A Compromise Programming Approach to Welding Flux Performance Optimization

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Abstract

Welding flux design is a multi-objective optimization problem with several conflicting objectives. The traditional welding flux development is unwieldy process involving lengthy and costly, trial and error experiments and the optimum welding flux formulation is not guaranteed. This paper proposed a methodology that will prescribe an optimal welding flux formulation that is the closest to the ideal flux with minimum cost and experimental effort. Response models developed by Kanjilal and co-investigators were used to determine the optimal flux formulation using compromise programming. Analytical hierarchy process was used to determine the weight (w_j) to reflect the relative importance of each criterion. The response models for the weld metal properties, were optimised individually to determine the ideal points and to set up the payoff matrix. The payoff matrix developed for the eight criteria showed that two criteria were complementary while others were conflicting. The side plate ferrite and charpy impact strength were the two complementary criteria. The Lp distance metric was used to determine the flux formulation for varying values of the p and w_j. Compromise programming is an efficient method in determining the welding flux formulation thereby eliminating the problem faced by the traditional method.

Keywords
Welding flux, compromise programming, payoff matrix, nadir points.

1.0 INTRODUCTION

Welding flux design is an unwieldy process requiring lengthy trial and error experiments based on the principles of metallurgy, physics, and chemistry tempered with experience. The extensive and expensive trial and error experiments are required because it is often difficult to know a priori how the flux ingredients interact to determine the operational characteristics of the flux during welding and the final properties of the weld-metal (Adeyeye and Oyawale, 2008). Kanjilal et al (2007b) proposed prediction models for submerged arc welding flux and pointed out that some of the individual flux ingredients and their binary mixtures have a predominant effect on weld metal transfer of oxygen, manganese, silicon, and carbon contents. Since the appearance of Kanjilal et al (2004, 2005, 2007a and 2007b) papers, there has been an increased interest in the development of prediction and optimization tools in submerged arc welding technology (Adeyeye and Oyawale, 2008, 2010; Kumar et al., 2012 and Rehal and Randhawa, 2014).

Welding Flux is a substance used to remove, dissolve or prevent the formation of undesirable oxide and other undesirable substances during welding. The chemical composition of a weld is affected by the composition of the base metal, filler metal and flux. It is a common practise to use a filler metal that has the same composition as the base metal but for some economic reasons they can be different. In such situation, it is important that the welding process deposits the weld metal with the required chemical composition. In other to achieve the required chemical composition, the flux ingredients and their respective proportions must be carefully selected. Remarkable attention has been given to the study different aspects of weld chemistry (Chai and Eager, 1981; Brooks et al., 1984; Siewert and Franke, 1990; Polar et al., 1991: Hunt et al., 1994; He and Edmond, 2002; kanjilal et al., 2005; Kanjilal et al., 2007; Magudeeswaran et al., 2009; Kumar et al., 2012; Naufal et al., 2013). It is quite understandable that compositions of base metal, electrode wire, and flux have profound effect on mechanical properties, of the welded joint, which in turn depends on microstructure of weld metal. This paper focuses on the development of a flux that will improve the mechanical and microstructural properties of the weld metal in Submerged Arc Welding.

da Trindade Filho (2004) identified the weld metal microstructure as a complex mixture of two or more constituents, such as proeutectoide ferrite, polygonal ferrite, aligned and non-aligned side plate ferrite, ferrite-carbide aggregate and acicular ferrite etc. Acicular ferrite that is formed at the weld joint has been proved to increase the toughness of the weld joint (Naufal et al., 2013). Grain boundary ferrite, side plate ferrite and ferrite aligned with aligned second phase are detrimental to toughness. Weld microstructure consisting of acicular ferrite provide optimal weld metal mechanical property (Hunt et al., 1994). The mechanical properties of the weld metal are yield strength, ultimate tensile strength and charpy impact toughness etc, all these determine the strength and toughness of the weld. A well designed flux will improve the mechanical and some desirable microstructural properties of the weld metal.

