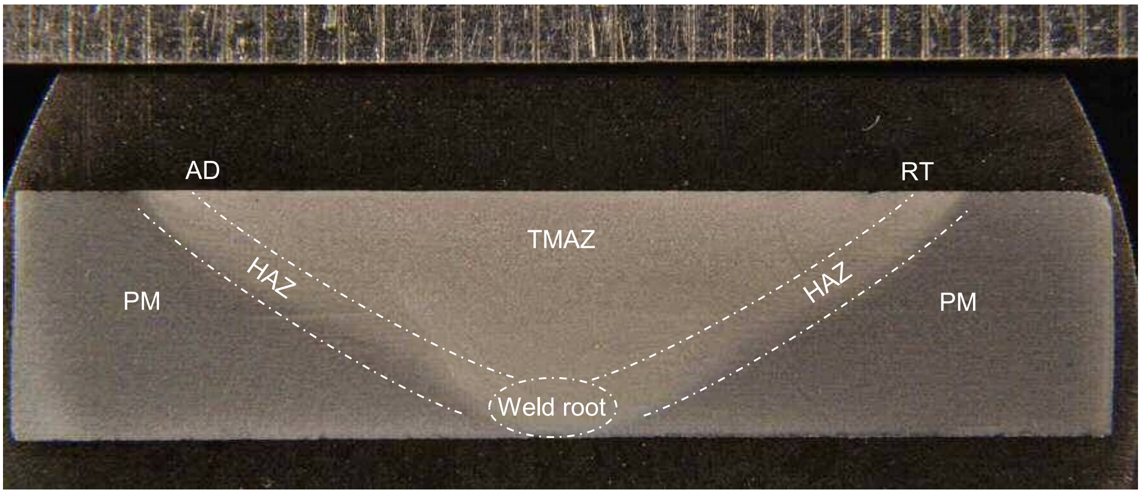


Fig. 2. A typical macrograph of the friction stir weld region.

A ferrite rich, homogeneous microstructure with highly refined grains of random geometry is observed in welds produced with traverse speeds of 100 – 200 mm/min (Figures 3a & 3b). Acicular-shaped bainitic ferrite appeared at a small ratio compared to the ferrite rich microstructure in samples produced with a welding speed of approximately 120 mm/min (Figure 3b); the acicular-shaped bainitic ferrite content was found to gradually increase with increasing traverse speed and constant rotational speed (200 rpm). The observed increase in bainite confirms that the cooling rate is increasing with increasing traverse speed. Another publication [5] reports a predominantly acicular shaped bainitic ferrite stir zone (TMAZ) microstructure using a similar traverse speed of 127 mm/min. It is noted that this is a product of the phase transformation of austenite in the supercritical stir zone (central TMAZ) to ferrite at a high cooling rate, as acicular bainitic ferrites nucleate mainly on the austenite grain boundaries. There is however an uncertainty on how this microstructure is developed considering the high rotational speed of 450 rpm for the stated traverse speed [5]; this could be the outcome of an undisclosed applied forced cooling method, and the steel's different chemical composition to DH36.

Fig. 3. Microstructure of mid-TMAZ [x1000, Etched] (a) 100 mm/min; (b) 120 mm/min; (c) 350 mm/min; (d) 375 mm/min.

As tool traverse and rotational speed are seen to increase, the microstructure becomes more heterogeneous, with regions of increasing bainite content (suggesting an increased cooling rate). However, this heterogeneous microstructure does not seem to have a significant effect on the mechanical properties (see later). Welding at 350 mm/min and 375 mm/min produces an acicular-shaped bainitic ferrite homogeneous microstructure (Figures 3c & 3d respectively) with prior austenite grain boundaries clearly observed in the former.

