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STRUCTURAL INTEGRITY ANALYSIS OF THE USABILITY OF HIGH STRENGTH STEELS (HSS)

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Abstract. High strength steels (HSS) of yield strength between 500 – 900 MPa are used in industries such as shipbuilding and automobile manufacturing and for applications like offshore structures due to their advantageous physical and mechanical properties, which surpass those of conventional steels. Although the strength levels of HSS make structural weight reduction possible, and corresponding reduction of transportation and other manufacturing costs, the usability of high strength steels is negatively affected by issues such as a susceptibility to cracking and heat affected zone (HAZ) softening due to the effects of welding heat input. These quality problems can have a detrimental effect on the structural integrity of HSS welded structures. This paper critically reviews the usability of high strength steels from a structural integrity viewpoint drawing attention to the key issues involved. A decision-making tool for risk assessment based on the analytical hierarchy process (AHP) is presented and its suitability for evaluation of structural integrity risk in welded HSS structures. Challenges regarding HSS usability from the weldability and service performance perspectives are related to factors such as heat input, cooling rate and type of filler material; and weld geometry and crack propagation, respectively. The potential of an on-line welding process monitoring system incorporating AHP as part of the risk assessment process is noted. Additionally, the study identifies a need for further research on neuro-fuzzy network systems as an optimization mechanism for mitigating potential flaws in welding usability of HSS and its variants (advanced high strength steels, and ultra-high strength steels).

1. INTRODUCTION

High Strength Steels (HSS) are in increasing demand since their superior physical and mechanical properties to conventional steels (e.g. grade S235, S355, etc.) permit their use in a wide range of industrial applications. However, a number of unfavorable characteristics, like susceptibility to cracking and heat affected zone (HAZ) softening, due to the effects of welding, limit the usability of high strength steels [1,2]. These undesirable characteristics can lower the integrity of structures constructed of HSS, making the structures weak, unstable and prone to fatigue failure, which in-turn can lead to catastrophic failure in some scenarios. It has been observed that HSS structures are sensitive to fatigue phenomena as a result of the welding heat input [3].

To be able to alleviate the detrimental effects of welding of HSS, thorough investigation of weldability and service performance, including effective, efficient and rigorous risk assessment, is required. This paper presents a framework that evaluates essential factors and processes in determining the structural integrity of welded HSS. As shown in Fig. 1, many elements associated with weldability, service performance, machine factors and human factors have effects on structural integrity. Also as depicted in Fig. 1, these elements need to be evaluated through structured risk assessment, for example, by use of

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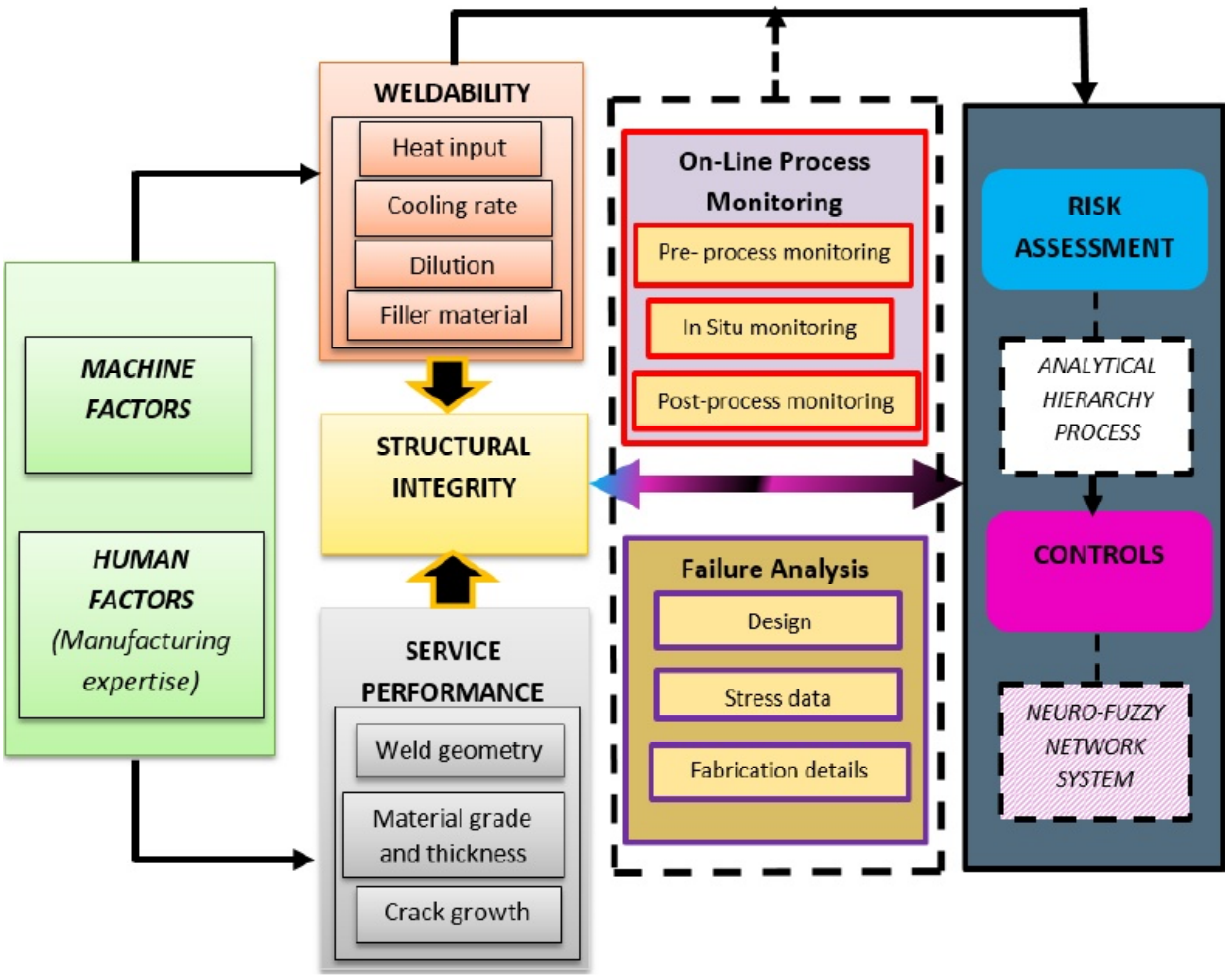


Fig. 1. Schematic framework for determining sound structural integrity in welded HSS structures.

a decision-making tool such as the analytical hierarchy process (AHP).

In addition to the risk assessment process, the framework includes on-line process monitoring and failure analysis procedures. These procedures serve as a new approach to facilitate the risk assessment process. The elements, factors, processes and procedures presented in the framework are elaborated in the paper.

Furthermore, the cross link shown in Fig. 1 represents a feedback loop system between the effects on structural integrity and the entire risk assessment and control process. Based on this cross link "feedback loop system", the adoption of a neuro-fuzzy network system approach is proposed as an optimization mechanism for eliminating potential flaws when welding HSS. This paper attempts to bridge a research gap observed in the literature pertaining to risk assessment of HSS for structural applications as well as expanding the knowledge base on the consequences of welding on fatigue in HSS welded structures.

2. STRUCTURAL INTEGRITY OF HSS

2.1. Weldability

HSS are often produced and delivered as quenched and tempered (Q&T) or thermo-mechanical controlled process (TMCP) steels. These steels are distinct due to their chemical properties, which are mainly determined by the addition of particular alloying elements, such as aluminum, vanadium, silicon, zirconium, and copper, to increase or decrease hardenability. The chemical composition of Q&T steels may contain alloying elements such as nickel, titanium, molybdenum and boron, and thus their qualities may differ slightly from those of TMCP steels. Moreover, carbon equivalent values (CEV) for Q&T and TMCP steels also differ significantly due to the carbon content, which contributes greatly to the hardness of the steels [4]. Table 1 shows examples of chemical composition of Q&T and TMCP steels.