The welding flux designer therefore designs a flux that is required to perform several functions such as metal refining, good arc striking and restriking, maintenance of stable arc and minimum spatter, and good slag detachability. All these characteristics combine to determine the weld-metal quality and the productivity of the welding process (Adeyeye and Oyawale, 2010). This paper seeks a welding flux that will deposit a weld-metal with maximum acicular ferrite content, maximum charpy impact toughness, maximum ultimate tensile strength, maximum tensile strength, minimum grain boundary ferrite content, minimum polygonal ferrite, minimum side plate ferrite content and minimum ferrite with aligned second phase. These objectives the welding flux is expected to achieve are mutually incompatible. The incompatibility arises because the improvement in one objective or quality characteristic can only be made at the detriment of one or more of the other quality characteristics. Compromises and balances are often provided and designed into the flux by the welding flux designer such that as many as possible of the quality characteristics or desirable objectives are met. This paper also develops an approach for trade off exploration for various flux formulation situations. Therefore, a welding flux formulation that is closest to the ideal can be obtained.

1.1 THE COMPROMISE MODEL

Model development may be described in two phases; the first phase deals development of mathematical relationships between the flux ingredient levels and the performance criteria. This has been addressed in the literature (Kanjilal et al 2004, 2005, 2007a, 2007b). The second phase involves using the developed mathematical relationship (regression equation) to perform optimisation which is the focus of this study. Specific steps to follow are summarised below:

Step 1: Identify the beneficial and cost performance criteria. From the set of performance criteria on which the evaluation of the welding flux will be fixed, identify those that are beneficial and those that are not beneficial. The beneficial criteria are those for which higher values indicate better performance while for non-beneficial criteria lower values indicate better performance.

Step 2: Optimise the performance criteria individually to identify their ideal values.

Step 3: Generate the payoff matrix to identify the anti-ideal or nadir values and the degree of conflict among the criteria. Identify the complementary criteria and reduce the number of criteria accordingly. Pick only one of the complementary criteria. The ideal values of each quality characteristics were used to set up the payoff table. The ideal values are the optimal values of each quality characteristics when they were optimised separately. The ideal values of a criterion optimised separately are used to calculate the index value of other criteria. After setting up the payoff table the nadir point can be determined.

Step 4: Assign weight to performance criteria. Assign weight to each criterion to reflect their relative importance using the appropriate method. The analytical hierarchical process (AHP) is used in this study. Details of analytical hierarchical process are presented in section 3.3.1.

Step 5: Performance optimisation. Select the performance criteria to be optimised using their respective regression functions as the objective functions. Construct the constraints of the flux formulation problem and determine the best flux ingredient levels using compromise programming the procedure of compromise.

In compromise programming the closeness between a solution and the ideal point is measured by a distance function L_P. The ideal point is not achievable, but is used as a reference point for the identification of the best compromise solution. A family of L_p metrics is given below.
For any two point in n dimensional space a general distance measure is given by

$$L_p = \left(\sum_{j=1}^{n} \left|X_j^1 - X_j^2\right|^p\right)^{\frac{1}{p}} \tag{1}$$

Where n is the number of responses or welding flux quality characteristics.
Minkowski distance is the generalized metric distance (Grabust, 2011). For each value of the parameter p, a particular distance is determined.

If the welding flux designer considers all distances from the ideal point to be of equal importance then p = 1. The equation becomes,

$$L_1 = \sum_{j=1}^{n} \left|X_j^1 - X_j^2\right| \tag{2}$$

This is the rectilinear distance or Manhattan distance between two points. Manhattan distance between two points is the sum of the absolute differences of their Cartesian coordinate.
If the welding flux designer weighs each deviation in proportion to its magnitude then p = 2, the equation becomes,

$$L_2 = \left(\sum_{j=1}^{n} \left|X_j^1 - X_j^2\right|^2\right)^{\frac{1}{2}} \tag{3}$$

This measures the Euclidean distance. It represents the Pythagorean distance between any two points.
If only the largest deviation counts to the welding flux designer then $p = \infty$, L_∞ is the largest deviation of $\left|X_j^1 - X_j^2\right|$.

$$L_\infty = \max\ |X_1^1 - X_1^2|, |X_2^1 - X_2^2|, \ldots\ldots |X_n^1 - X_n^2| \tag{4}$$

This metric is the chebyshev distance. The chebyshev distance on a vector space is the distance between two vectors with the greatest differences along coordinate dimension.