A step change improvement to the conventionally adopted FSW speeds is established by the high welding speed of 500 mm/min. Welding at this speed generates a heterogeneous microstructure with poorly mixed regions of acicular ferrite and varying bainite content

(Figure 4). As above, prior austenite grain boundaries are very pronounced particularly on the regions of bainite predominant microstructure. One weld at 500 mm/min – 700 rpm exhibits two distinct microstructures in the TMAZ (Figure 4b), hence these would be expected to act as stress concentration regions. Still, this weld's satisfactory tensile behaviour (see later) seems to suggest that a good balance of traverse and rotational speed has been obtained which could be attributed to the grain refinement and a suitable ratio of microstructures overtaking the negative effects of heterogeneity. A bainitic and martensitic (thus acicular) microstructure in the TMAZ is reported in a previous study [2] using the same grade of steel and a marginally lower traverse speed of 450 mm/min. No ferrite phase is detected in this region hence the observed phases are attributed to the phase transformation of austenite during fast cooling, after FSW has raised the steel's temperature above A_3. Although the specific rotational speed is not disclosed, the presence of martensite suggests that the cooling rate developed during welding [2] is higher than the rate occurring herein.

Fig. 4. Microstructure of mid-TMAZ AD side at 500 mm/min [x1000, Etched] (a) 675 rpm; (b) 700 rpm.

The two welds of Figure 4, 500 mm/min – 675 rpm and 500 mm/min – 700 rpm, only vary by 25 rpm but the former can be described as an unstable weld (see later). In addition, incomplete fusion characteristics can be observed on the advancing side of two welds at 500 mm/min (600 & 650 rpm) and these can be expected to affect the mechanical properties of the relevant welds. These observations demonstrate that the FSW process is quite sensitive to minor variations in welding parameters such as rotational speed in the high traverse speed of 500 mm/min.

3.2. Transverse tensile testing

Stress – strain charts were plotted to calculate the yield strength and UTS outlined in Table 2 by groups of traverse speed. It was found that:

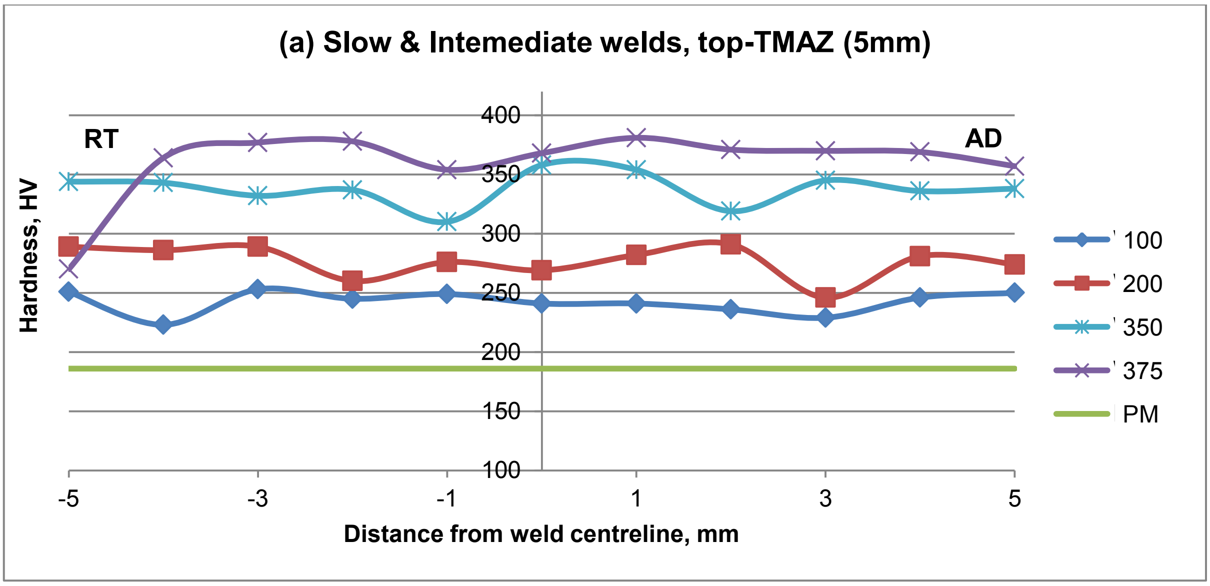
- The samples of all slow (100 – 200 mm/min) and intermediate (250 – 400 mm/min) welds fractured in the PM, away from the weld, suggesting weld yield strength higher than PM. This behaviour has been reported previously [2,3] for similar welding parameters.
- The fast welds (500 mm/min) confirmed the sensitivity to parameter variations discussed previously; samples from one weld (700 rpm) fractured in the PM indicating the good balance of weld parameters noted in the microstructural observations above.
- The samples from three welds at 500 mm/min (600, 650, 575 rpm) fractured on the outer AD side boundary in a brittle-like manner. The incomplete fusion characteristics observed on the same side of two of these welds during microscopy are thought to be responsible for fracture initiation at this region.
- Two samples from a fifth weld at 500 mm/min (675 rpm) fractured on the outer AD side, revealing low heat input related features on the fracture faces (i.e. insufficient material flow markings). A third sample fractured in the parent material in a typical ductile manner. This mixed tensile behaviour points to a weld where steady state conditions have not been reached (an “unstable” weld).

