Structural Integrity of Welded Structures: Process –Property – Performance (3P) Relationship

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Houdremont Lecture

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Abstract

In most engineering metallic structures, welded joints are often the locations for the crack initiation due to inherent metallurgical, geometrical defects as well as heterogeneity in mechanical properties and presence of residual stresses. In order to maintain structural integrity of welded structures for whole service life of the structure, relationship between welding **process**, **properties** (of base metal & weld joint) and **performance** of the structure (requirements & controlling factors of the service conditions) should be well-understood and established. The quality of the relationship between this 3P is crucial to obtain economic and safe design, fabrication and service life.

Specific features of each welding and joining process should ideally be well understood by the designer for a selected material at the early stage of the design. Resulting microstructural & mechanical and geometrical properties should be obtained to have defined or intended structural performance under either specific environment or stresses.

Nowadays, use of advanced welding processes with high performance steels and aluminium alloys together with well established and high quality welding consumables ensures safe and economic design, fabrication, inspection and service of the welded components and structures. Additionally, new developments in the fitness-for-service (FFS) procedures (e.g. BS 7910, R6 and FITNET FFS) and codes have significantly increased the accuracy of the structural integrity assessment of weld flaws.

More and more engineering structures are built using *multi-material design approach* where numbers of materials with significantly different mechanical properties are joined to create weight and cost-efficient structures. Structural safety evaluation of such *material-mix structures* require sound understanding and description of the welding process, interfacial & weld joint properties in conjunction with global behaviour of the component under external loadings. The existing knowledge on the weld strength *mis-match* will significantly help to design innovative products and resolve complex deformation and fracture problems of such emerging structures. Such structures are expected to perform under severe service conditions with minimum maintenance and safely.

This Houdremont Lecture will, therefore, address to the engineering significance of the relationship between different stages of the "*life of the welded structure*" which I have been describing as 3P (Process-Property-Performance) of welded structures.

Keywords: *Welding process, weld property, structural performance, mis-match, weld metal, fracture, residual strength, fitness-for-service, FITNET, flaw assessment, line pipe, structural integrity, laser weld, aerospace, Al-alloys.*

1. Introduction

In recent years, significant new developments have taken place in the field of steel and weldability developments while new major projects and application fields require challenging properties from selected welding process and material combination. For example, possible new applications in arctic regions require steel structures and their weldments need to be designed and tested at -60°C to -70°C. Furthermore, the weldability in different positions may require to use different welding processes and welding consumables.

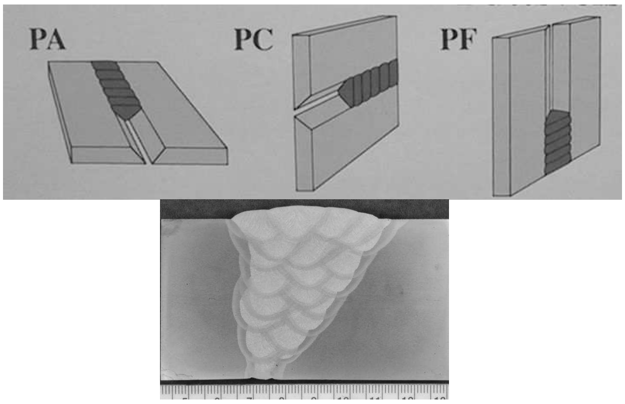


Figure 1. Three different welding positions for weldability testing of Steel Grade S420G2 and utilised weld cross-section [I. M. Kulbotten, StatoilHydro ASA, 2008, Low temperature properties of welded constructional steel]

An example to this case could be seen in Figure 1 where same steel is welded at different positions using accordingly different welding process and consumables. PA refers to submerged arc welding (SAW), PC and PF are gas shielded flux cored arc welding with different heat inputs. It is most probable that these different welding positions (process variations) may lead to different joint properties and hence welded structure depending on the loading conditions may differ at different points.

Therefore, it is essential to consider weld joint performance an integral part of the welding process and local properties (strength, notch etc.). For example, welding process parameters and selected consumables and base metal grade of line pipes are of major importance for the integrity of pipelines. The use of fitness-for-service analysis at the design stage will enhance the accuracy of the decisions and hence will improve the productivity, safety of welded fabrication and integrity respectively.

Weld joints usually exhibits heterogeneous properties across the joint. This particularly effects the performance of the structure. For this known reason weld strength mis-match has been a topic of research for same time. This paper gives special attention to this topic.

2. Weld Strength Mis-match

Structural weld joints, particularly bi-material (dissimilar) joints usually exhibit substantial mechanical heterogeneity with respect to elastic-plastic deformation and fracture properties. This heterogeneity is commonly called as „strength mis-match“ and expressed as yield strength mis-match;

$$M=\sigma_{YW}/\sigma_{YB}$$

Where σ_{YW} is the weld metal yield strength and σ_{YB} is the base metal yield strength. It is referred to as „overmatching if M>1 and called as „undermatching“ if M<1.

It is common practise in fabrication to select welding process and consumables to achieve overmatching weld zone to protect the weld zone from deformations and hence limit the risk of failure at the weld joint. Many welding codes require the weld filler metal to be overmatched, primarily to protect weld from localization of plastic strain in the event that the yield load of the structure is exceeded. However, this requirement most needed for welds subjected to tension normal to the effective area (e.g. girth welds in pipes). Non-critical components and weld joints subjected to other types of loadings may have undermatched welds. The strength overmatch requirement usually does not cause any difficulty for structural steels up to 600 MPa yield strength. However, for high strength steels, production of strength overmatching weld deposit usually creates difficulties while maintaining adequate fracture toughness and resistance against hydrogen assisted cracking. In addition to this difficulty, there exists unintentional strength undermatching in high strength steel weldments. The weld joints may unknowingly be undermatched because the base metal has much higher yield strength than the SMYS (specified minimum yield strength). It should be noted that the undermatched welds can have a significant effect on the strength level, resistance to fracture and ductility of welded components. The undermatched welds are particularly sensitive if the welds operate under tension perpendicular to the weld seam. If the undermatched welds are loaded in a direction parallel to the weld length should present no problem, since the strain will not localise in the soft weld seam.

Particularly, since early nineties, numerous investigations have been conducted by the author [e.g 1-6] to describe the effects of mis-matching on the fracture behaviour and toughness. Two special international conferences, ***Mis-match 93*** [7] and ***Mis-match 96*** [8] have provided international forum and showed the significant progress had been made in this field. For example, currently, unified method to perform defect assessments in mis-matched welds exists. In this context, recently developed fitness-for-service procedure FITNET has provided clear guidline for assessment for such welds. However, significant amount of work is still needed, particularly in the areas of high strength steel weldments, treatment of HAZ softening and highly undermatched Al-alloy weldments while extensive validation cases of proposed approaches as well as treatment of material-mix (multi-material) structures are still missing.

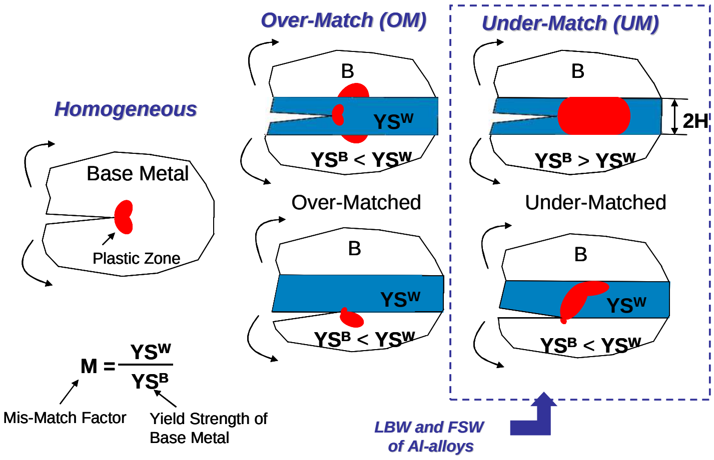


Figure 2. Schematic description of crack tip plasticity due to weld strength mis-match. LBW: Laser Beam Welding, FSW: Friction Stir Welding

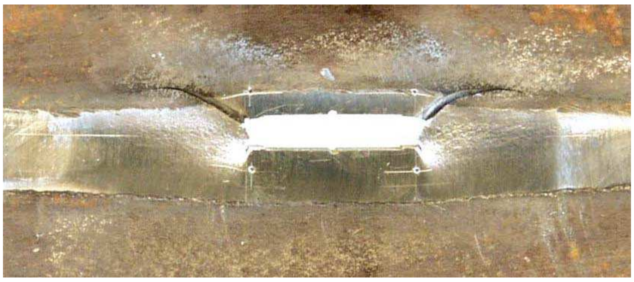


Figure 2. Fracture path deviation into lower strength base metal of the centre cracked wide plate under tension. The weld metal exhibits strength overmatching.