In the L_p metrics, L_1 is the longest distance and L_∞ is the shortest distance. Therefore, all possible distances are bounded by L_1 and L_∞. The distance measure is used as a proxy for human preferences (Gan et al., 1996). The degree of closeness is represented by D_j between the jth objective or response and its ideal when the jth objective is optimised. Let $f_j^*(x)$ be the anti-ideal or nadir value of the jth objective or welding flux quality characteristics and $f_j^{**}(x)$ be the ideal or best value of the jth objective. Also, let $f_j(x)$ be the achievement level of the jth objective or welding flux quality characteristics. If the jth flux quality characteristic is a desirable characteristic, then it is maximised. The distance D_j between the achievement level $f_j(x)$ and the ideal value $f_j^{**}(x)$ is given by

$$D_j = f_j^{**}(x) - f_j(x) \quad , j = 1, 2, 3\ldots..n \tag{5}$$

And if the welding flux quality characteristic is not a desirable characteristic, then it is minimised and the distance D_j between the achievement level $f_j(x)$ and the ideal value $f_j^{**}(x)$ is given by

$$D_j = f_j(x) - f_j^{**}(x) \quad , \text{j = 1, 2, 3…..n} \tag{6}$$

The achievement levels and the units of the objective may be different, therefore, the degree of closeness must be normalised by using relative deviations rather than the absolute one. The normalised degree of closeness is given by

$$D_j = \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|} \quad , \text{j = 1, 2, 3…..n} \tag{7}$$

By adding the degree of closeness of each objective and its ideal, compromise programming minimises the following family of L_p metrics

$$L_p = \left(\sum_{j=1}^{n} (w_j D_j)^p\right)^{\frac{1}{p}} \tag{8}$$

$w_j \geq 0$, for every j and $\sum_{j=1}^{n} w_j = 1$

Where w_j is the weight of the jth objective. This denotes the relative importance of the quality characteristic or responses.

Therefore L_p can be written as

$$L_p = \left(\sum_{j=1}^{n} \left(w_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|}\right)^p\right)^{\frac{1}{p}} \tag{9}$$

1.2 THE COMPROMISE PROGRAMMING DESIGN PROBLEM

Compromise programming problem can be formulated as

$$\text{Min } L_p = \left(\sum_{j=1}^{n} \left(w_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|}\right)^p\right)^{\frac{1}{p}}$$

Subject to

$$g_i(x) \leq, \geq, = h_i \quad ; \text{i = 1, 2, 3,…. m}$$
$$x \geq 0 \tag{10}$$

where, m is the number of constraints and h_i is the right hand value of the ith constraint.

If the welding flux designer considers all distances from the ideal point to be of equal importance, then *p* =1 and the best compromise flux formulation is obtained by solving;

$$\text{Min } L_p = \sum_{j=1}^{n} \left(w_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|}\right)$$

Subject to

$$g_i(x) \leq, \geq, = h_i; \text{i = 1, 2, 3,…. m}$$
$$x \geq 0 \tag{11}$$

If the welding flux designer weighs each deviation according to its magnitude, then p = 2, the problem becomes

$$\text{Min } L_p = \left(\sum_{j=1}^{n} \left(w_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|}\right)^2\right)^{\frac{1}{2}}$$

Subject to

$$g_i(x) \leq, \geq, = h_i \quad ; \text{i = 1, 2, 3,…. m}$$
$$x \geq 0 \tag{12}$$

If only the largest deviation counts to the welding flux designer, then the problem becomes a min-max problem and $p = \infty$. The welding flux designer determines the best compromise flux formulation by solving:

$$\text{Min } L_\infty = \text{Min } D_\infty$$

Subject to

$$w_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|} \leq D_\infty$$

$$g_i(x) \leq, \geq, = h_i \quad ; \text{i} = 1, 2, 3, \ldots \text{m}$$

$$x \geq 0 \tag{13}$$

where D_∞ is the largest distance or deviation.
Solving the above equations for a particular value of w_j and p, the best compromise solution can be obtained.