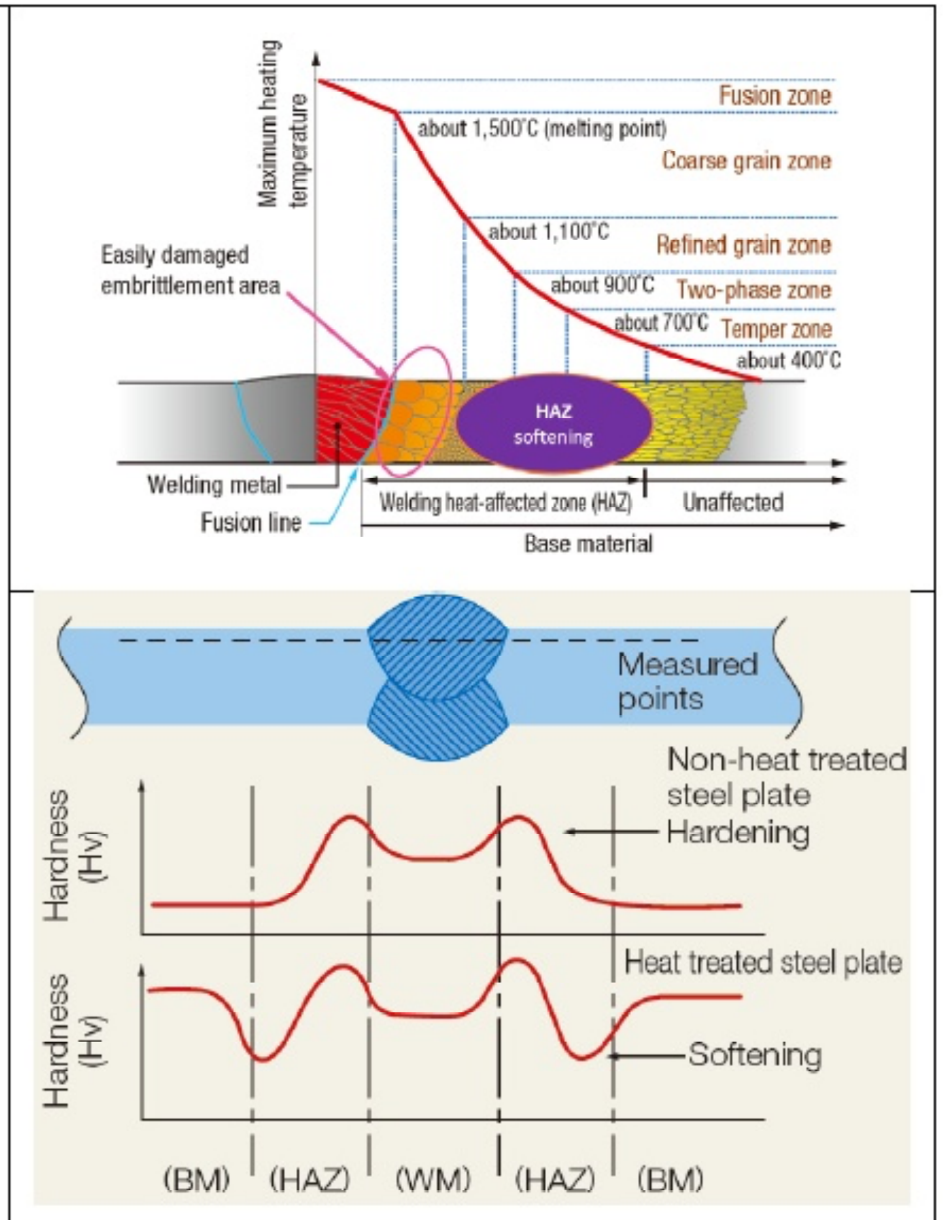
Some typical Q&T steels for structural applications are the steel grades S500, S550, S620, S690, S890, and S960 [EN10025-6] [5]. Q&T high strength structural steels (usually up to S690) are ideal for applications with heavy sections and heavy live loads (e.g. long span bridges), where weight reduction is important.

Generally, the alloying composition of Q&T steels increases with increasing plate thickness in order to ensure sufficient hardening of the plate in the core region. Therefore, the CEV of a Q&T plate increases with increasing thickness. It is known that Q&T and TMCP steels have fairly similar physical properties such as good strength to weight ratio and high load carrying capacity [5,6].

Table 1. Chemical composition of Q&T and TMCP steels for low temperature applications.

	Typical Composition (wt.%)	Thickness (mm)	CE IIW	Typical Mechanical Yield Strength / CVN range
TMCP Steels	C, Mn, Si, S, P, Nb, V, Al, Cu, Ni, Cr	30	0.35	400 MPa/190J @ -40°C
		32	-	398 MPa/300J @ -20°C
		32	0.32	400 MPa/>300J @ -20°C
		30	0.37	460 MPa/220J @ -40°C
Q&T Steels	C, Mn, Si, S,P, Nb, V, Al, Ti, Cu, Ni, Cr, Mo, B	6-140	0.81	550 – 690 MPa/80J @ -84°C
		30	0.45	450 MPa/>35J @ -40°C
		50-64	0.43 (Ti)	480 MPa/>40J @ -40°C
		50	0.64 (Ti, Mo, B)	690 MPa/>40J @ -40°C
		30	0.64 (B)	960 MPa/>40J @ -40°C

Table 2. Thermal cycles influencing HAZ softening of HSS characteristics and examples.

Inter-critical reheating occurring at the two-phase zone, i.e. between 900-700 ^{0}C, produces martensitic microstructure during rapid cooling, which undermines toughness in the HAZ. But when slowly cooled, a pearlitic microstructure with good toughness is achieved in the HAZ. However, HAZ softening occurs when HSS is heated at high temperature above tempering temperature (above 700 ^{0}C). As HSS is a heat treated steel, welding conditions must be determined carefully so that changes to the maximum hardness or softness of the HAZ may be as minimal as possible.	

Exploring the use of HSS makes it possible to reduce construction weight and cost, lower consumption of welding consumables, and reduce welding time as a result of decreased thickness of the material [7,8].

Conventional welding processes such as shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW), and submerged arc welding (SAW) have proven to be suitable for welding HSS. Nevertheless, the characteristic softening phenomenon due to uncontrolled heat input and cooling time [9] impairs tensile strength [10-11] and joint strength properties [6,12], as well creating weld crack tendencies, and leaves HSS weldability issues unsolved. Table 2 illustrates the thermal cycles influencing the heat affected zone softening phenomenon of HSS.

The risk of cracking and HAZ softening phenomena during welding of HSS places limitations on both the maximum and minimum total heat input, as illustrated schematically in Fig. 2 [14]. The shaded region shows the permissible heat input. The risk of cold cracking and excessive hardening, as depicted on the left side of the diagram, occurs when mini-