It is known that the essence of the strength mis-match lies on the crack tip plasticity development and effect of the strength difference between weld and base metals on the deformation pattern at the crack tip and ahead of the crack tip (uncracked ligament). Figure 2 schematically showing the principal deformation patterns of the overmatching and undermatching cases with weld metal and HAZ cracked bodies as well as two major governing factors of M and 2H (weld width). The structural steels (up to some strength level) usually show overmatching while laser beam [9,11] and friction stir welded (FSW) high strength Al-alloys usually exhibit undermatching situations [4, 8]. Due to rapid cooling rate, LB welded ferritic steels and Ti-alloy show high hardness, and hence high degree of overmatching.

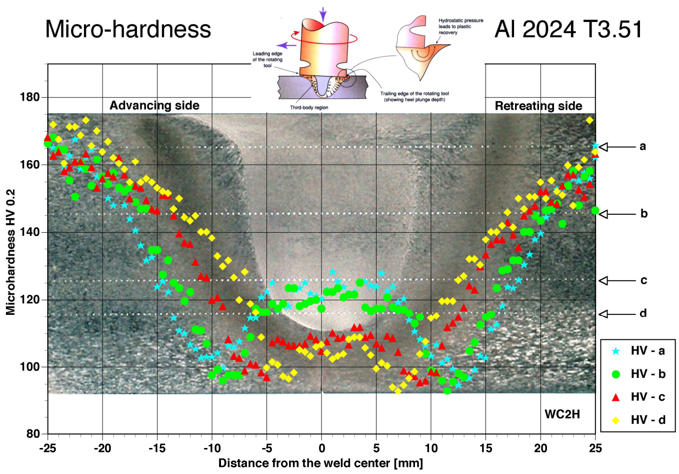
3. Properties of Weldments

3.1 Tensile Properties

Welded joints have heterogeneous mechanical properties and also exhibit highly heterogeneous microstructural variations in a local region. Adequate tensile and fracture toughness testing techniques consequently should incorporate such highly heterogeneous mechanical/microstructural features. The micro-flat-tensile (MFT) test technique [6, 9-11] is extremely useful to measure tensile properties of HAZ of multi-pass welds and very thin weld regions such as laser beam (LB) and electron beam (EB) welds. During the tensile testing of weld joint, transverse welded specimens usually fail away from the weld joint, if weld metal exhibits high strength overmatching, as shown in Figure.4. The results of such tests will inevitably provide base metal strength values but with reduced ductility, due to the presence of high strength zone within the gauge length. Advanced testing techniques with the use of image analysis system, it is possible to monitor the evolution of the plasticity across the specimen. Figure 5b is illustrating heterogeneous plastic strain localisation process for the undermatched FSW containing flat tensile specimen.

Figure 4. Typical strength overmatched flat tensile specimens failed away from the weld zone.

Micro-hardness variation across the FSW welded 2024 Al-alloy 20 mm thick plate is showing Figure 5a the heterogeneous nature of the weld joint. During the testing of flat tensile specimen, one surface of the specimen was monitored to determine the strain localisation and hence ductile failure location with respect to heterogeneous cross-section of the joint. The images shown in Figure 4b are illustrating and verifying the indications of the micro-hardness results. The micro-hardness results have revealed that the centre part (nugget) of the joint is not the region with lowest strength, whereas HAZ (or TMHAZ) regions, particularly retreating side of the joint may have lowest strength and hence failure location. Indeed, during the tensile testing of the specimens of the EU project WAFS) of joint failed due to localisation of the plastic strain. The reason for this heterogeneity of the joint with respect to advancing and retreating sides of the FSW process is due to the temperature distribution during the process.



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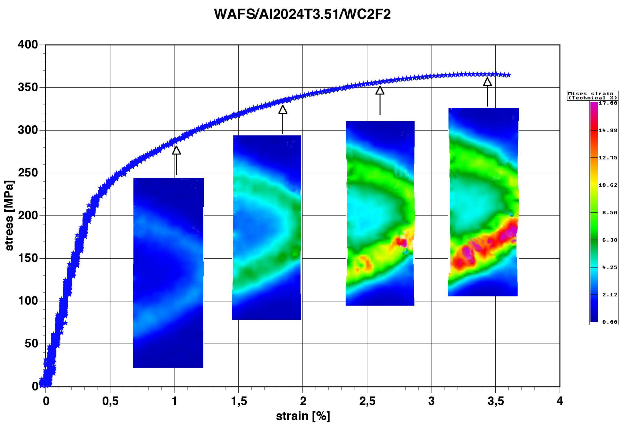


(b)

Figure 5. Microhardness and tensile testing of strength undermatched Al-alloy 2024 FSW joint.
a) Micro-hardness distribution at different depths of the FSW weld joint of 2024 Al-alloy
b) ARAMIS images of the FSW joint during the tensile testing of the joint. Images are showing at different stress levels corresponding strain distributions. [EU project WAFS]

Figure 6 is showing the specimen extraction technique from EB welded material for determination of local tensile properties of the weld joint. The micro-flat-tensile specimens are 0.5 mm thick and 2.0 mm wide and most suitable for determination of mis-match level for HAZ regions of high strength steels where HAZ softening usually occur.

Furthermore, this technique can be applied to determine the mechanical property gradient of the surface treated components which usually exhibit high degree of strength mis-match. Figure 7 is illustrating the specimen extraction of laser surface cladded (hard layer) heavy section cast material (CuAl10Ni5Fe5) to determine the property gradient of the surface layer and substrate in thickness direction. This novel testing technique provides all needed tensile properties and their variations, associated with microhardness gradient, as shown in Figure 8.

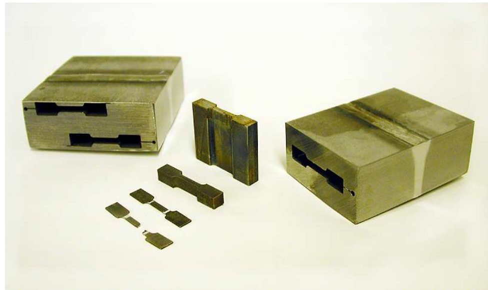


Figure 6. Extraction of micro flat tensile specimens from EB weld [10]

Furthermore, this technique was applied to determine the tensile property variation of bi-material (2024 and 6056) FSW welds of aerospace Al-alloys. Figure 9 is showing the yield and tensile strength in combination of micro-hardness distributions across the FSW joint between two different Al-alloys.

Strength mis-matching between weld metal and base metal is not always control the plastic deformation and hence fracture of the weld joint. The weld joints of the high strength steels may exhibit lower strength at the heat affected zones (**HAZ softening**) and this leads to strain localization under high external loading and hence show lower resistance to fracture at this location. An example for the HAZ softening is shown in Figure 10

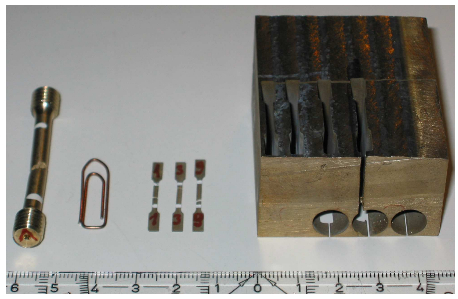


Figure 7. Micro flat tensile specimens and standard round tensile specimen extracted from laser surface cladded thick section material