1.3 WEIGHT DETERMINATION

The most creative task in making a decision is to choose factors or quality characteristics that are important. It is important to note that there is no standard scale to show the varying importance of the quality criteria. The paper therefore adopts a method for quantifying the relative importance of the quality criteria. Analytical hierarchy process (AHP) was adopted and the steps taken are shown below;

1. Develop a pair wise comparison matrix for each criterion.
2. Normalize the resulting matrix.
3. Find the average values of each row to get the weighted average (priority vector). The priority vector or the weighted average represents the weights of each criterion. Once the weights have been identified the consistency must be checked. The steps were explained below.
4. Calculate the consistency measure (CM). This is the matrix multiplication of each row of the pairwise comparison by the priority vector (weighted average) column divided by the equivalent cell in the priority vector. An example is given by the matrix multiplication shown below (pairwise comparison × weighted average = consistency measure)

$$\begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nn} \end{bmatrix} \times \begin{bmatrix} W_{11} \\ \vdots \\ W_{n1} \end{bmatrix} = \begin{bmatrix} WD_{11} \\ \vdots \\ WD_{n1} \end{bmatrix}$$

5. Calculate the consistency index (CI). To calculate the consistency index, the formula is CI = $\frac{\lambda max - n}{n-1}$ (14)
   Where λmax = average of the values of the consistency measure. This involves summing up the consistency measure for each row and then subtracting it from n= 8 (number of criteria) and dividing the answer by n-1.
6. Calculate the consistency ratio (CR). This is given by
   $CR = \frac{CI}{RI}$ (15)
   Where RI = random consistency index (Table 1 below).

Table 1: Saaty's random consistency index

N	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56

Source: Saaty (2008)

7. Check for consistency. If the CR value is less than 10%, then the consistency is within the acceptable limit. On the other hand, if the consistency ratio is greater than 10%, re-evaluate the pairwise comparison. Go to step 1 and continue until the consistency ratio is within acceptable limit.

2.0 MODEL APPLICATION

This section illustrates how the compromise programming can be integrated with the models of Kanjilal et al. prescribe the flux ingredient levels that give the best balance between the conflicting objectives. Kanjilal and co-investigators developed prediction models for acicular ferrite, polygonal ferrite, yield strength, charpy impact strength, ultimate tensile strength, side plate ferrite, grain boundary ferrite and ferrite with aligned second plate in the weld deposit as a function of flux ingredient levels for submerged arc welding of C-Mn steel. The flux ingredients used were the reagent-grade CaO, MgO, CaF_2 and Al_2O_3. The experiments were conducted with a low-carbon filler wire with a diameter of 3.15 mm at fixed welding parameters (current 400A, voltage 26V, speed 4.65 mm/s and electrode extension of 25mm). The response equation of the microstructure and mechanical property of the weld deposit given Kanjilal et al (2007) is shown below;

Acicular ferrite $f_{AF}(x)$

$$f_{AF}(x) = -4.8335\mathrm{X_{CaO}} + 2.0808\mathrm{X_{MgO}} - 0.3680\mathrm{X_{CaF_2}} - 0.6867\mathrm{X_{Al_2O_3}} + 0.0756\mathrm{X_{CaO}X_{MgO}} + 0.1551\mathrm{X_{CaO}X_{CaF_2}} + 0.1701\mathrm{X_{CaO}X_{Al_2O_3}} - 0.\,0731\mathrm{X_{MgO}X_{CaF_2}} - 0.0721\mathrm{X_{MgO}X_{Al_2O_3}} - 0.0068\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{16}$$

Grain boundary ferrite $f_{GBF}(x)$

$$f_{GBF}(x) = 2.6632\mathrm{X_{CaO}} + 0.1473\mathrm{X_{MgO}} + 0.7965\mathrm{X_{CaF_2}} + 1.2687\mathrm{X_{Al_2O_3}} - 0.0455\mathrm{X_{CaO}X_{MgO}} - 0.0720\mathrm{X_{CaO}X_{CaF_2}} - 0.0752\mathrm{X_{CaO}X_{Al_2O_3}} + 0.0254\mathrm{X_{MgO}X_{CaF_2}} + 0.0029\mathrm{X_{MgO}X_{Al_2O_3}} - 0.0086\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{17}$$