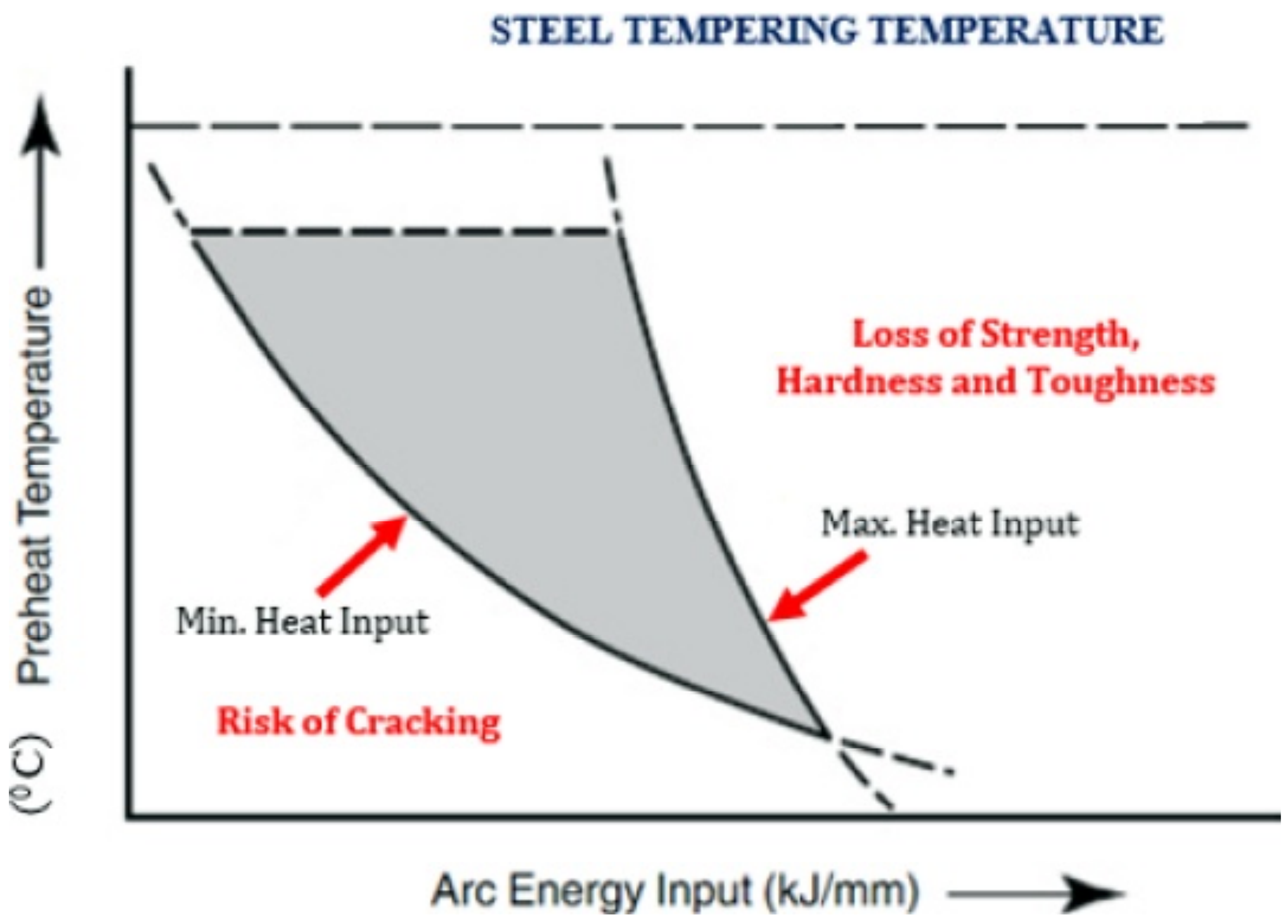


Fig. 2. Total weld heat input relations for welding Q&T steels characteristic. Reprinted with permission from Welding Technology Institute of Australia, Quenched and Tempered Steels, WTIA (Technical Note 15, Milsons Point, 1985). © 2016 WTIA.

mum heat inputs are used. Also, loss of strength and hardness due to over-tempering and possible loss of toughness as a result of re-transformation to upper bainitic microstructures during cooling occurs when high or maximum heat inputs are used [13,14].

For Q&T steels, the harder the microstructure, the greater is the cold cracking risk [15]. For TMCP steels, due to their low carbon equivalent content (CEV), there is high tendency of decreased welded joint strength as a result of the softening of the HAZ caused by uncontrolled heat input. As an important variable governing cooling rate/time, the higher the heat input the slower the cooling rate. This phenomenon has a key role in the phase balance and mechanical properties of HAZ and the weld [16]. In practice, the cooling rate is dependent on many factors: heat input, process efficiency, material properties, preheat temperature, material thickness and wire feeding rate [17,18]. The total weld heat input involving preheat temperature, interpass temperature and arc energy input has to be considered when determining appropriate cooling times [14].

It has been shown [16] that martensite-bainite microstructural transformation is prevalent when welding HSS of the Q&T type under appropriate welding conditions and when using suitable filler materials. For TMCP steels, a ferrite-bainite microstructure is obtained. Therefore selection of under-matched, matched or over-matched filler material must be done with accuracy since wrong judgments can lead to low toughness properties in the HAZ or weld metal (dilution of the base metal and the filler material) and consequently affect the microstructural transformation. Nevertheless, the microstructural formations in both Q&T and TMCP steels exhibit excellent ductility, and higher strength and toughness properties [16]. Therefore to ensure sound structural integrity of a welded HSS structure, such microstructures aforementioned should be obtained. Considering cold cracking in Q&T steels, low hydrogen filler materials are used to prevent or limit the introduction of hydrogen into the welded joints or HAZ [19]. Furthermore, it has been reported that welding of Q&T steels often require pre-weld or post-weld heat treatment in order to also minimize susceptibility of hydrogen-induced cracking thereby promoting sound microstructural formation [20]. On the other hand, TMCP steels exhibit sufficient strength and toughness, and they do not require hot working and post-weld heat treatment (PWHT), as they can create strength problems [21-23]. However, service performance conditions also revile the need to lessen weldability problems of HSS.

2.2. Service performance

The usability of HSS in the contest of service lifetime is influenced by effects of welding. For this reason, factors related to service performance of HSS, such as static strength, ductility, fatigue life, and corrosion resistance require particular attention, because, as a structural detail, a weld is initially prone to fatigue as a result of fatigue stresses, discontinuities, and welding defects. Therefore pre-existing cracks from welding defects promote crack formation, which has repercussions on fatigue life. Welded HSS have been observed to be more sensitive to fatigue phenomenon and more likely to experience fatigue failure [3].

Traditionally, fatigue life has been expressed as the total number of stress cycles required for a fatigue crack to initiate and grow large enough to produce catastrophic failure [24]. Generally, fatigue phenomena occur as a result of fatigue stresses and discontinuities. Fatigue stress therefore increases as a result of stress components (nominal stress, bending stress, nonlinear stress peak) whereas discontinuities occur mainly due to effect of notches, crack initiation, and crack propagation. Fatigue failure is common in welded structures due to notch geometries, which act locally as stress concentrator. Thus, the fatigue life of a notched specimen depends on the material and the notch geometry [3]. On the other hand, the geometry of a weld determines its fatigue strength whereas the static strength of the parent material (and of the filler metal) is of less importance in determining the fatigue strength [25,26].