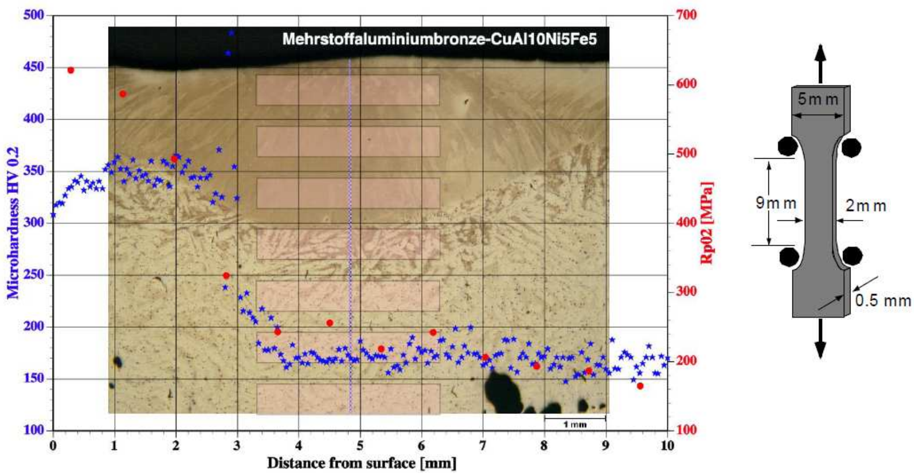
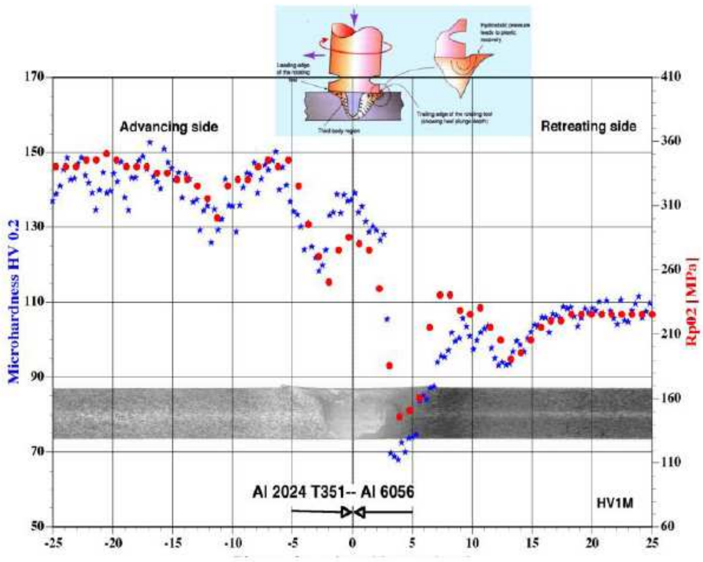


Figure 8. Microhardness and yield strength (red solid symbols) variations obtained from laser claded (surface hard layer) cast material and principle illustration of the loading type of the micro-flat tensile specimens



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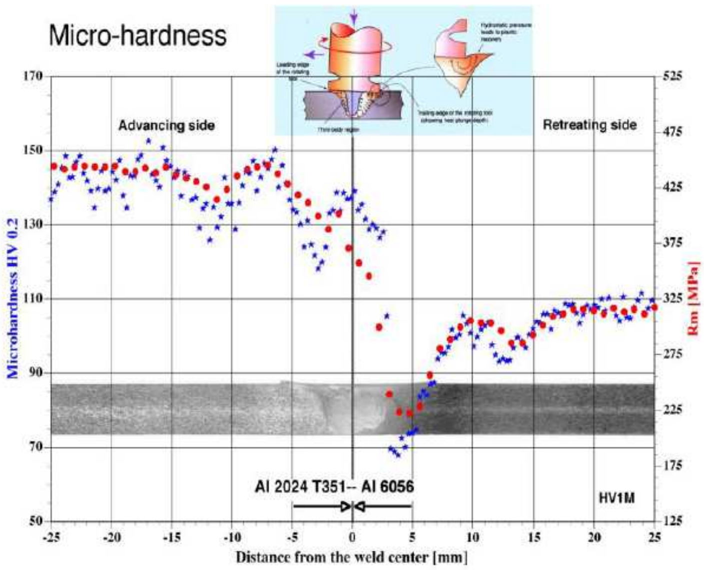


b)

Figure 9. Distribution of the micro-hardness, yield strength and tensile strength values across the friction stir welded dissimilar aerospace grade Al-alloys (2024 and 6056) butt-joint. The tensile properties are determined by testing of 0.5 mm thick micro-flat tensile specimens. [EU project WAFS]

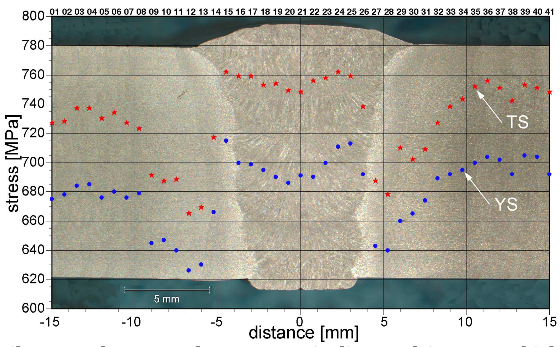


Figure 10. Distribution of yield and tensile strengths across the APIX80 pipeline steel (14.0 mm thick) weld (5 layer) showing HAZ softening. The values were obtained by testing of 0.5 mm thick micro-flat-tensile specimens (46 of them) extracted across the weld joint at the GKSS.

In the absence of yield strength value (and full stress-strain curves) of narrow HAZ zone of high strength pipeline steel welds, a flaw assessment will use the base metal properties will then be potentially unsafe. Therefore, it is recommended to obtain full stress-strain curves of all regions of the weld joint if complex mis-match situation is of a concern, as demonstrated in Figure 10.

3.2 Fracture Toughness Determination of Strength Mis-matched Welds

Strength mis-match affects the constraint conditions near the crack tip, and hence effects of mis-match on the fracture toughness properties are to be expected. During the fracture toughness testing of very narrow weld metal zones (laser and electron beam welds, or HAZ regions) crack path deviation occurs towards lower strength regions as shown in Figure 11 below. Hence, the toughness value generated from such specimens will not represent “intrinsic fracture toughness” properties of the zone of interest. This situation is a consequence of the remote plasticity development in the neighbouring base metal, as illustrated in Figure 2 and hence obtained fracture toughness values are meaningless. It is obvious that plastically heterogeneous interfaces (both sides of the narrow fusion zone with much lower strength level than fusion zone) near to the crack tips experience high strain concentrations and this often leads to crack kinking out of the high strength but lower toughness region as illustrated in Figure 11.

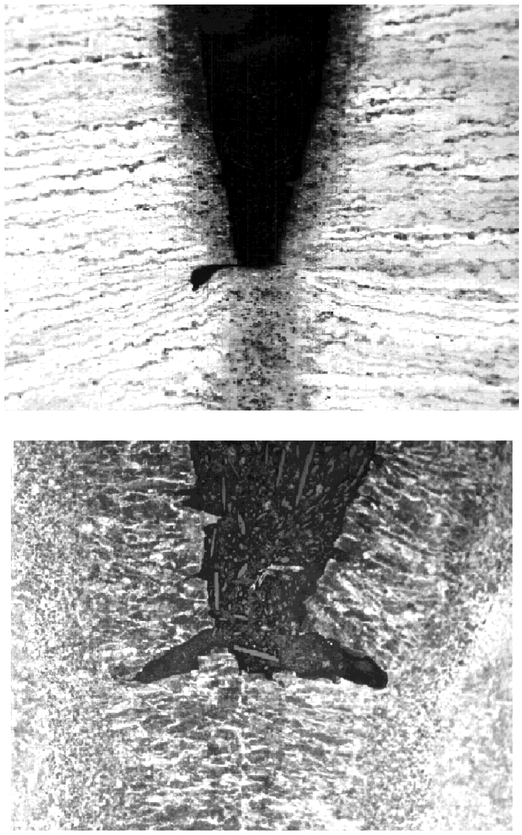


Figure 11. Two types of fracture path deviations into the lower strength base metal regions during the fracture toughness testing of highly overmatched laser beam welds of ferritic steels [12, Doc. X-F-078-98]

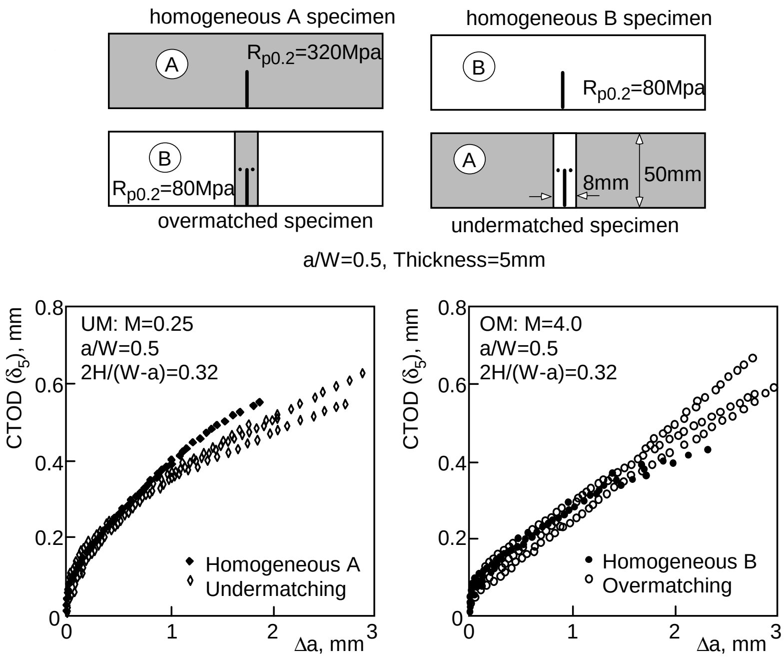


Figure 12. CTOD δ5-R-curves for highly over- and undermatched model weldments to demonstrate the geometry independency of the local CTOD measurement technique. Here, homogeneous means all weld metal SENB specimen [8]

In this context, mis-match adjusted toughness evaluation methodology need to be used to compensate the mis-match induced constraint on toughness. Alternatively, fracture toughness can be obtained directly at the crack tip, using clip or non-contact displacement measurement/monitoring unit. One of the techniques in this field is the CTOD-δ5 technique (known as GKSS method) and this uses direct crack tip opening displacement measurements as toughness measurement. This toughness determination technique does not require any mis-match adjustments. This was demonstrated by using model weldments (EB welded bi-material SENB specimens) in Figure 12. The unique R-curves indicate the fact that local CTOD is not being influenced with the mechanical properties of the neighbouring zones.