Table 2. Summary of DH36 FSW transverse tensile test results at room temperature.

Welding speed, mm/min	Rotation speed, rpm	Yield Strength (0.2%), MPa	UTS, MPa	Fracture region	Fracture mode
Slow traverse speed welds					
100 – 200	200 – 400	386 – 409	521 – 540	PM	Ductile
Intermediate traverse speed welds					
250 – 400	300 – 550	378 – 405	514 – 544	PM	Ductile
Fast traverse speed welds					
500	600	383 – 400	488 – 457	Weld, AD side	Brittle
500	650	408 – 417	526 – 563	Weld, AD side	Brittle
500	575	423 – 442	433 – 480	Weld, AD side	Brittle
500	700	382 – 401	519 – 546	PM	Ductile
500	675	390, 397	458, 514	Weld, AD side	Brittle
		394	532	PM	Ductile

3.3. Hardness

Two indicative welds’ hardness measurements from each group of slow, intermediate and fast traverse speeds (as outlined in Table 2) are reported herein and specifically the measurements for the top-TMAZ of each weld, i.e. 1 mm below the top surface. The hardness of the slow and intermediate welds (Figure 5a) is higher than that of PM but without any detrimental effects to their yield strength, and relatively evenly distributed in the TMAZ from AD to RT side. Hardness values are seen to increase with increasing welding speed, hence increasing cooling rate in the weld which in turn suggests increasing bainite content.


(a) Slow & Intemediate welds, top-TMAZ (5mm)

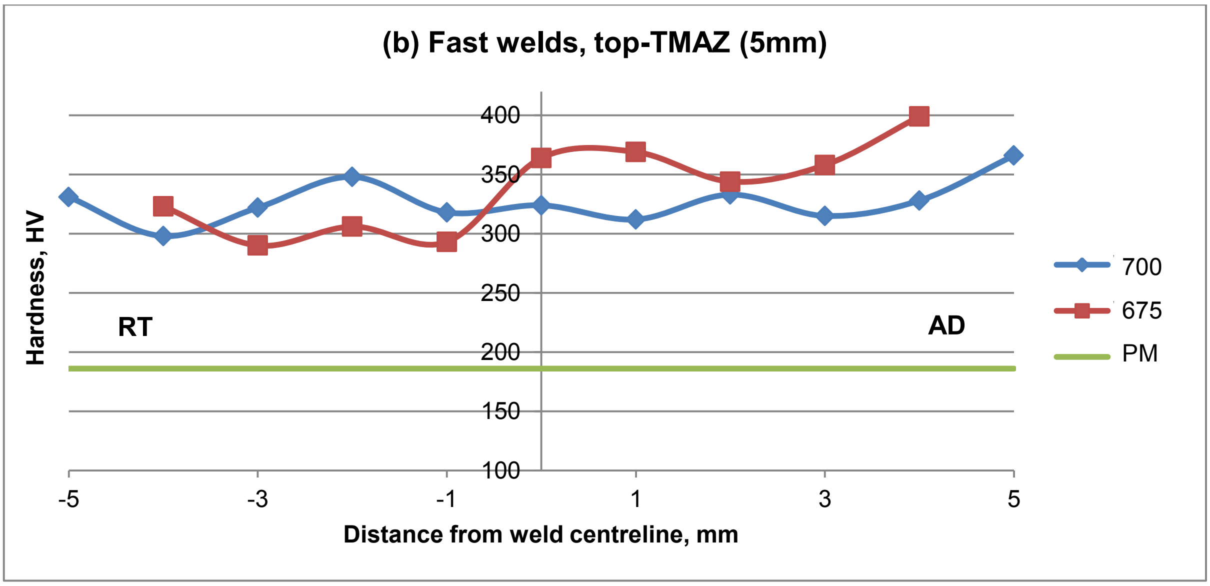

(b) Fast welds, top-TMAZ (5mm)