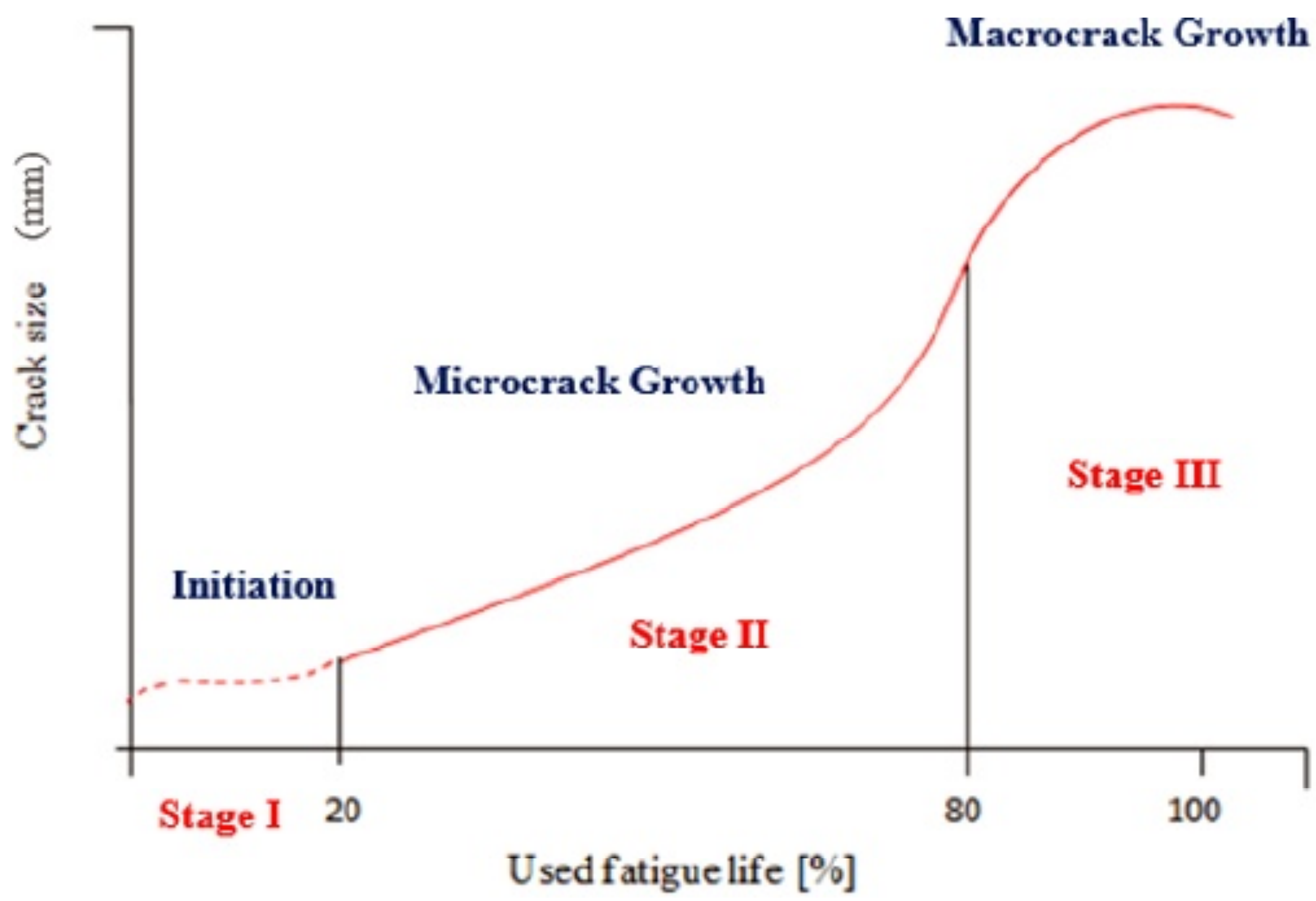


Fig. 3. Phases of crack growth in fatigue cracking. Reprinted with permission from T. Rantalainen, Simulation of Structural Stress History Based on Dynamic Analysis (Acta Universitatis Lappeenrantaensis 494, Finland, 2012). © 2012 Acta Universitatis.

Structural fracture and failure is divided into two phases: the crack initiation phase and the crack propagation phase. In the crack initiation phase, one or more small cracks begin to form in the material, while in the crack propagation phase, the initial crack propagates until it results in the failure of the structure. Fig. 3 illustrates the three fatigue cracking stages. Microcrack initiation and microcrack growth are together referred to as Stage I crack growth. Once the Stage I crack achieves a critical length, it will become a Stage II crack. In stage III, crack growth changes direction and begins propagating normal to the maximum principal stress [3].

For loaded welded structures, fatigue damage is caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If any one of these three elements is not present, a fatigue crack will not initiate and propagate [24]. Cyclic stress initiate cracks, the tensile stress propagates crack growth, and together they produce plastic strain. In the case of a brittle material, the released energy exceeds the absorption capacity of the material, and the crack propagation continues unstably, and hence the material fractures in a brittle way [3].

Some studies have shown that the fatigue strength of steels is usually proportional to their yield strength [27]. This generalization is not true for all cases because for high tensile strength values, toughness and critical flaw size may govern ultimate load carrying ability. Therefore, fatigue tests performed on small specimens are not always sufficient to precisely establish the fatigue life of a part. These small specimen tests are, however, useful for rating the relative resistance of a material to cyclic stressing and ascertaining the baseline properties of the material.

For example, a recent experiment compared the fatigue behavior of mild steel (S355) and high strength steel (S690) [28]. The two specimens were experimented using strain control, fatigue crack propagation and cyclic elastoplastic tests. The results indicated that although the S690 steel grade showed higher resistance to fatigue crack initiation than the S355 steel, its resistance to fatigue crack propagation was lower. Fig. 4 compares the fatigue crack propagation rates between the two steels. It is evident that the S690 steel shows the highest fatigue crack growth rates for all four tested stress ratios of 0.0, 0.25, 0.50, and 0.75 respectively. This finding was explained as being due to the finer grain of the S690 steel promoting fatigue crack propagation.

These results confirm an inverse dependence between static strength and fatigue life of HSS. Therefore utilizing HSS for applications where fatigue crack propagation is the governing phenomenon requires critical design consideration [28].

The superior fatigue crack initiation resistance of the HSS may not be relevant in HSS welded joints, since fatigue life is often affected by fatigue crack propagation. Data found in literature shows that fatigue resistance of welded high and ultra-high strength steel structural parts is similar to that of conventional steels with much lower yield stress [29].

This is due to short fatigue crack initiation period caused by stress concentration and weld defects. Nevertheless, crack propagation plays a key role on fatigue life [30]. Therefore when subjecting

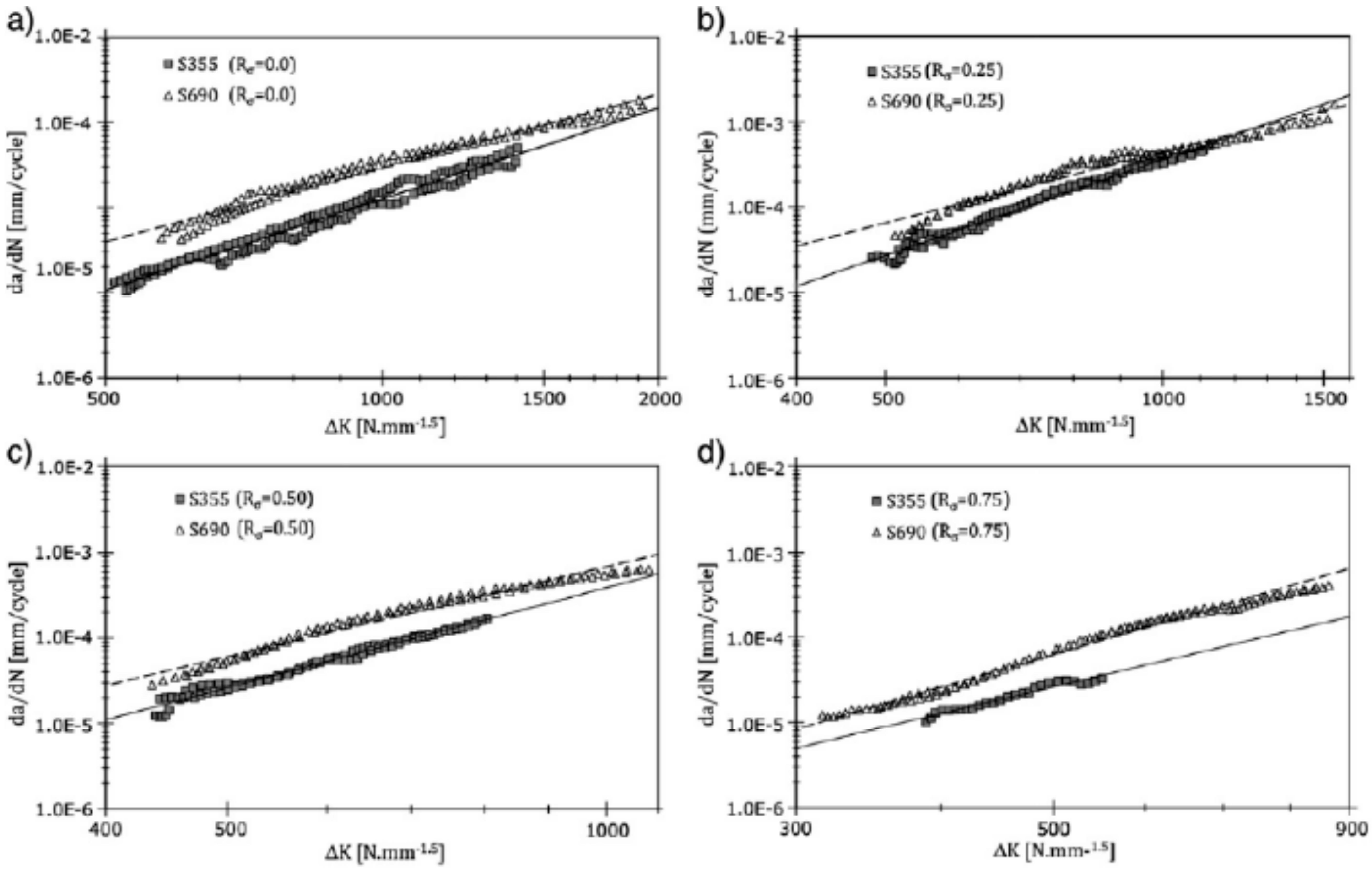


Fig. 4. Comparison of crack propagation growth between S355 and S690 steel grades. Reprinted with permission from M. P. A. Jesus, R. Matos, F. C. Bruno, C. Rebelo, L. S. Silva and M. Veljkovi // Journal of Construction Steel Research, Elsevier. **79** (2012) 140. © 2012 Elsevier Ltd.