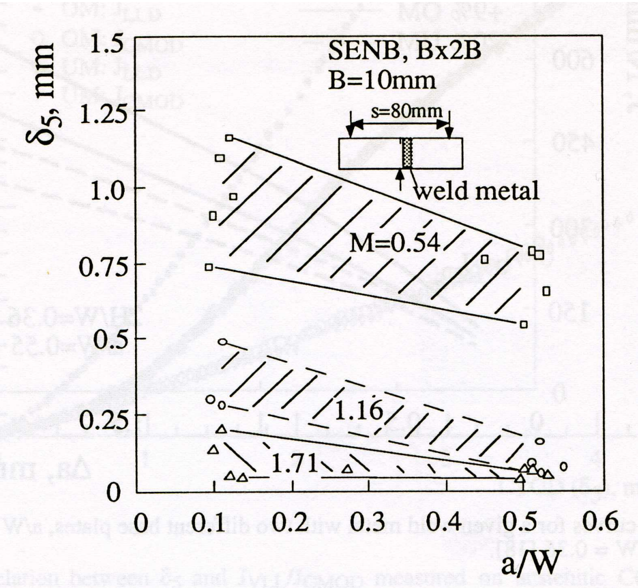


Figure 13. Effect of weld metal strength on HAZ fracture toughness for two notch depths [1, 8]

The strength level of the weld metal influences the toughness values of the HAZ. This was demonstrated by testing of HAZ notched SENB specimens with shallow and deep notched specimens with using different wires which produced three distinct levels of mis-match conditions for the same base metal. Figure 13 is illustrating the effect of weld metal strength on the measured CTOD values for both lower (a/W=0.1) and higher constraint (a/W=0.5) specimens. Here, it should be noted that the local CTOD measurements were made with clip gauges, which enveloped both weld and HAZ+BM regions. Inevitably, obtained fracture toughness values exhibit "apparent HAZ toughness" values which do not represent intrinsic fracture toughness properties of the martensitic microstructure of the HAZ region.

In order to investigate the interfacial fracture between two highly different metallic materials with respect to elastic and plastic properties, a bi-material model weld has been produced using ferritic and austenitic steels and diffusion bonding process. This project was studied together with EDF-France to improve understanding of strength mis-match effect on the fracture toughness. Figure 14 is showing a round tensile specimen after testing of a such bi-material specimen where complete plastic strain accumulated within the weaker austenitic material part. Figure 15 is presenting the yield strength properties obtained from testing of micro flat tensile specimens across the interface. These results are also compared with the testing of standard round tensile specimens, as shown in Figure 15.

Figure 14. Post-test view of the bi-material round tensile specimen between ferritic and austenitic steels joined using diffusion bonding process.

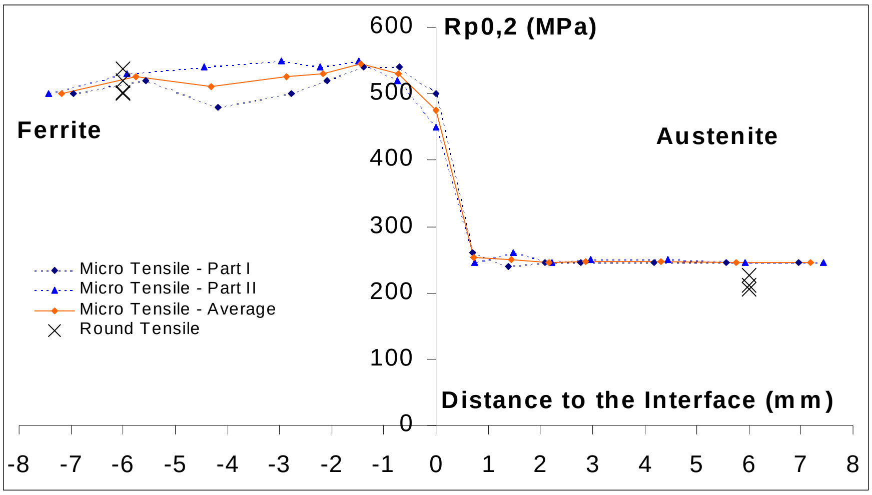


Figure 15. Yield strength values of bi-material joint between austenitic and ferritic steel. The results are generated with the testing of 0.5 mm thick micro-flat tensile specimens. Bulk material properties are compared with round specimens extracted away from the interface.

Fracture toughness properties of such bi-material interfaces were determined using SENB specimens notched at various locations at the vicinity of the bi-material interface. The initial notch was located at the interface (I), ferrite (F) and austenite (A) materials with constant distance to the interface. Figure 16 is showing the load vs. CMOD curves obtained from various specimen types, which are schematically shown with obtained respective curve. The specimen with interfacial crack shows immediate effect of higher strength ferrite material by having higher load carrying capacity. However, most striking effect of lower strength material on the fracture toughness of ferrite material is to prevention (orange colour curve) of unstable fracture phenomena which is the intrinsic property of the ferrite (red curve). It appears that the critical stress state needed for a brittle or unstable crack initiation is not reached by relaxation of the crack tip stress by remote plasticity within the austenite. Accompanying numerical investigations of this bi-material system was conducted in France has also materialised these results. These test results have shown significant effect of the material properties of neighbouring zone adjacent to the interface.

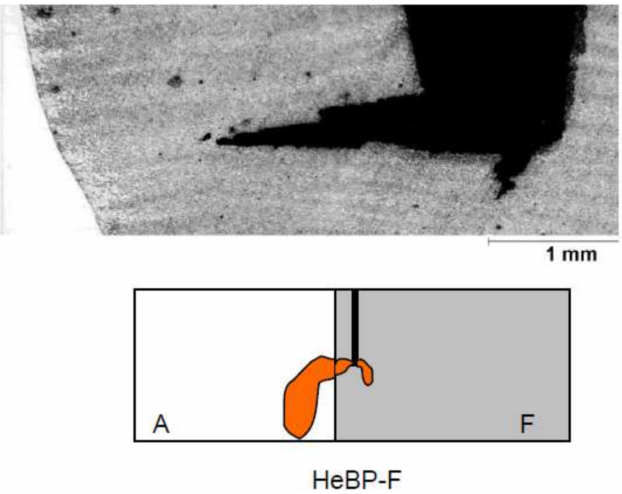


Figure 17. Macro section of the sub-interface crack tip (located into the ferritic-F- steel side of the interface) and strong crack path deviation towards lower strength (but toughnes) austenitic-A- material. The figure is also schematically showing the development of heterogeneous plastic zone at the interface region.

Unstable deformation behaviour of all-ferrite specimen (shown in red colour curve) becomes stable once specimen contains soft (lower strength) austenite material, as orange colour curve demonstrates.

