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Process Constraints and Integrity Evaluation of Quasi-Structured Composites In High-Strength Steel Welded Joints

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***Abstract*: -** In this study, weld integrity has been viewed in terms of ability to withstand load transmission and distribution in post weld heat treatment conditions. This concern is necessitated by the fact that some industrial applications require metals that can be used in continuous elevated temperature conditions. Sometimes these metals are joined together by various forms of welding alternatives. The key issue in this constraints evaluation has to do with the integrity profile of the welded joints on prolonged engagement under elevated temperatures. Evaluation of this feat has been understood to be achievable by the weld process constraints optimization as analyzed below.

***Keywords:* -** *weld integrity, characteristic heterogeneities, compromised integrity, energy matrix, reactive diffusibility, metallic composites*

I. INTRODUCTION

Process constraints with respect to welding conditions has to do with critical specifications and technical requirements in the areas of heating and temperature control, rate of heat application, thermal properties of base and filler metals (which controls and enhance temperature distribution in the joint). In this list are also, infrastructure and grain size of welded joint, degree of prior cold work on the metals; rate of cooling and solidification after welding, operational and technical requirements relative to specified weld type and operations. Thus, process constraints define the operational limits allowable for the achievement of standardized weld design that is responsive to the adopted weld strategy.

It should therefore be pointed out that the high point of welding practice has to do with fracture toughness which is dependent on the extent of microstructure and non-metallic inclusions [1]. Further, other thermodynamic and chemical agents such as segregated metallic microphases, nitrogen, and hydrogen and impurity elements can result embrittlement of the welded joint. In view of the foregoing, it is imperative to state that the principal essence of these process constraints enunciated above is quality and consequent *weld integrity*. Therefore, the extent of this integrity can only be ascertained by conscious evaluation of performance characterizations and indices of the defined parameters of interest. Thus, integrity evaluation for welded joints would be greatly influenced by geometrical and matrixial co-ordinates, which would instructively reveal the presence of cracks, residual stress, non-metallic inclusions, metallic oxides films and voids due to gas entrapments [2] [3].

It is therefore important to note that when these process constraints are optimized, the tendency for enhanced weld integrity is highly significant. This implies that weld profile integrity is crucially dependant on the ability to exercise relative and extended control over these constraints [2]. Conversely, failure to keep these constraints within defined limits would result the emergence of quasi-structured bi-, tetra-, and poly- metallic composites with *characteristic heterogeneities* resulting varying nucleation, grain boundaries and thermodynamically defective grain orientations [3].

In view of the foregoing assertions, suffice it to mention that while weld joints are intended to be alloys with improved mechanical and thermal properties (that are supportive of load transmission and distribution); *compromised integrity* resulting quasi-structured metallic orientations fall below this requirement and thus restructures the energy flow matrix at such joints. The cumulative effect of such grain boundary redefinition is a weld joint with *marginal* metallic and thermal properties, which upon integrity evaluation can be better referred to as quasi-structured metallic composites, rather than characteristic weld joints. It should be noted that this study is based on high-strength steel welded joints referred to as H_{factor} steel. This imply that the characterization of H_{factor} weld metals are critically dependant on their metallic composition, microstructural orientation and proclivities in the forms for non *metallic singularities*, (as in silicate contaminations), aggregates and clusters (as in aluminum content inclusions), [4], [5] .

As would be seen later, these quasi-structured metallic orientations are also the result of anti-bonding gaseous presence entrapped within orbital delineations. Characteristically, the diffusibility of these gases is significantly low and this account for their ability to assume partially empty spaces within the *weld energy matrix* of the lattice structure of the weld. These voids are component by-products of chemical reactions between alloying agents of filler metals in contact with base metals [2].

However, these voids contribute to the problems of porosity in the sense that during solidification of the molten weld, gases resulting from high temperature chemical reactions find ways to exit the complex structures where liquid metal solubility does not encourage *reactive diffusibility*. When this happens, voids occupied by these gases aggregately contribute to uneven complicated structural dispositions, considered in this paper as quasi-structural composites of weld microstructure. The structural effect of these developments is low profile weld integrity that is not supportive of the H_{factor} internal stress requirement in high tension steel fabrications.