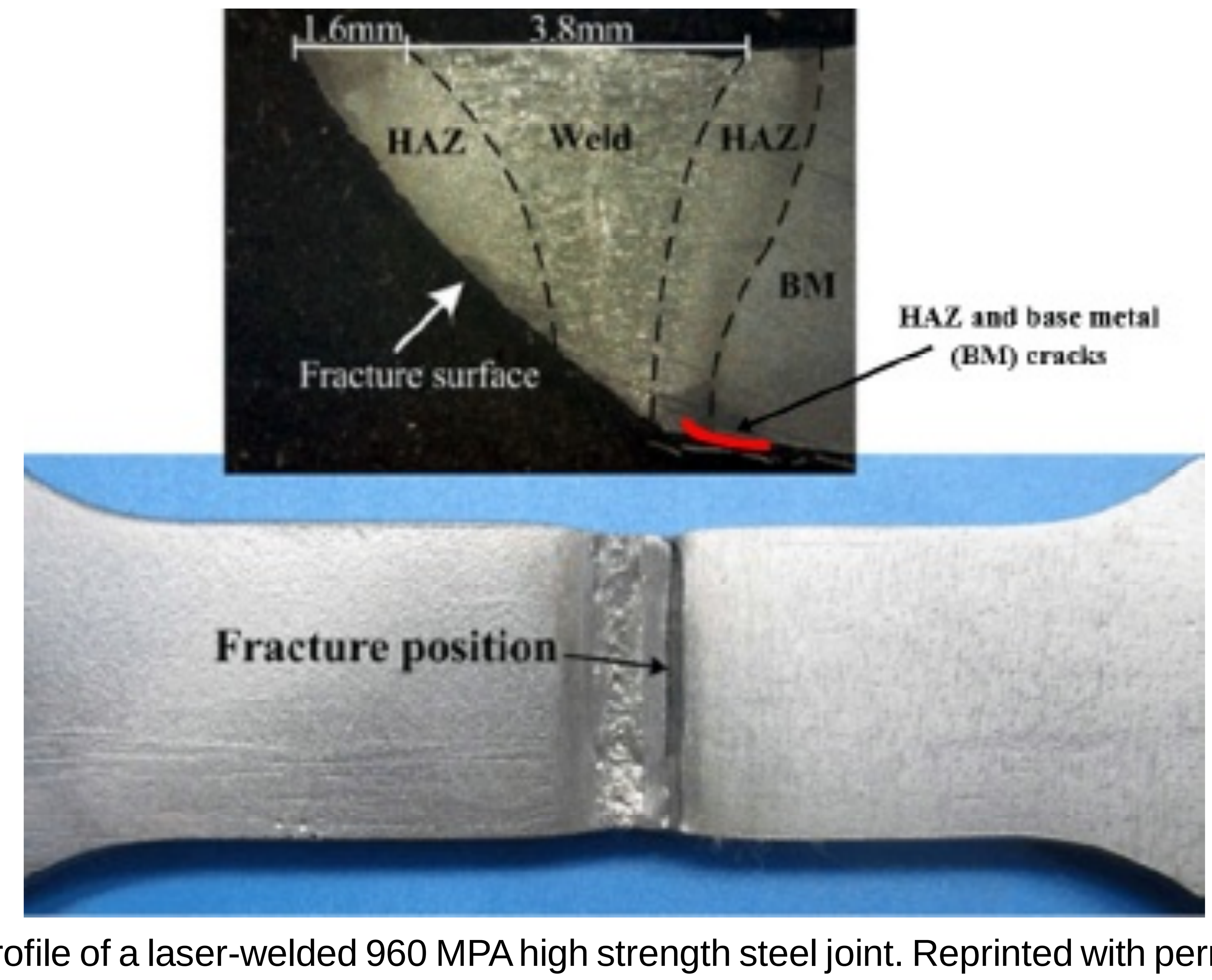


Fig. 5. Weld profile of a laser-welded 960 MPA high strength steel joint. Reprinted with permission from W. Meng, Z. Li, J. Huang, Y. Wu and S. Katayama // JMEPEG 23:538-544, ASM International. **23** (2013) 541. © 2014 ASM International.

welded HSS structures to fatigue loads, it should be noted that the fatigue strength does not increase proportionally to the static strength of the base metal [28,31]. Fig. 5 shows an example of a laser-welded 960 MPA high strength steel joint. The study concluded that the weld joint profile was affected by welding heat input leading to HAZ softening and cracks, and also base metal cracks, as shown in Fig. 5. The HAZ exhibited lower yield and tensile strength properties in the weld joint than the base material. However, on occurrence of fatigue failure, the weld joint fractured along the HAZ soft zone and cracked areas [32].

Research has shown that fatigue life of HSS can be improved by it fatigue strength. Several researchers have proposed a number of techniques for improving the fatigue strength of welded joints. Techniques suggested include: high frequency mechanical impact (HFMI) [33-35] and low transformation temperature filler materials [36]. Although these repair methods contribute to improving weld quality, from economic point of view they slow down productivity, which in turn affects profitability, and affects quality if wrongly executed.

2.3. Machine and human factors consideration

Machine factors involving the selection of welding processes play a vital role when establishing procedures to ensure the structural integrity of an HSS structure. With arc welding processes such as SMAW, GMAW, gas tungsten arc welding (GTAW), SAW, and FCAW, the electrode coating, shielding gases and mode of transfer of the filler materials are contributing factors in determining the strength of a welded joint as they affect porosity, and hydrogen inclusion in the weld. Since most arc welding processes employ either manual, semi-automatic, automatic, or robotic welding techniques, the welding position and directional formation of the weld puddle plays a key role in determining the strength of a welded joint since lack of fusion, undercut, etc. are potential flaws. For an HSS structure, these combined effects account for the structural integrity as these affect the quality of welded joints.

From the human factors viewpoint, the skills and knowledge of the welder/operator are influential in determining if the structural integrity of a welded HSS structure meets required standards and specifications. Therefore considering risk assessment and controls as a holistic approach in assuring accuracy, consistency and flawless parameters when defining and implementing welding procedure specifications for HSS welding is vital and demands attention.

3. RISK ASSESSMENT

This part of the paper presents a methodological approach for assessing risk and structural integrity of welded HSS structures. As an effective management tool, the analytical hierarchy process (AHP) [37] is used in the risk assessment process, as shown in Fig. 6. From Fig. 6, the layout depicts a scheme of risk assessment using the AHP approach as follows:

· Risk assessment based on quantitative factors and qualitative factors.

· Converting quantitative and qualitative factors into attribute and alternative factors.

· Decision making using the AHP for selection preferences. Thus selecting the most suitable process based on total priority weight.

The scheme as illustrated in Fig. 6 is to ensure that all relevant aspects and steps are considered in the risk assessment process. The risk assessment process therefore considers the identification of both intrinsic and extrinsic factors that might have an impact on the structural integrity. For each of these impacts, identification of the criteria and quantifiable indicators for the criteria that could be used as a measure for decision making and risk assessment is vital. Developing a graphical representation of the problem in terms of the overall goal, the factors, the criteria, and the decision alternatives is also essential.

From Fig. 6, the qualitative component, as described in Table 3, and the quantitative component, i.e. welding processes, are converted into attributes and alternative factors respectively in order to establish criteria that could be used as a measure for risk assessment. For the alternative factors, the criteria that could be used as measures include weld bead profile/geometry evaluations (i.e. percentage of dilution obtained from the various welding processes), destructive test values (bend test, hardness test, impact test, microstructural evaluations), or non-destructive test values (ultrasonic test, radiography test, penetrant test).