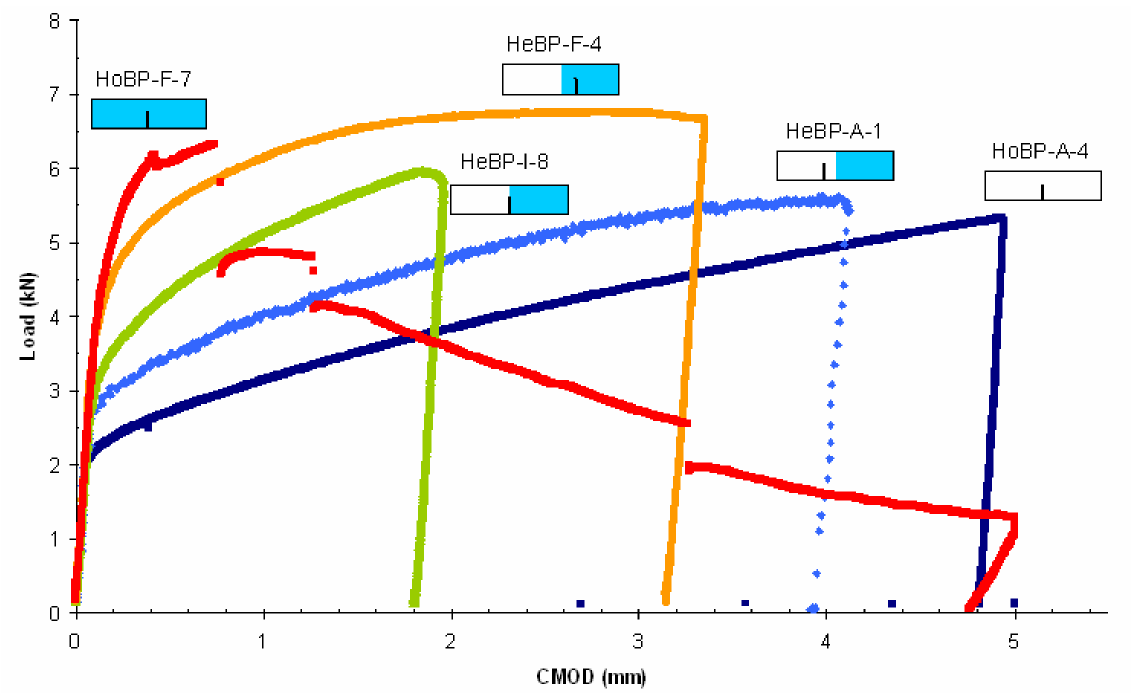


Figure 16. Load vs. CMOD curves of SENB specimens containing bi-material interface. Notch locations were varied, where blue colour SENB specimen (HoBP-F-7) representing all-ferrite homogeneous specimen while white coloured specimen (HoBP-A-4) refers to all austenite material.

An extensive development of plasticity at the lower strength (A) side of the bi-material specimen has inevitably occurred and crack growth took place taking into account of least resistance path of the interface region. Apparently, banded microstructural feature of the ferritic steel has provided easy crack path to develop a ductile crack towards lower strength material. These tests confirm that cracks tend to go into the lower strength material or zone due to localisation of the plastic deformation. Fracture toughness values obtained from such systems will not represent "intrinsic" material properties of the material where crack tip originally placed.

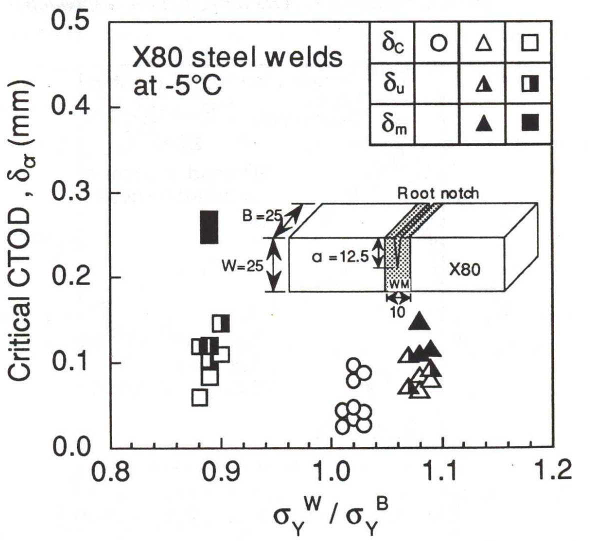


Figure 18. CTOD results for undermatched, matched and overmatched welds of X80 steel [58].

Further implications of such investigations on model welds with respect to strength-undermatched systems are clearly visible. Weld joints of high strength Al-alloy welds and HAZ softened regions of pipeline steel welds will be potential failure locations due to the localization of plastic deformation.

The work of M. Ohata and M. Toyoda *[38]* was conducted on the X-80 pipeline steel weldments using three different wires and analysing the fracture performance of these welds with surface cracked wide plates showed the effect of mis-match on the fracture performance of these welds. Figure 14 is showing the fracture toughness values for different strength mis-match conditions. Fracture toughness of the EB welds (highly overmatched) on 38 mm thick steel was determined using deep notched SENB specimen to investigate the effect of specimen thickness (B) on the fracture toughness of the EB weld fusion zone (FZ).

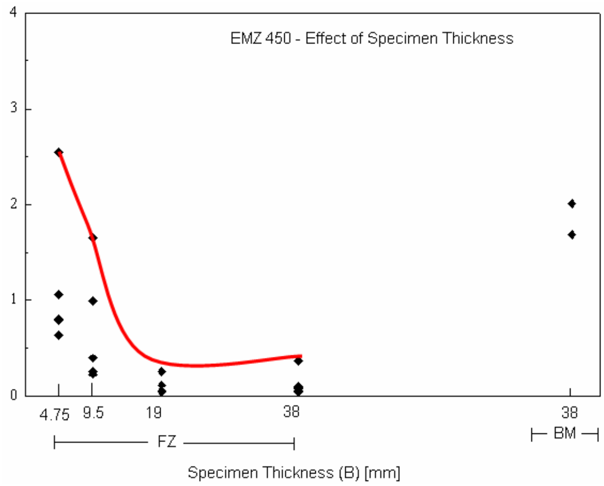


Figure 19. Effect of specimen thickness (B) on fracture toughness of 38 mm thick steel welded EBW process [Unpublished results from EU Project ASPOW]

In addition to the SENB specimens with full plate thickness of 38 mm, the specimens with 19mm, 9.5 mm and 4.75 mm thickness were prepared and tested with identical a/W ratio of 0.5. The results are presented in Figure 15. The results are showing clearly the effect of the specimen thickness (B) for a given weld width (2H) and uncracked ligament (W-a) on the so-called "*apparent fracture toughness*". Although, crack tip was located at the identical microstructure, reduction of specimen thickness caused an increase of apparent toughness (and of scatter) of highly overmatched EB weld fusion zone. Reduction of the constraint (a decrease of B/2H or B/(W-a) of the overmatched SENB specimen, therefore, shows an increase of "apparent toughness' which does not represent an "*intrinsic fracture toughness*" of the EB weld zone.

3.3 Weld Strength Mis-matched Structures under Cyclic Loading

Weld strength mis-match principally plays a significant role under elastic-plastic loading conditions where large plasticity at the crack tip interacts with different materials/regions with different mechanical properties. Once interaction occurs and neighbouring material influences the evolution of the crack tip stress/strain state, under external loading, one should expect an influence of mis-match on the deformation and/or failure behaviour of the welded component. Numerous investigations have been conducted to characterise the constrained plasticity and interface fracture toughness issues both under small and large-scale yielding conditions and some of these are reported in the proceedings of the Mis-match 93 and Mis-match 96 International conferences.

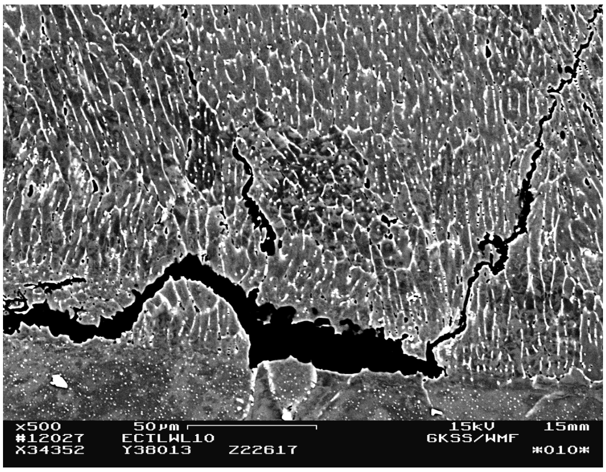
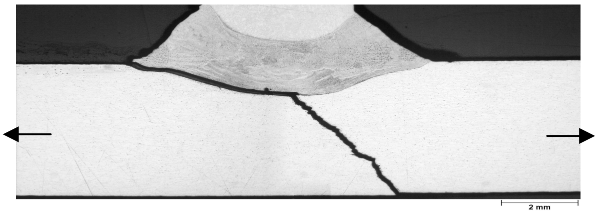


Figure 20. Fatigue crack growth at the fusion line region of the laser welded Al-alloy which exhibits strong undermatching [24]

Recent studies at the GKSS have focussed on the strength undermatched structures operating both under cyclic (constant and variable amplitude) and static loadings due to the increasingly use of higher strength materials. The evaluation of fatigue crack in laser beam and friction stir welded Al-alloy weldments exhibiting highly strength undermatching conditions have been investigated. Figure 16 is showing the fatigue crack growing at the interface (fusion line) between highly undermatched weld zone and base metal.