II. EXPERIMENTAL EVALUATION OF WELD PROCESS CONSTRAINTS

Process constraints in weld situations have been viewed as *allowable tolerance limits in the area of temperature control, thermal and mechanical property specificities*, etc. A test case pursuant to ASME B31.3-2006 for 5% Cr-0.5% Mo weld joint has been analyzed [6] based on the position that the sequestration of the constituents of martensite in exchange for a structure with significant plasticity defines a better applicable material [7] in terms of toughness as indicated by a depleted internal stress which also reduces hardinability. The requirement for this comparative treatment revolves around material behavioral studies that have been conducted under varying degrees of thermal exposure of 5%Cr -0.5% Mo steel. The unserviced specimen as indicated in Fig. 1 below show raw Cr-Mo weld, that is yet to be heat treated.

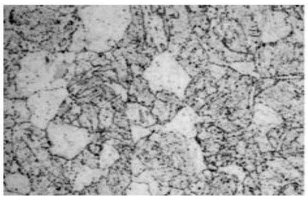


Figure 1: Unserviced cutout of Cr-Mo steel

A careful study of Fig. 1 would reveal a microstructure of ferrite bounded with carbides having clearly defined mixture of ferrite and carbides of SiC, TiC, Mo_2C, etc. It should be noted that the heterogeneous nature of these scattered carbides constitute metallic inclusions which in the view of this study tantamount to *derivative quasi-structured metallic composites* in varying grain sizes and shapes.

2.1 Post-weld microstructure (temperatures ranging: 400^{o}C-500^{o}C)

Further, as could be observed in the specimen below i.e. Fig. 2; the specimen is the result of solid 5%Cr -0.5% Mo steel weld deposit with controlled post-weld heating operation. It shows structural arrangements akin to *ocicular shapes* that are degrades of austenite and have undergone structural transmutation to martensitic profiles and patterns. The location of carbides could be noticed around the ocicular patterns in the form of dark plate-like patches. This figure further illustrate the integrity profile of Cr-Mo steel when exposed to post-weld temperatures between 400^{o}C and 500^{o}C for time limits between 1hr - 2 hrs.

Figure 2: structural ambivalence of weld joint under post-weld heating (T = 400^{o}C - 500^{o}C)

A comparison of Fig. 1 and Fig. 2 would reveal a partially bleached pattern indicative of the effect of temperature in creating a passive alignment of metallic inclusions in the form of carbides. Thus, thermal characterization of the foregoing implies a process constraint intended to sequestrate the composite structure. In this regard, Fig. 2 therefore is a structural refinement process that reduces the integrity of the microstructured weld deposit and also reduce its hardinability.

2.2 Post-weld microstructure (temperatures ranging: 500°C-700°C)

The third stage of this process constraints evaluation to define relative weld integrity conditions requires an increase in temperature from 500°C to 700°C. The remarkable structural implication of this increment in the refinement process is phenomenal as could be seen in Fig. 3 below. In this figure, thermodynamic and chemical reaction forces results same structure alignment and thus has occasioned an undefineable orientation for the metallic inclusions.

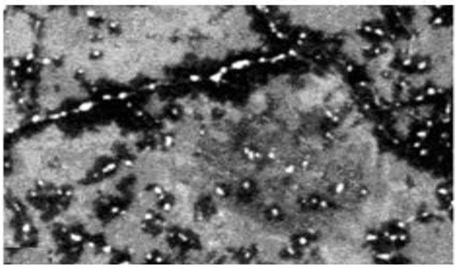


Figure 3: Structural ambivalence of weld joint under post-weld heating (T = 500°C - 700°C)

Thus, a thermal forcing function on the post-weld molten deposit material has resulted a transformation of martensite into a material with better thermal and mechanical properties. As could be seen, the ferrite grains have been sequestrated from the carbides which have formed lines, curves and inclusion sites within ferrite matrixes.

2.3 Post-weld microstructure (temperatures ranging: 700°C-800°C)

In the last stage of this test, temperature was raised from 700°C to 800°C for an extended period of about 8 hours and Fig. 4 emerged indicating clearly defined boundaries of carbides enclosing ferrite grains.

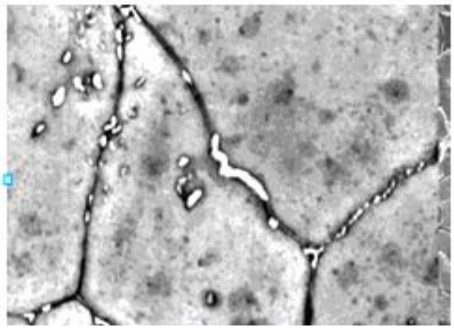


Figure 4: structural ambivalence of weld joint under post-weld heating (T = 700°C - 800°C)

Thus, the formation of chain and branch network of inclusions that are irregularly distributed along and around the steel material establishes the fact that the refinement process results a restructuring of the grain boundary and re-alignment of the metallic inclusions. The gross effect of this re-orientation being a reduction in hardinability due to cumulative depletion of internal stress, which are contributed by the unevenly distributed presence of the inclusion materials. Conversely, toughness increases per μm^2 of the refined weld profile, thus impinging on the integrity of the solid weld deposit.