For the attribute factors, the criteria that could be used as a measure involve the establishment of priorities through the use of a pairwise comparison procedure. This is done to determine the relative importance of the attributes, to determine the relative importance of each of the alternatives with respect to each attribute, and to determine the overall priority weight of each of the alternatives. The scale for pairwise comparison used for preparing the pairwise comparison matrix elements for each criterion is as shown in Table 4.

From Fig. 6, the first level shows that the overall goal is to minimize risk through decision making in selecting the most suitable welding process available to ensure sound structural integrity of a welded HSS structure. At the second level, factors such as the welder's skill requirement, operator fatigue and

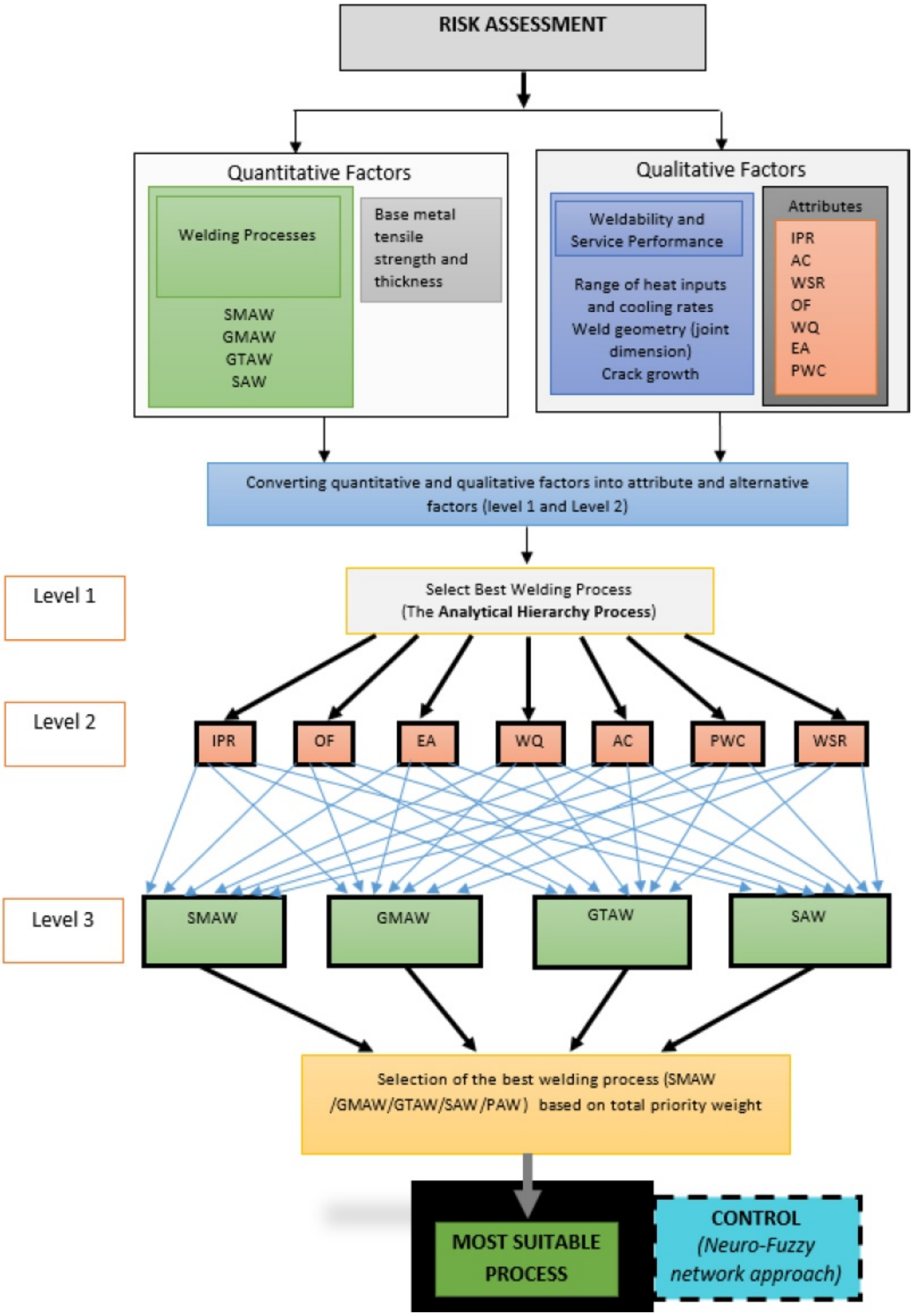


Fig. 6. Schematic diagram in performing Risk Assessment.

availability of consumables contribute to the achievement of the overall goal. At the third level, the alternatives (SMAW, GMAW, GTAW, and SAW) are presented and these must be evaluated through the criteria with respect to each attribute.

The following steps describe the arithmetic behind the AHP model [37]:

1. Assign weights to each alternative on the basis of the relative importance of its contribution to each decision criterion. This is carried out through a pairwise comparison of the alternatives based on the decision criterion.

2. Once the pairwise comparison matrix has been formed for a criterion, the normalized priority of each

Table 3. Description of process attributes considered.

No	Attributes	Description
1	Initial preparation required (IPR)	Preparation of joint, fit-ups and clamping in fixtures, setting welding parameters (voltage, current, welding, speed, gas flow rate, wire feed, etc.), and electrode/filler metal preparation, cleaning the base metal.
2	Availability of consumables (AC)	Electrodes, filler wires, shielding gases
3	Welder skill requirements (WSR)	Pre-heating requirement, root pass requirement, number of passes required, interpass temperature maintenance, and post-heating requirements.
4	Operator fatigue (OF)	Arc glare, smoke and fumes, electrode changing, and nozzle cleaning.
5	Weld Quality	Weld bead appearance, percentage of rejects due to welding defects (e.g. distortion, misalignment, porosity, lack of penetration, etc.).
6	Ease of automation (EA)	Manual, semi-automatic, fully automatic, robotics
7	Positional welding capacity (PWC)	Horizontal welding, vertical welding, overhead welding, and root pass welding.

Table 4. Scale for pairwise comparison characteristics and example.

Degree of importance	Definition
1	Equal (no preference)
2	Intermediate between 1 and 3
3	Moderately preferable
4	Intermediate between 3 and 5
5	Strongly preferable
6	Intermediate between 5 and 7
7	Very strong preferable
8	Intermediate between 7 and 9
9	Extremely strong preferable
Reciprocal of above numbers (1/2, 1/3, 1/4, etc.)	If a criterion is assigned to one of the above numbers when it is compared with another, the second will be assigned the reciprocal of the number when it is compared with the first

alternative is synthesized. The procedure for this is as follows: (a) sum up the values in each column, (b) divide each element in the column by its column total, which results in a normalized pairwise comparison matrix, and (c) compute the average of the elements in each row of the normalized comparison matrix, thus providing an estimate of the relative priorities of the alternatives.

3. In addition to the pairwise comparisons of the alternatives, use the same pairwise comparison procedures to set the priorities for all the criteria in terms of the importance of each in contributing towards the overall goal.

4. The priority is synthesized in a manner similar to Step 2.

5. Calculate the overall priority for each alternative.

6. Select the alternative having the highest priority.

The basic algorithm to forming the M X N pairwise comparison matrix is shown in Table 5. Depending on the nature of the assessment to be made, a set of well-defined algorithms is used for arithmetic processing of the data. The AHP model has been implemented for risk assessment and decision making in the field of science in diverse disciplines through different algorithmic approaches. Typical examples are sited in the paper to buttress the implications of this paper. However, risk assessment methods such as fault tree analysis, bow tie analysis, and preliminary hazard analysis methods for qualitative analysis; and risk level analysis, quantitative risk analysis, and Monte Carlo Simulation methods for quantitative risk analysis also are available. Nonetheless, the AHP method was chosen in this paper due to data consistencies.

Table 5. Pairwise comparison matrix for AHP computation.

M X N matrix

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mj} & \cdots & a_{mn} \end{bmatrix}$$

After establishing the *M X N* matrix, a reciprocal matrix is formed. This step is preceded by normalizing the matrix by totaling the numbers in each column. To check for consistency of original preference rating, a consistency analysis is made through consistency index and ratio calculations [37,38].