Fig. 5. Weld region micro-hardness distribution for 6 indicative welds (a) weld speed in mm/min; (b) tool rotational speed in rpm.

The weld of 500 mm/min – 700 rpm (Figure 5b) exhibits high hardness with minor variations across the weld region, an observation which may partly explain the weld's excellent transverse tensile behaviour. The weld of 500 mm/min – 675 rpm displays higher hardness values with considerable deviations, i.e. an indication of its microstructural heterogeneity, and peak hardness on the outer AD side which is expected to correlate with its tensile samples fracture position. Other studies [5,6] have reported similar variations in the hardness distribution within the weld TMAZ; the significant variations of hardness within the weld zone of all welding parameters examined by Ghosh *et al.* [6] are associated with the heterogeneity of the resultant microstructure. Cho *et al.* [5] argue that the substantially higher hardness found in the stir zone (central TMAZ) is caused by the acicular shaped bainitic ferrite microstructure. Most intermediate and high traverse speed welds of this study exhibit a comparable but reasonably homogeneous microstructure, and this homogeneity seems to be responsible for the smaller variations found in the TMAZ hardness distribution.

3.4. Impact toughness

Table 3 incorporates impact toughness data for 6 representative welds, normalised to a 10 x 10 mm equivalent by a scaling factor of 3/2, as discussed by McPherson *et al.* [3]. The impact toughness of most welds at 20°C appears to have been reduced compared to the parent material (Table 3). The weld of 200 mm/min – 400 rpm shows reduced impact toughness, presumably due to the observed acicular ferrite microstructure, when compared to the impact toughness of weld 100 mm/min – 200 rpm with a highly grain refined, ferrite-rich microstructure.

The intermediate and fast traverse speed welds display a similar trend in impact toughness distribution with a peak observed in the inner AD side TMAZ and gradual decrease with noticeable variations towards the outer boundaries of the TMAZ on both sides. It is worth noting that two sets of parameters which produced welds of yield strength higher than PM, 375 mm/min – 400 rpm and 500 mm/min – 700 rpm, overmatch the parent plate’s impact toughness in the inner AD TMAZ. Weld impact toughness is seen to improve as the welding speed is increased from 100 mm/min to 375 mm/min and 500 mm/min, particularly on the AD side; this improvement offers a level of confidence in increasing the FSW traverse speed. However, the minor improvement on the RT side and the rather stable impact toughness in both sides of the outer TMAZ suggest that there is scope for further refinement of the welding parameters.

Table 3. Impact toughness data in the weld region for six welds at 20°C (CL: centreline).

Distance from weld centreline:		**4.5**	**3**	**1.5**	**0**	**-1.5**	**-3**	**-4.5**
Welding speed, mm/min	**Rotation speed, rpm**	**AD**			**CL**	**RT**		
100	200	91	83	75	112	78	80	105
200	400	108	40	37	101	51	48	44
350	450	67	80	102	92	93	74	69
375	400	65.5	76	134	91	81	76.5	65
500	700	80.5	84.5	127	106	94.5	67	66
500	675	75	82.5	119	96	92	64	66.5
PM		122.5						

4. Economic comparator study

Evidence of high speed welds of acceptable quality and mechanical properties have been presented; this step change in welding speed is expected to assist in FSW becoming highly technical competitive to fusion welding methods. The economic competitiveness of FSW compared to other joining processes also needs to be assessed. A potential application of FSW of steel is in the fabrication of large panels for the shipbuilding industry, hence an economic assessment comparing SAW to FSW for the production of a typical Roll-on Roll-off Ferry is introduced with the following assumptions:

- New butt welding panel line installation including operational infrastructure (cranes, etc.) but excluding buildings and related overhead costs.
- Butt welds over a plate thickness range from 5 mm to 15 mm in DH36 steel.