III. DISCUSSIONS

The study shall therefore correlate the relative influence of elevated temperatures on the weld inclusions and how this influence compromises and affects the integrity of the weld in terms of design serviceability. It is therefore imperative to note that, inclusions were originally intended to enhance the strength and hardinability of the welded joints. Bearing this in mind, the result of the assessment could then be used to predict a possible failure time or rate of such welds when exposed to constant temperature operations.

3.1 Analysis: Structural integrity implication of unserviced specimen

As mentioned earlier, Fig. 1 represent the unserviced cutout piece of ASTM A387 5% Cr- 0.5% Mo alloy whose chemical composition as detailed in Table 1, below favor reactivity within the *p* and *d-orbitals.*

Table 1: Chemical Composition of ASTM A387 $\boldsymbol{H_{factor}}$ Steel

Elements	C	Mn	P	S	Si	Ni	Cr	Mo	V
Composition in % wt	0.33-0.43	0.20-0.50	0.030	0.030	0.80-1.20	0.30	4.75-5.50	1.10-1.60	0.30-0.60

In the said Fig. 1, the circulation of the carbide particles on the general surface of the Cr-Mo alloy indicate evenly distributed internal stress which generated hardinability but with reduced toughness. In addition, the presence of varying degrees and types of inclusion further creates boundaries and delineations around the ferrite particles. These boundaries are signs of insolubility of the inclusion particles in the alloy metal microsturcture. This microstructure thus supports the requirement for austenitic formation under volume fraction relativity [8] expressed as;

$$V = \frac{\pi d^3}{6} . N_v \text{ ....(1)}$$

where the harmonic mean of inclusion diameter, *d* and the number of inclusions per unit volume, N_v were found by a proposed model, and which further yields [9]:

$$Nv = \frac{2}{\pi} . \frac{N_A}{d} \text{ ....(2)}$$

$$\frac{1}{d} = 1/n\sum 1/d_i \text{ ....(3)}$$

where d_i is the apparent diameter of the i^{th} inclusion among the *n* inclusions, N_A is the number of inclusion per unit area. Pursuant to the foregoing, it is imperative to state that the utilization of scanning election microscopy (SEM) revealed inclusion sizes between 0.2 μm and 6.0μm in diameter and as such explains the reason for the nucleation of intragranular ferrites.

Further, the profound presence of non-metallic inclusions in this specimen also implies a significant density when compared with purer materials. Thus, these inclusion locations can better be seen as nucleation sites for voids on the event of thermodynamically induced migration based on *surface potentiations* and differences. Hence, weld integrity under the consideration of high internal stress is higher under post-weld operational regimes devoid of post-weld heating conditions.

3.2 Analysis: Structural integrity implication for specimen at: $T \leq 500^0C$

In Fig. 2, structural rearrangements due to temperature at $T \leq 500^0C$ resulted a more evenly distributed pattern of extended white patches bounded by dark patterns of irregular orientations. In this regard, the chemostructrial consequence of elevated temperature implies an increased mobility condition for the inclusion particles; with migrations from areas of low density to areas of high or accumulated density. Thus, while anti-bonding conditions (except for partial affinities) are prevalent between particles of inclusion and the alloying metals (the Cr-Mo particles); bounding conditions are widespread among the inclusion particles and this is achieved by a thermodynamically propelled coagulation of inclusion particles. The implication of Fig. 2 to the integrity of the welded joint is that the thermodynamic migration and consequent *limited dispersed coagulation* streamlines the hardnability of the welded joint in such a disequilibrium of internal stress, characterized by strength profile segmentations, thus reducing the overall weld profile integrity.

3.3 Analysis: Structural integrity implication for specimen at: $T \geq 500^0C \leq 700^0C$

It has been observed that phenomenal structural result accompany an increased temperature profile above 500°C but not exceeding 700°C. Thus, Fig. 3 depicts a strength demographic sequence of inclusion outlay indicating scattered sites and network of chains formed; this formation is in line with earlier stated reasons. The network of chains thus implies, areas of marginal strength for which, the weak Cr-Mo/inclusion affinity exposes the microstructure to failure due to reduced internal stress.