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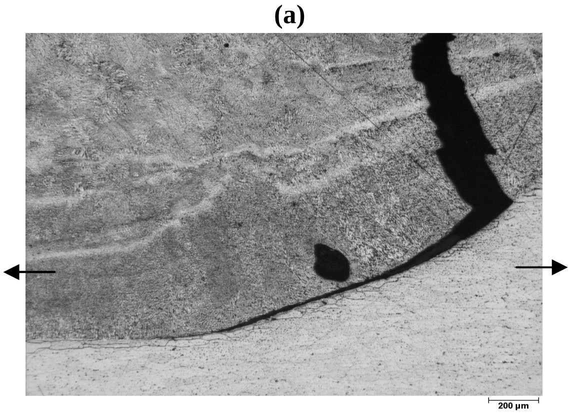

(b)

Figure 21. Fatigue crack growth features along the interface of the laser welded fillet welds of 6xxx series of aerospace Al-alloy, a) crack initiates at the weld toe and propagates along the fusion line towards bottom of the fillet weld, b) micrograph of a crack initiated and advanced within the soft weld, but once reaches to the interface turns into the much softer interface layer.

Figure 17 a illustrates the fatigue testing of fillet weld (laser welded skin-stringer joints of airframes) where horizontal plate (i.e skin) was subjected to the cyclic loading, as arrows are indicating. When this welded configuration (with highly strength undermatched joint) is subjected to fatigue loading, a fatigue crack easily initiates at the weld toe and advances along the fusion line, almost parallel to the loading axis and turns into sheet thickness direction once reaches to the bottom of the fillet weld where angle of the weld changes. Figure 17b reveals further effect of interface mis-match on the growing fatigue crack. It appears that as the plastic zone ahead of the fatigue crack in the soft weld zone touches the interface (very thin layer of precipitation free soft zone) with adjacent base metal with higher strength, the crack kinks to the interface which is not perpendicular to the loading axis. Continued cyclic loading causes micro-bifurcation within the soft interface region before penetrating back into the base metal region. These examples are clearly showing how strength heterogeneity both large scale and micro-level operate to control the advance of the damage and failure of the component. This kind of information can be utilised to design effective crack arresters/barriers to achieve fatigue resistant heterogeneous or bi-material systems.

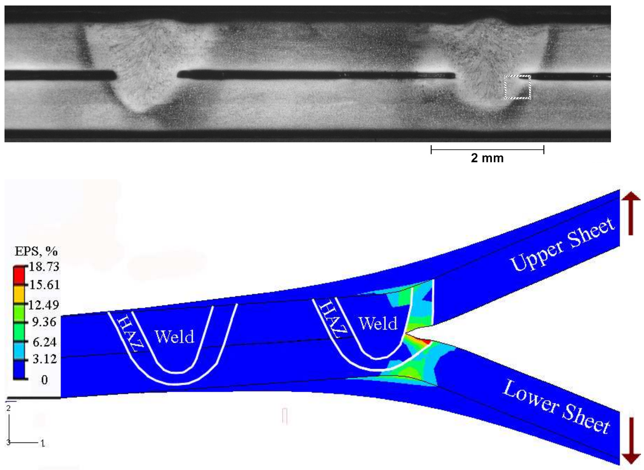

Figure 22. Macro-section of the laser spot welded steel Sheets and strain distribution at the vicinity of the strength overmatched weld vicinity during the coach peel test [36]

Recently developed advanced high strength steels (AHSS) are used in car body using resistance spot welding. This welding technology is being challenged with developments in laser beam welding. Laser spot welding for such applications create highly overmatched spot welds. Figure 18 is showing a cross section and FE simulation of such joints under peel testing conditions. Strength overmatch of weld and smaller weld volume in the lower sheet determines the failure location in the lower sheet.

4. Performance of Welds

4.1 Structural Integrity Assessment of Weld Strength Mis-matched Structures

Structural integrity assessment of components containing flaw can be conducted to determine one of the following objectives [27];

- to select suitable material for a given tolearable defect size, as specified in the design;
- to find the defect tolerance of a welded structure;
- to find if a known defect is acceptable; to determine or extend the life of a structure;
- to determine cause of failure.

Analysis Options	Type of tensile data required	Type of fracture toughness data required	Other information
0 Basic	YS or SMYS only	None; Charpy energy only	Relies on correlations; applicable to ferritic steels only
1 Standard	YS and UTS	Single-point fracture toughness data or tearing resistance curves	Based on tensile properties of the weaker material (typically the PM) and the fracture toughness of the material in which the flaw is located
2 Mismatch	YS and UTS of PM and WM	Single-point fracture toughness data or tearing resistance curves	Takes account of strength mismatch; typically worth applying only if M≥1.1 or M<0.9
3 Stress-strain	Full stress-strain curves for PM and WM	Single-point fracture toughness data or tearing resistance curves	Can take into account both strength mismatch and the shape of the stress-strain curve
4 J-integral	Full stress-strain curves for PM and WM	Single-point fracture toughness data or tearing resistance curves	CDF approach only; elastic-plastic FEA is used to calculate the driving force for the cracked body
5 Constraint	Full stress-strain curves for PM and WM	Relationship between fracture toughness and crack-tip constraint, eg J as a function of T-stress	Can take into account constraint effects, by matching crack-tip constraint in the test specimen and the cracked structure

YS: yield (or proof) strength, SMYS: Specified Minimum Yield Strength, PM: Parent Metal, WM: Weld Metal
M: mismatch ratio (ratio of WM yield strength to PM yield strength)

Figure 23. Analysis of Options of Fracture Module of the FINTET FFS Procedure [34, 35]

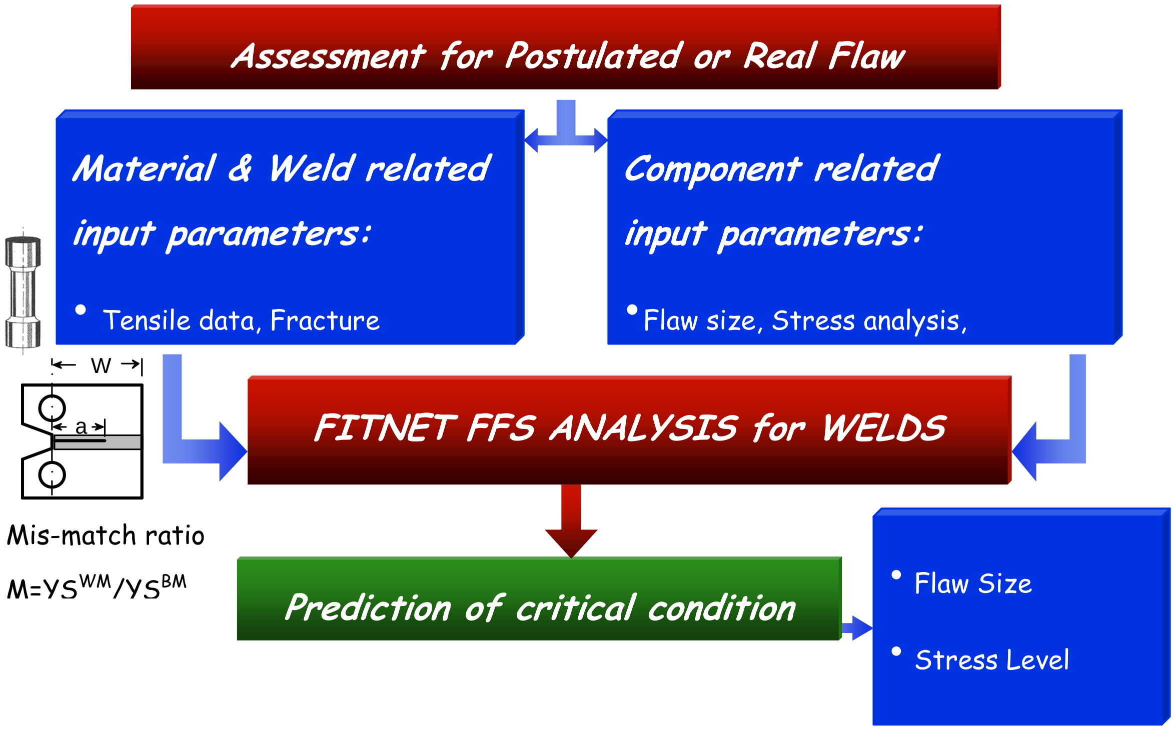

Figure 24. Flow chart of the Fracture Module of the FITNET FFS Procedure for assessment of the weld flaw.

Defects in welded structures often occur within or near welds across which tensile properties significantly vary. As described in previous sections, this strength mis-match in tensile properties can affect the plastic deformation pattern of the defective component, and thus the crack driving force such as CTOD or J integral. Until research work was conducted within European project SINTAP [18, 37], existing defect assessment methods were restricted to the homogeneous structures. In principle, the methods for homogenous structures can be applied to welded structures, if the tensile properties of the weakest material are used; for instance, for overmatched welds (M>1), those of the base metal. However, such a simplified approach can lead to an unduly conservative result, and thus a FFS methodology specific to strength mismatched structures was needed to reduce excessive conservatism. For this very reason, the SINTAP Procedure [14, 18, 25, 37] introduced a novel flaw assessment route for strength mis-match welds. FITNET FFS Procedure [34, 35] takes over these routes (Options 2 and 3), Figure 18, for treatment of conventional multi-pass and advanced (laser and friction stir) welded structures [25, 31, 32]. The latter one particularly exhibits significant (up to 50%) strength undermatching in structural welds used in aluminium structures of automobile, marine and aerospace. Figure 20 illustrates the principle of the FITNET FFS procedure for weldments.