Table 4 summarises the global parameters for the economic assessment, i.e. a number of commercially sensitive data which are provided by suppliers, shipyards and other industry sources, therefore not cited.

Table 4. Global parameters for economic assessment

Parameter	Unit	Value
Useful economic life	[a]	8
Welding metres per year	[m]	60,000
Material	-	DH36
Detail	-	Butt weld
Plate length	[m]	10
Plate field length	[m]	30
Typical plate thicknesses	[mm]	5-15

Table 5 presents the input and result figures for the economic comparison; FSW total investment costs are lower than SAW because of factors such as the absence of a turning plate for double sided welding, lower plate edge preparation requirements, etc. Welding speeds and usage of consumables are related to plate thickness therefore included in the machine direct costs for a thickness range given in Table 4. The following observations can be made on the analysis outlined in Table 5:

- Although the average welding speed of SAW is 40% higher, the plates are usually welded with pass and capping pass (double sided welds) to avoid root failure. Therefore, there is an auxiliary process time 2.6 times higher than FSW.
- The overhead and personnel costs are in both methods equal, but the machine direct costs in FSW are 13 times higher compared to SAW. This leads to a compelling difference in welding costs per metre and per hour.
- The SAW costs per metre are in accordance with typical shipyard figures from the literature; FSW production costs however are outside any economical acceptability [7].

- In total production time, FSW demonstrates a 20% advantage due to the quality of the root in single side welded butt joints.

Table 5. Economic assessment results.

	SAW	FSW
Number of passes	2	1
Pass / capping pass	Yes	No
Average welding speed	575 mm/min	400 mm/min
Primary processing time	1,800 h	2,500 h
Auxiliary process time	3,000 h	1,200 h
Investment costs machinery	830,000 €	500,000 €
Machine hourly rate	31 €	20 €
Machine direct costs	139 €	1,805 €
Overhead and personal costs	41 €	41 €
Production costs per metre	11 €	80 €
Production costs per hour	136 €	1,307 €
Total production time	~4,800 h	~3,700 h

A more detailed analysis of the single cost components regarding the undesirable disparity in production cost per metre for FSW and SAW is presented in Figure 6. Noticeably, the FSW machine direct costs represent a massive percentage of the total cost (Figure 6b). Further analysis of this cost category reveals that the cost of the FSW tool is dominant (Figure 6c). The market for FSW tools for steel is very limited, hence the cost of a FSW tool for steel remains in the region of €3,000 while its service life is limited to approx. 40 metres of welding. Therefore, the economic assessment of FSW and SAW has established the following:

- FSW will only become economically viable for steel when solutions are found to decrease the tool cost or increase the tool life.
- A further increase in welding speed is not expected to significantly influence the above finding due to the predominant tool costs.
- FSW delivers other benefits such as low investment costs, as well as shorter production times with high quality welds.
- FSW introduces considerable advantages with respect to its solid-sate, low heat input nature. As an example, less rework and fairing of welded structures are not considered in this economic assessment but are predicted to be a striking factor to decrease the overall production costs and time.
- The use of FSW in shipbuilding is not only dependent upon cost related issues but also on the process' capability to weld more geometries than butt welds, e.g. fillet welds. After all, butt welding is generally not a time-related bottleneck in shipbuilding production.