Table 6. Pairwise comparison of attributes. Reprinted with permission from V. Balasubramanian, V. Ravisankar, C. S. Ramachandran and C. Muralidharan // Int J Adv Manuf Technol, Springer-Verlag, London. **40** (2009) 887. © 2008 Springer-Verlag London Limited.

Process	SMAW	GMAW	GTAW	SAW	PTAW	Priority
SMAW	1 (0.559)	5 (0.535)	3 (0.0642)	9 (0.333)	7 (0.382)	0.491
GMAW	1/5 (0.112)	1 (0.107)	1/3 (0.071)	7 (0.259)	5 (0.273)	0.164
GTAW	1/3 (0.185)	3 (0.321)	1 (0.0214)	7 (0.259)	5 (0.273)	0.251
SAW	1/9 (0.062)	1/7 (0.015)	1/7 (0.030)	1 (0.037)	1/3 (0.018)	0.032
PTAW	1/7 (0.079)	1/5 (0.021)	1/5 (0.043)	3 (0.111)	1 (0.055)	0.062
	1.787	9.342	4.675	27	18.333	1.000

Table 7. Pairwise comparison of welding processes on initial preparation requirement. Reprinted with permission from V. Balasubramanian, V. Ravisankar, C. S. Ramachandran and C. Muralidharan // Int J Adv Manuf Technol, Springer-Verlag, London. **40** (2009) 887. © 2008 Springer-Verlag London Limited.

#	Attributes	IPR	AC	WSR	OF	PC	EA	PWC	Priority weight
1	IPR	1 (0.031)	1/2 (0.022)	1/7 (0.015)	1/9 (0.045)	1/3 (0.013)	1/5 (0.022)	1/6 (0.033)	0.025
2	AC	2 (0.061)	1 (0.043)	1/5 (0.021)	1/7 (0.058)	1/2 (0.021)	1/3 (0.036)	1/5 (0.039)	0.038
3	WSR	7 (0.212)	5 (0.213)	1 (0.104)	1/3 (0.136)	4 (0.161)	1/2 (0.054)	1/3 (0.065)	0.135
4	OF	9 (0.273)	7 (0.298)	3 (0.3130)	1 (0.408)	5 (0.201)	3 (0.327)	3 (0.589)	0.344
5	PC	3 (0.091)	2 (0.085)	1/4 (0.261)	1/5 (0.082)	1 (0.041)	1/7 (0.016)	1/7 (0.028)	0.085
6	EA	5 (0.152)	3 (0.128)	2 (0.209)	1/3 (0.136)	7 (0.282)	1 (0.109)	1/4 (0.049)	0.152
7	PWC	6 (0.182)	5 (0.213)	3 (0.313)	1/3 (0.136)	7 (0.282)	4 (0.436)	1 (0.196)	0.251
		33	23.5	9.59	2.453	24.83	9.18	5.09	1.000

In the field of welding, several studies have utilized AHP for decision-making. Selection of a welding process to fabricate a butt joint of high strength aluminum alloy of AA 7075 grade using AHP was investigated in [39]. In the work, several activities and cost drivers were used as the criteria to measure the alternating factors of GMAW, GTAW and plasma arc welding (PAW). With reference to Table 3, the results of the experiment revealed that weld quality was the most important attribute, thus giving rise to GTAW as the process with the higher priority weight.

In a recent study [40], AHP was used for selection of a welding process for hardfacing on carbon steels. In the work, a number of carbon steel specimen were hardfaced with varying heat inputs from welding processes such as SMAW, GMAW, GTAW, SAW and plasma transfer arc welding (PTAW). Percentages of dilution were used as the criteria to measure the alternating factors. Table 6 shows the pairwise comparison matrix for the attribute factors. In Table 7, the pairwise comparison matrix of the welding processes on initial preparation requirement is illustrated. The tables of the pairwise comparison matrix for the other attributes (AC, WSR, OF, PC, EA, and PWC) are omitted in this paper. However, Table 8 shows the final composite rating of the welding processes.

Based on the quantitative factors (percentage of dilution), the PTWA process was preferred since it produced the lowest percentage of dilution level as a result of the low percentage of the base metal in the deposited weld metal. Moreover, from the qualitative factors, it was noticed that operator fatigue was the most important attribute with the highest priority weight. Based on this result, the welding

Table 8. Final composite rating of the welding processes. Reprinted with permission from V. Balasubramanian, V. Ravisankar, C. S. Ramachandran and C. Muralidharan // Int J Adv Manuf Technol, Springer-Verlag, London. **40** (2009) 887. © 2008 Springer-Verlag London Limited.

Specimen no.	Attributes	Attributes priority weight	Process priority weight									
			SMAW		GMAW		GTAW		SAW		PTAW	
1	IPR	0.025	0.491	(0.0123)	0.164	(0.0004)	0.251	(0.0063)	0.032	(0.0008)	0.062	(0.0016)
2	AC	0.038	0.246	(0.0093)	0.072	(0.0027)	0.132	(0.0051)	0.038	(0.0014)	0.502	(0.0191)
3	WSR	0.135	0.121	(0.0163)	0.081	(0.0109)	0.036	(0.0049)	0.258	(0.0348)	0.504	(0.0681)
4	OF	0.344	0.068	(0.0234)	0.134	(0.0461)	0.035	(0.0121)	0.260	(0.0894)	0.503	(0.1730)
5	PC	0.085	0.074	(0.0063)	0.031	(0.0026)	0.247	(0.0209)	0.162	(0.0138)	0.486	(0.0413)
6	EA	0.152	0.058	(0.0088)	0.164	(0.0249)	0.038	(0.0058)	0.251	(0.0382)	0.489	(0.0743)
7	PWC	0.251	0.491	(0.1232)	0.164	(0.0412)	0.251	(0.0630)	0.032	(0.0081)	0.062	(0.0156)
Total				0.1996		0.1288		0.1181		0.1865		0.3930
Rating			2	2	4	4	5	5	3	3	1	1

process selected was PTAW, since it had the highest composite weight of 0.503 with the highest priority weight of 0.3930 as shown in Table 8.

The scientific relevance of the AHP therefore serves as a step beyond the conventional way of determining structural integrity where destructive and non-destructive tests are solely performed. In addition, the AHP create new ways for expressing variables and welding parameters when defining and implementing welding procedure specification. Moreover, it create avenues to develop new approaches like the utilization of on-line process monitoring and fatigue analysis systems to facilitate risk assessment process when considering structural integrity in welding.

4. ON-LINE PROCESS MONITORING AND FATIGUE ANALYSIS

A practical developmental case is the utilization of machine-human interface equipment such as sensor and camera based systems for on-line process monitoring, as indicated in the framework and introduction part of this paper. Fig. 7 describes on-line process monitoring and failure analysis layout for the risk assessment process. In on-line process monitoring, the key aspects are pre-process monitoring, in-situ monitoring and post-process monitoring. Seam tracking, groove volume and groove shape are observed with pre-process monitoring, and temperature, metal vapor, back reflection and metal pool