4.2 Mis-match Limit Load

The limit load of the welded structure is the most crucial parameter for the assessment of the strength mis-matched welded structures. The limit load of mis-matched structures differs from those of homogeneous all base metal or all weld metal structures or considerations. It lies between these two limits and controls the evolution of plastic deformation of the cracked body and hence of the crack driving force. In classical solid mechanics the limit load is defined as the maximum load a component of elastic-ideally plastic material is able to withstand, above this limit ligament yielding becomes unlimited. In contrast to this definition, real materials strain harden with the consequence that the applied load may increase beyond the value given by the non-hardening limit load. Sometimes strain hardening is roughly taken into account by replacing the yield strength of the material by an equivalent yield strength (flow strength) in the limit load equation. In the fitness-for-service (FFS) analysis procedure FITNET, numbers of limit load solutions, including newly developed [e.g 13, 15,] are given in Annex B (Vol II) [35]. The results and recent developments of SINTAP, BS7910, R6 sources are used to generate this Annex.

Extensive validation works have been conducted during the development of the FITNET FFS Procedure. Some of these investigations can be found in [21-33]. Furthermore, series of collected case studies used both during validation and training of young engineers (Hand outs and lecture notes for FITNET Training Seminars) and this volume will also be released soon.

4.3 Weld Strength Mis-match in Steel Pipelines

Extensive investigations have been conducted during last decades to develop steels, welding technologies and improvements of design and flaw assessment guidelines for oil and gas linepipes. These developments have played a significant role for safe and economic transportation of natural gas and oil as well as their field developments. Offshore pipelines in deep water and long distance gas transporation produced challenges to develop high strength and high toughness steels to reduce cost. Up to X120 steel grades have been developed and weldability, strength mis-match and crack arrest issues were intensely investigated. The higher strength and toughness could be reached by the TMCP while maintaining the good weldability (keeping Ceq at a suitable level).
It is known that for high strength steels, the potential for only slightly overmatching or even matching is more likely to occur than the lower strength steels. Therefore, whenever the seam weld or girth weld of the pipe may influence the limit state of the pipe, weld strength overmatching should be maintained to start with. This situation appears to be more difficult to fulfil for X120 (827 MPa) steel pipes and strength undermatching most likely to occur to satisfy the toughness and ductility requirements. The steel producers of X120 grade utilizes a different microstructural system which is different than typically used in X80 (quench and temper microstructure). This in turn may affect the crack arrest (propagating ductile fracture) behaviour of such steels and welds.
The strength of linepipe is generally increasing to reduce the cost and hence the linepipe steel X100 has been developed by many steel manufacturers using basically steel chemistries of low C- high Mb, Mo, Nb (V) microalloyed system with Cu, Ni and Cr using TMCP technology. However, these steels show significant HAZ softening and insufficient overmatching weld metal. During the last decades, the Y/T (yield to tensile) ratio of pipeline steels has increased from about 0.80 to 0.9 and above. Today, pipeline steel standards (e.g API 5L and DIN 17172) specify a maximum Y/T ratio of 0.93 to ensure sufficient ductility.
It is often reported that cross-weld tensile properties determined by the properties of HAZ and weld metal fractures. Even most of the burst tests reported to be failed in the weld joints of high strength steel pipes. It is obvious that designers of pipelines (especially for strain based applications) are unlikely select weld metal that is undermatched compared to the base metal. However, lower strength regions in girth weld applications can still occur, even when the weld metal is overmatched. For example, root pass is often welded manually with an undermatched consumable to reduce the risk of hydrogen cracking and promote better tie-ins. Further, HAZ regions, can exhibit lower strength then either the weld metal and base material, as shown in Figure 21.
These results have been presented during recent pipeline conferences (e.g. Pipe Dreamer's Conference, 7-8 Nov. 2002, Yokohama, Japan and 4th Pipeline Technology conference, 9-13 May 2004, Ostend, Belgium).

It has been also shown [19] that internal pressure of pipelines can concentrate the strain into low-strength HAZ of girth welds and an elevation of strain in the HAZ may not be proportionally increase with the remote strain to failure. This and similar other investigations [e.g. 16, 20 see also proceedings of Pipe dreamers conference and Pipeline technology conference volumes] have revealed that the structural significance of local strain elevation topic needs further investigations.

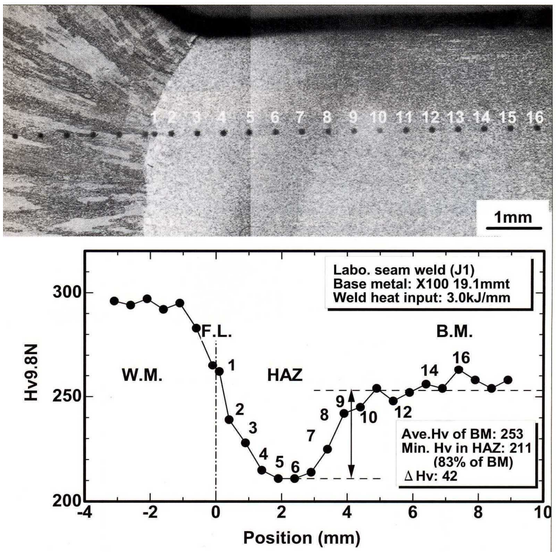

Figure 25. Hardness distribution across the weld joint of X100 steel, showing HAZ softening (undermatching) while weld metal exhibit overmatching [16].

Furthermore, high longitudinal strain is one of the most critical loading conditions experienced by pipeline girth welds. Such high longitudinal strain in onshore pipelines is often associated with soil movements (seismic activity, slope instability etc.). On the otherhand ofor offshore pipelines, high longitudinal strains occur during the pipe laying operation (reeling) and it can be as high as 2-3%. Presently, DNV Offshore Standard F101 provides substantial guideline for defect acceptance criteria for under longitidunal strain condition and this guideline suggest to use BS7910 (Level 3) type of analysis (which is also stress based), if the accumulated strain is higher than 0.3%. Recently developed FITNET Fitness for Service Procedure does not provide a strain based analysis and it is planned to develop a section addressing to this topic including analysis of higher grade steel pipes (higher Y/T ratio materials) and welds (beyond X80) and crack arrest issues of these steel linepipes.

One of the open issues that need to be dealt with is the generation of low-constraint fracture toughness values of the welds and HAZ regions using SENT specimens. Currently, no solution is available to conduct mis-match corrected toughness (CTOD and J) testing procedure for such specimens. Particularly, testing of welds with HAZ softening (together with weld metal mis-match ratio) and inclusion of its effect on fracture toughness and crack driving force estimation (beyond the elastic strain range) is a complex issue and need further research.

4.4 Weld Strength Undermatching: Welded Thin-walled Al-alloy Aerospace Structures

Thin-walled components such as used in aerospace and ship structures are designed to satisfy the damage tolerance requirements of fatigue and residual strength. The residual strength of a homogeneous structure is basically a function of material properties (strength, toughness etc.), flaw and component geometries as well as the applied stress. The residual strength assessment route, therefore, is well established and successfully used for the riveted (differential) structures in the last decades. However, assessment of welded (integral) structures requires detailed information on the local weld joint (fusion or nugget area and heat affected zone) properties and weld geometry. This information is of particular importance if the weld joint exhibits mechanical heterogeneity (strength mismatch). Joining of aluminium alloys by friction stir (FSW) or laser beam welding (LBW) usually produces a weld joint area having significantly lower strength (undermatching) than the base metal and this needs to be taken into account during the structural integrity assessment. In such welded structures, a lower strength weld zone may lead to a plastic strain concentration in the weld joint if it is loaded beyond the yield stress of the weld material and, hence, to the development of higher constraint within the weld region due to this heterogeneous deformation behaviour. Therefore, this strength mismatch induced complexity needs to be considered when residual strength analysis is conducted for such structures. Most of the published validation cases of the FITNET FFS Procedure deal with strength overmatched welded thick-walled components where such welds are common for steel structures. There was a need to generate new experimental data on highly undermatched thin-walled structures to provide validation cases for the FITNET FFS Procedure [35] where welded structures with strength mismatch can be assessed. Recently, some validation cases [18, 22-25]. were successfully undertaken with particular interest to structures welded with advanced joining techniques and containing strength mismatched welds. The recent studies, therefore, focussed to the application and validation of the FITNET FFS Procedure on thin-walled Al-alloy airframe structures where base metal and LBW and FSW welded large panel tests provide experimental data [20]. These investigations need to be extended to the improvement of damage tolerance performance of weld strength mis-matched components using so-called “local engineering” methods. These methods include modifications of stress state around the weld area by tailoring of the joint design, welding process and surface treatments.