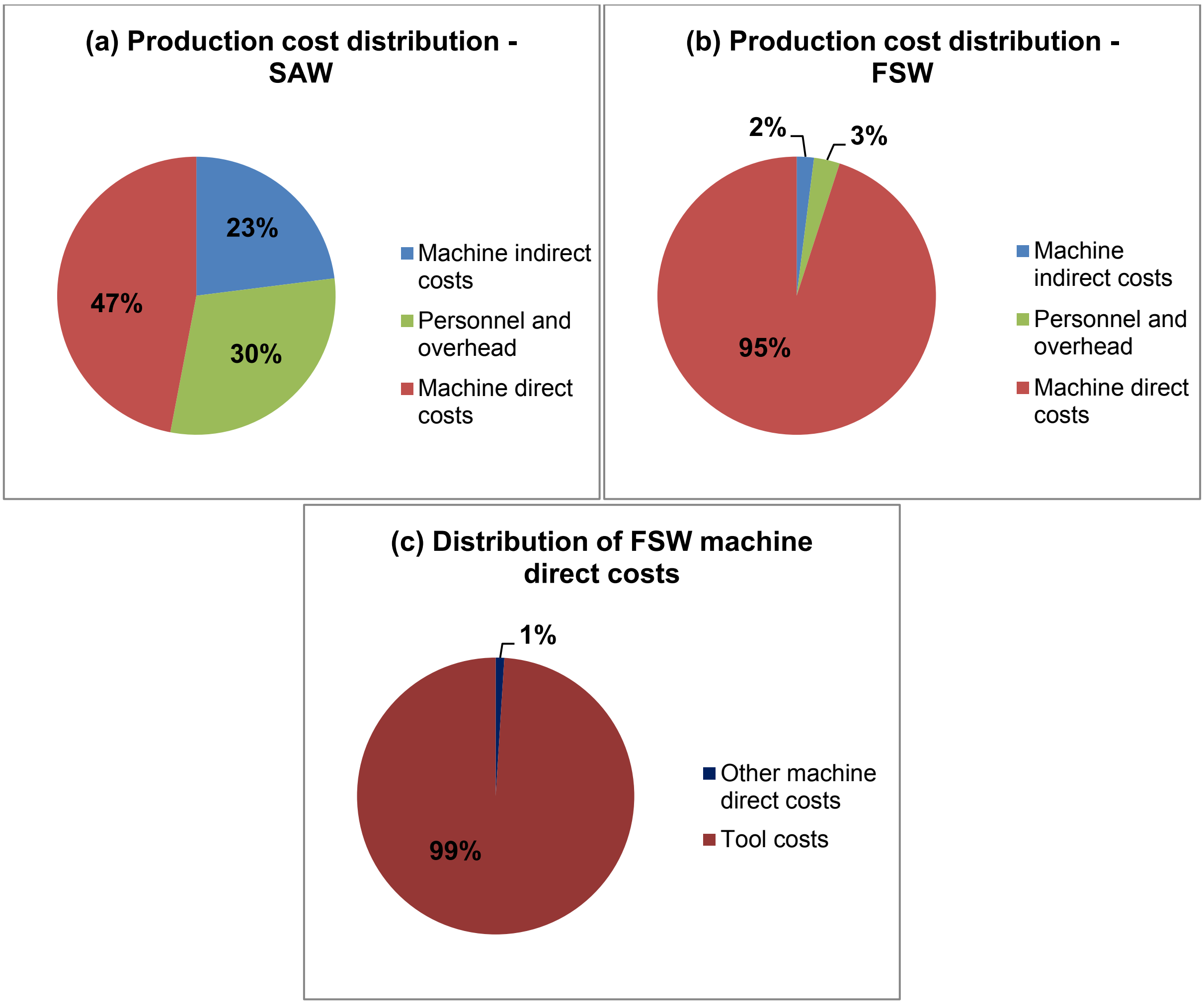


Fig. 6. Distribution of production costs for (a) SAW; (b) FSW; (c) FSW machine direct costs.

5. Conclusions

- A comprehensive study of FSW of DH36 steel has resulted in the development of a large number of parameter sets based on the outcomes of microstructural evaluation and mechanical testing.
- The welding traverse speed on DH36 steel has been greatly increased compared to the conventionally used speed of 100 mm/min. A number of weld parameters have been identified which may produce fast (in the region of 400 – 500 mm/min) welds of acceptable quality that are highly competitive to conventional fusion welding techniques on a technical level.
- An investigation of weld microstructures and resultant mechanical properties as a function of weld parameters has determined that FSW generates a very complex metallurgical system.
- An economic comparator study of FSW to SAW has found the former to be superior in many categories. Still, the FSW tooling cost in conjunction with the tool’s limited service life present a serious obstacle for the wider commercial acceptance of the process.

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