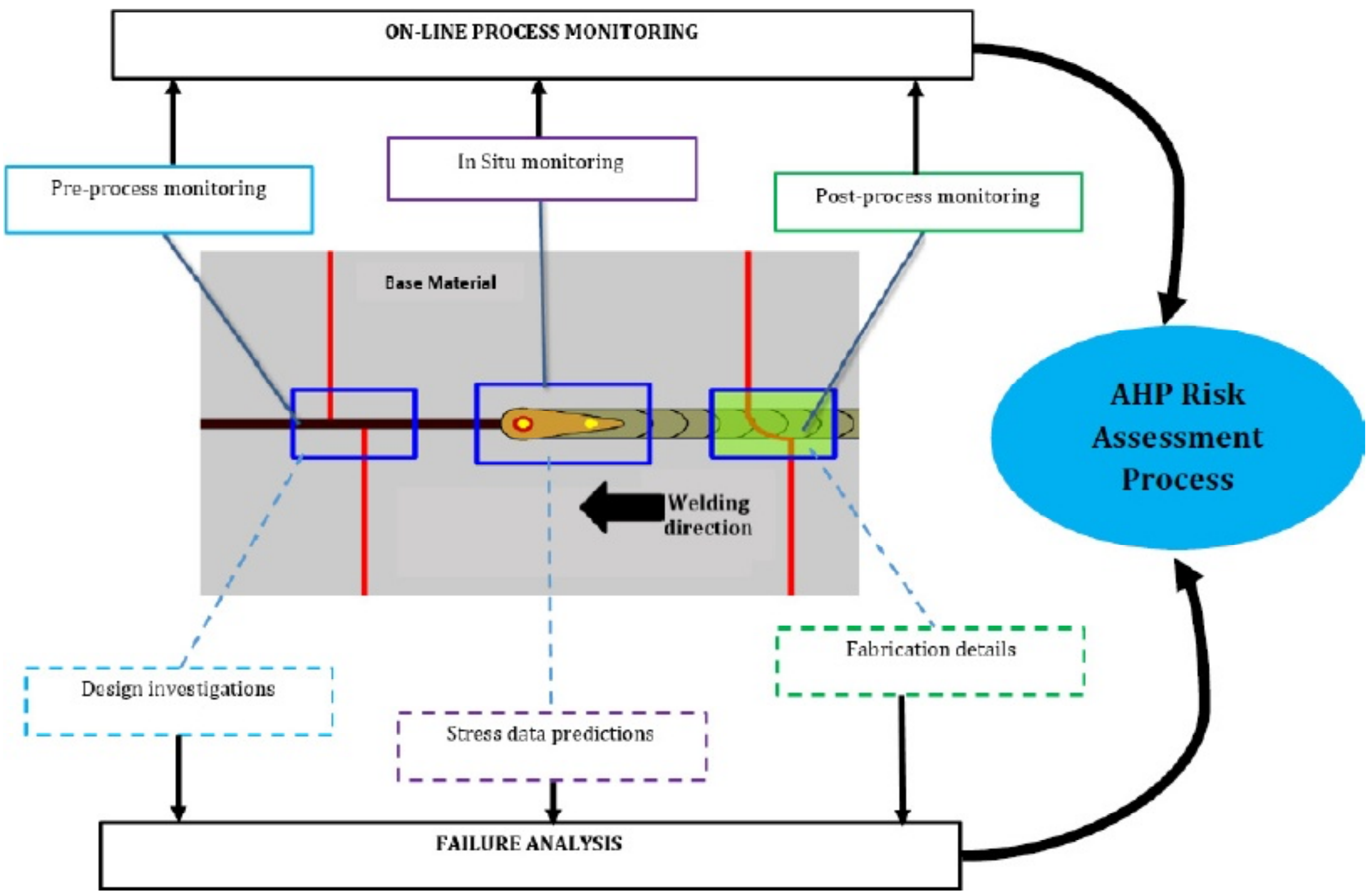


Fig. 7. On-line process monitoring and failure analysis layout for risk assessment process.

shape are monitored with in-situ monitoring. Post-process monitoring is used to monitor the shape of the weld bead, and to evaluate surface flaws. Failure analysis involving design investigations of weld profile/geometry, stress data predictions from thermal history of microstructural transformations, and fabrication detail assessment rely on feedback information obtained from the on-line process monitoring system.

The on-line process monitoring and failure analysis system with AHP risk assessment process system enables effective structural integrity analysis of weldability and service performance as it helps to identify flaws before, during and after welding. Therefore incorporating the digitalized computational system with AHP risk assessment process system would provide a high degree for quality improvement and assurance when establishing procedures to ensuring structural integrity of an HSS structure.

5. DISCUSSION

From the weldability viewpoint, risks associated with welding of HSS include HAZ softening, cracking, and brittleness in the weld bead. HAZ softening is a result of microstructural changes that occur when high heat inputs are applied. Heat input is consequently a critical factor which significantly affects the strength and properties of HSS welded joints. For instance, if heat input is too low, there is a risk of lack of fusion, and on the other hand if the heat input is too high, the heat affected zone gets too wide, which can cause HAZ softening and brittleness in the weld bead [41]. Although such risks lead to ductility, strength, and toughness problems, they also affect the quality of weld joints and bring about low welding productivity. In addition, risk of cracking is a factor in the choice of filler materials. This occurrence is usually due to improper weld metal (base metal plus filler material) dilution. As heat-input plays a significant role in such phenomenon thereby causing low toughness in the HAZ and the weld metal, care must be taken when selecting or choosing matched, under-matched or over-matched filler materials in welding HSS. Productivity wise, this situation leads to consumable wastage and also lots of repair work due to low quality welds which are also prone to fracture toughness failure.

Secondly, from the viewpoint of service performance, fatigue strength of HSS does not increase with increasing yield strength, but strength properties of the material are associated with load carrying capacity. Fatigue strength is consequently reduced by means of welding as a result of the softening phenomenon of the HAZ. Risk factors associated with service performance of a welded HSS include weld geometry, material grade and thickness, and crack growth. For weld geometry, design and fabrication play a critical role as both variables are closely dependent on each other. Therefore poor design leads to wrong fabrication and vice versa. The process of fabrication and welding create levels of stress on the geometric profile of the weld. Additionally, stress concentration arises as the welded structure is subjected to static or dynamic loading, thus reducing fatigue life. Furthermore, the risk of crack growth is highly pronounced when there are imperfections in the weldment. For instance, defects such as undercut, porosity, etc. create notches and discontinuities which give rise to further stress concentrations. In such events, crack initiation, usually located at the weld toe or at the weld root, begins, followed by crack propagation.

In order to alleviate such potential flaws, risk assessment and controls should be performed. Using the AHP model could yield satisfactory results in decision making since qualitative and quantitative factors can be assessed in detail. Several criteria with relative importance could be used as measures in the risk assessment process. The ability to lower risk to ensuring sound structural integrity in the process of welding HSS could be high. As part of HSS weldability predictions, on-line welding process monitoring system could be employed for seam and groove tracking, weld pool shape monitoring, and weld bead and weld metal surface flaws monitoring as a measure to identify flaw before, during and after welding

For service performance of HSS, the design and fabrication aspects must be precise. In addition, despite the limitations of correcting weld flaws with the on-line process monitoring system, obtaining digital feedback from the system would help in the computation and controllability of welding parameters to level with fatigue strength and also fatigue life of the parent metal. Minimization of elastic stress concentration and decrease of fatigue notch factor becomes achievable. These procedures when critically examined and practiced would also serve a great deal to reduce extra costs in HSS welding.

6. CONCLUSIONS

Potential benefits from utilization of HSS for industrial applications cannot be under-estimated despite the material's drawbacks due to welding effects. As new applications are emerging in the metal industry, the weldability and service performance of HSS proves to be an intriguing issue which needs to be understood from industrial and scientific point of views. Therefore, a rigorous risk assessment process needs to be performed, considering the metallurgical, physical and mechanical flaws observed in previous studies, when selecting welding processes and filler material in welding HSS of different material grade and thickness.

Adapting the AHP system would be an effective approach for evaluating the selection of welding processes and filler material in HSS welding. The AHP system therefore creates a paradigm shift from the conventional method of selecting and assessing welding processes and filler materials in welding HSS. Likewise, design and fabrication processes need to be pre-assessed under welding conditions to lessen flaws in weld geometry, crack formation, and to prevent fatigue failure in order to ascertain considerable fatigue life. This is achievable by employing sensor and camera based systems for on-line welding process monitoring and advanced simulation tools for failure analysis during and after design and fabrication phases.

However, the limitations of the on-line welding process monitoring system mean that further research is required, for example, on neuro-fuzzy network system as an optimization mechanism for identifying, correcting and eliminating potential flaws before, during and after welding. The arguments presented in this paper not only emphasize on weldability and service performance of HSS, but also provides effective new ways of developing justifiable variables for welding procedure specifications. Therefore the neuro-fuzzy system when developed and incorporated with AHP and on-line welding process monitoring would create a new trend for ensuring quality and assuring structural integrity in welding usability of materials for demanding applications.

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