If should be pointed that while toughness has improved, hardinability has reduced. The possible explanation for this condition is that during the rising temperature from 500°C to 700°C, the *nucleation sites* of the inclusion constitute areas of lower energy potentials, due to thermal conductivity along matrixial lines. Thus, inclusion distribution sites with aggregate higher energy potentials due to density of inclusion particles exert energy drag on the scattered inclusion particles adjourning those aggregates. Further, due to the weakness in the bonding between inclusion and metallic orbitals of the Cr-Mo complex, temperature rise breaks the affinity and the inclusion particles find their way to the aggregate locations where they further re-characterize the weld strength profile.

The implication of the foregoing is that, since the presence of inclusions increases melting point and hardinability, the absence of inclusion reduces tensile strength due to compromised internal stress of the alloy. This also means that the more there is increase in the number of inclusions the more there is increment in the melting point due to varying contributions of the various inclusions to the melting points of the alloy.

3.4 Analysis: Structural integrity implication for specimen at: $T \geq 700^0C \leq 800^0C$

As the test progressed, it should be noted that for period exceeding 7hrs but less than 8hrs, and constant temperature above 700°C but not below 800°C, the microstructure in Fig. 4 was noticed. In this figure, the network of chains indicating inclusion coagulations are more defined and looking much like defined fault lines. Further, this paper is of the view that the network of inclusion sites are energy sinking locations since a weak affinity exist between inclusion particles and the particles of Cr-Mo. Thus, the weakest point in the outlay of the microstructure is the boundary between inclusion particles and the Cr-Mo orbitals.

IV. YIELD STRENGTH DETERMINATION

In view of the foregoing, an empirical determination is necessary to validate the position that weld integrity in terms of hardinability reduces with prolonged constant temperature over a period of measured time. In this regard, a temperature (T) and time (t) dependant calculation using equation (4) [10] expressed as:

$$P = T\,(20+\lg t) \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

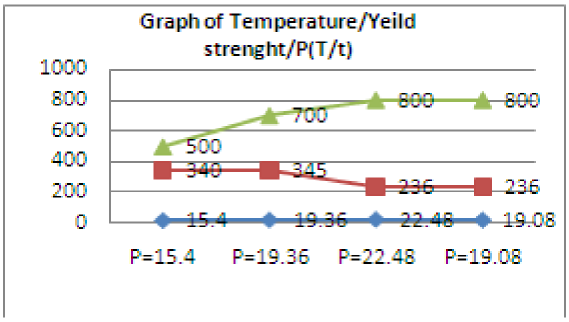
and defined for the three temperature ranges (that has been discussed), resulted the following table which are fundamentally in agreement with other related studies [6], [7], though with negligible disparities.

Table 1 Temperature / Time Parameter Evaluation

Test Stages	Heating per hour °C	Cooling per hour °C	Temp. range °C	Exposure time hrs	P (T/t)	Yield strength Mpa (approx)
Test :1	50	100	400	1 - 2	15.40	340
Test :2	50	100	500 - 700	≤ 7 ≤ 8	19.36	345
Test :3	50	100	700 - 800	≤ 8	22.48	236

From Table 1 above and Fig. 7 below, it could be seen that increase in temperature and time facilitated the formation of carbide inclusions at the irregular boundary locations delineating the alloys and this also implies that the sequenced structure of the Cr-Mo alloy wherein the inclusion particles have aligned themselves away from the original evenly scattered situations has a direct impact on the yield strength of the weld. This is observable from Fig. 7 where the center line (yield strength) indicates a downward trend as the upper line (temperature) rises. And when temperature was kept constant at 800°C the Yeild strength was also seen to maintain a straight line at 236 Mpa, implying that the integrity of the weld joint is directly affected by rise in temperature.

Figure 5: Graph of T/Ys/P(T/t)



V. CONCLUSION

The *P*(*T/t)* parameter line at the lower end of Fig. 7 appears evenly spread out, due to the closeness of the values. The difference would have been more noticeable if more test exposures were recorded, implying that as heating and temperature rise progresses, the austenitic profile of the weld transforms into other composite microstructures that over a period of operational life would not be able to sustain the load transmitting and distribution capacity it was designed to support. Thus, increasing temperature is reducing weld integrity due to re-alignment of internal stress factors of the intermediate microstructures of inclusion. Hence, further analysis of Fig. 7 at the extended point of T= 800^{o}C and Ys=236 MPa, shows that for every 3.4^{o}C rise in temperature, 1 MPa of weld integrity (strength) is lost.

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