The use of adequate and precise input parameters (based on the experimental observations of the damage process in the undermatched weld area) is particularly essential to describe and predict the critical condition in such structures. The selection of strength and toughness values to be used in the assessment has significant implications on the outcome of the analysis and require new considerations to avoid excessive conservatism of the predictions.

The treatment of the significantly strength undermatched thin-walled laser welded Al-alloys both in butt-joint and stiffened panel configurations have been investigated and Refs. [18-21] report the results. A large number of mis-match limit load solutions in the existing SINTAP procedure is being reviewed and extended (for example covering clad (bi-material) structures) and given in Annex B of the second volume of FITNET FFS.

As an example, two panel results of the strength undermatched laser welded aerospace Al-alloys programme [18, 22-24] was selected to demonstrate the application of FITNET FFS Mis-match Option. Figures 26 and 27 are showing both experimental results of the panels and comparison with the FITNET predictions where three different m-values (intends to quantify the constraint at the crack tip) are used to determine the sensitivity of the analysis to the m-values (where $\delta_5 = K_J^2 / m\, R_{p0.2}\, E$).

The mis-match yield load and load carrying capacity level of the cracked panels provide information on the stress state in the uncracked ligament ahead of the crack. The failure of the undermatched panel occurred above the yield load indicating an elastic-plastic regime but it was far below the tensile strength (approx. 350 kN) of the laser welded joint giving rise to failure caused by a critical crack tip condition (mis-matched induced) and not by plastic collapse.

The variation of parameter m shows that for larger m, the predicted curve becomes stiffer, reaching its maximum at smaller CTOD values, Figure 27. For m=2.0, the FITNET prediction is in good agreement with the experimental failure load as well as the deformation behaviour. This result shows that strength undermatching indeed increases the crack tip constraint to the level of plane strain, although 2.0 mm thick panel under tension, if it was homogeneous, should operate under plane-stress condition.

Furthermore, FITNET analysis carried out in [24] for a much more complex case of reinforced thin panels containing laser welded multiple stringers. In this case, Al-alloy panels with three longitudinally laser welded stringers are tested (test 1 and test 2) and load vs. CTOD curves are predicted with FITNET FFS Procedure. Two analysis Options are used, that the predictions are in good agreement with experimental results while predictions are remaining at the conservative side, Figure 27.

The Fracture Module provides a hierarchical assessment structure (Options) based on the quality of available input data. Using a higher assessment option ensures a decrease in conservatism due to an increase of data quality. Refining the stress analysis of the component and/or improving the sizing of the flaw under consideration can also achieve a decrease in conservatism. The use of Option 3, as shown in Figure 28, proves that the higher analysis Option decreases the conservatism in predictions.

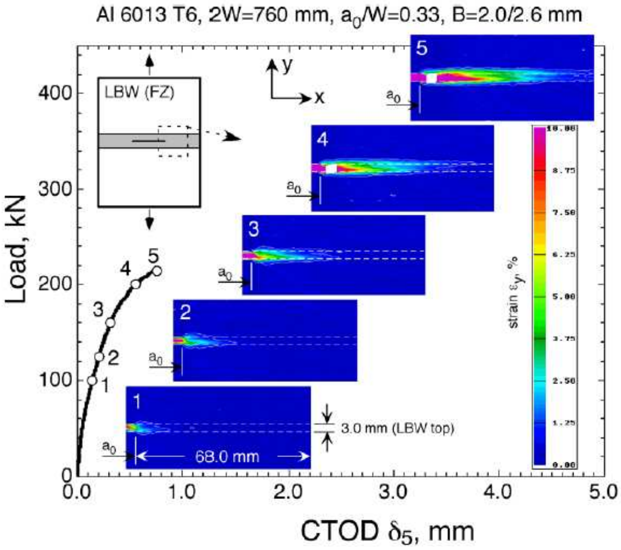

Figure 26. Load vs. CTOD curve of the center cracked 760 mm wide plate. The panel was 2.0 mm thick (weld joint area 2.6mm) aerospace grade Al-alloy 6013 and contained highly undermatched 3.0 mm wide laser weld. Furthermore, figure contains images of the plasticity development at the crack tip and within the strength undermatched weld. FITNET FFS Procedure was applied to predict the failure load (point 5) of this thin-walled and highly mis-matched weld panel under tension [24]

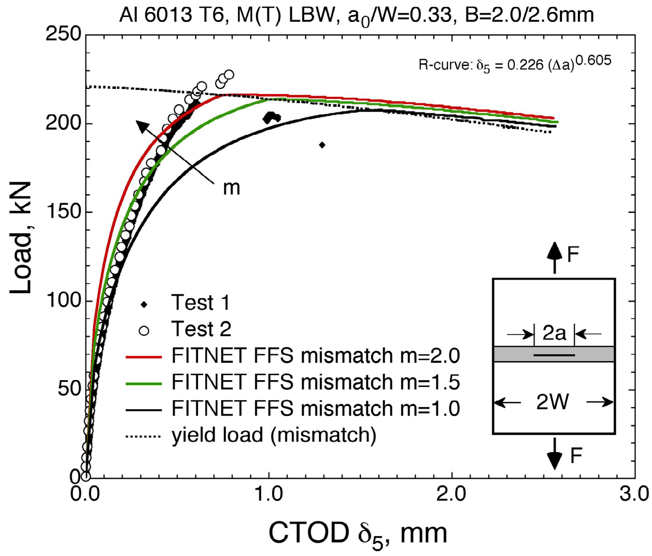

Figure 27. Comparison between FITNET FFS Fracture Module Option 2 (mis-match) predictions and experimentally obtained load vs. CTOD curves of the thin-walled panels described in Fig. 5. The R-curve was used in the analysis was obtained from small C(T)50 type fracture toughness specimens [24]

4.5 Current status of the FITNET procedure

The FITNET FFS procedure is currently available, Figure 9 to interested parties in the form of a final document, Revision MK8 [34, 35]. The ultimate aim remains to publish the procedure (Volumes I and II) as a CEN document, via a CEN workshop agreement (CWA 22). It is likely that the volume containing validation, case studies and tutorials will remain the intellectual property of the FITNET consortium, and will be published separately by them. In the meantime, plans are underway to adopt relevant parts of FITNET into a future edition of the BS 7910, the UK national procedure.

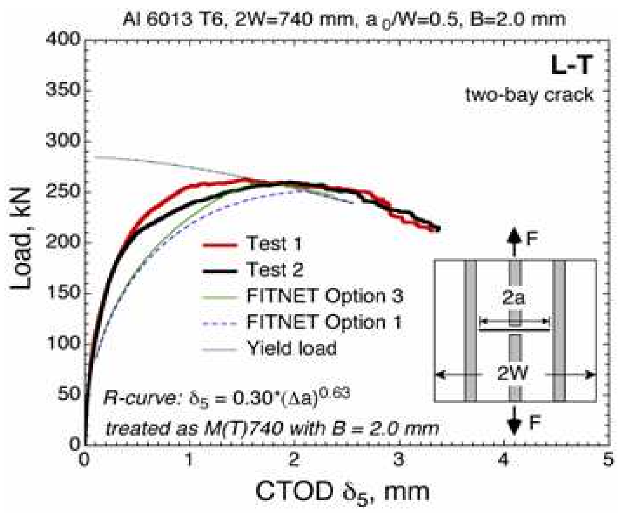

Figure 28. FITNET FFS predictions (Option 1 and Option 3) of a residual strength of laser welded 3-stringer panel with large central crack (broken central stiffener) [24].

5. Final Remarks

Extensive international efforts have been made to design and assess the primary welded engineering structures for safer operation provided framework for significant progress and numbers of sucess stories to develop. For this process-property-performance relationships have been established for various systems.

Research should continue to develop technology and knowledge applicable to all industrial sectors operating load-bearing structures, which require safety to be properly inbuilt in the design and fabrication processes as well as structural health monitoring, quality inspections and maintenance to ensure the structural safety throughout their lifetime.

On the other hand, engineering structures will increasingly be fabricated using "multi-material design" principles, which will use different materials with different mechanical properties to increase the structural efficiency and for cost and weight reduction purposes. This will expand the heterogeneous nature of the components with numbers of dissimilar joint interfaces. Treatment of defects and cracks in such components will require new approaches and methodologies. Long - term research is therefore, needed to develop and establish the structural safety principles of the hybrid components increasingly used in various manufacturing industries. Multi-material design principles should make use of the existing knowledge on the strength mis-match.

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