Polygonal ferrite $f_{PF}(x)$

$$f_{PF}(x) = 2.2848\mathrm{X_{CaO}} - 1.2764\mathrm{X_{MgO}} + 0.3102\mathrm{X_{CaF_2}} + 0.1682\mathrm{X_{Al_2O_3}} - 0.0135\mathrm{X_{CaO}X_{MgO}} - 0.0540\mathrm{X_{CaO}X_{CaF_2}} - 0.0646\mathrm{X_{CaO}X_{Al_2O_3}} + 0.0461\mathrm{X_{MgO}X_{CaF_2}} + 0.0656\mathrm{X_{MgO}X_{Al_2O_3}} + 0.0145\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{18}$$

Ferrite with aligned second phase $f_{FASP}(x)$

$$f_{FASP}(x) = -0.3141\mathrm{X_{CaO}} + 0.5034\mathrm{X_{MgO}} + 0.0727\mathrm{X_{CaF_2}} - 0.0957\mathrm{X_{Al_2O_3}} - 0.0021\mathrm{X_{CaO}X_{MgO}} + 0.0126\mathrm{X_{CaO}X_{CaF_2}} + 0.0192\mathrm{X_{CaO}X_{Al_2O_3}} - 0.\,0123\mathrm{X_{MgO}X_{CaF_2}} - 0.0095\mathrm{X_{MgO}X_{Al_2O_3}} + 0.0030\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{19}$$

Slide plate ferrite $f_{SPT}(x)$

$$f_{SPF}(x) = 1.4496\mathrm{X_{CaO}} - 0.2051\mathrm{X_{MgO}} + 0.4395\mathrm{X_{CaF_2}} + 0.5953\mathrm{X_{Al_2O_3}} - 0.0145\mathrm{X_{CaO}X_{MgO}} - 0.0415\mathrm{X_{CaO}X_{CaF_2}} - 0.0496\mathrm{X_{CaO}X_{Al_2O_3}} + 0.\,0140\mathrm{X_{MgO}X_{CaF_2}} + 0.0130\mathrm{X_{MgO}X_{Al_2O_3}} + 0.0038\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{20}$$

And the mechanical properties
Ultimate tensile strength

$$f_{UTS}(x) = -7.95374\mathrm{X_{CaO}} + 20.16304\mathrm{X_{MgO}} + 4.24123\mathrm{X_{CaF_2}} + 6.74286\mathrm{X_{Al_2O_3}} - 0.02189\mathrm{X_{CaO}X_{MgO}} + 0.48070\mathrm{X_{CaO}X_{CaF_2}} + 0.50277\mathrm{X_{CaO}X_{Al_2O_3}} - 0.38560\mathrm{X_{MgO}X_{CaF_2}} - 0.48676\mathrm{X_{MgO}X_{Al_2O_3}} - 0.12777\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{21}$$

Yield strength

$$f_{YS}(x) = -12.1431\mathrm{X_{CaO}} + 16.1571\mathrm{X_{MgO}} + 2.5666\mathrm{X_{CaF_2}} - 2.2240\mathrm{X_{Al_2O_3}} + 0.0878\mathrm{X_{CaO}X_{MgO}} + 0.5069\mathrm{X_{CaO}X_{CaF_2}} + 0.6429\mathrm{X_{CaO}X_{Al_2O_3}} - 0.3743\mathrm{X_{MgO}X_{CaF_2}} - 0.2713\mathrm{X_{MgO}X_{Al_2O_3}} - 0.0063\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{22}$$

Charpy impact strength

$$f_{CIS}(x) = -3.31038\mathrm{X_{CaO}} + 0.62389\mathrm{X_{MgO}} - 0.26209\mathrm{X_{CaF_2}} - 0.84441\mathrm{X_{Al_2O_3}} + 0.06680\mathrm{X_{CaO}X_{MgO}} + 0.10098\mathrm{X_{CaO}X_{CaF_2}} + 0.12913\mathrm{X_{CaO}X_{Al_2O_3}} - 0.\,03063\mathrm{X_{MgO}X_{CaF_2}} - 0.02394\mathrm{X_{MgO}X_{Al_2O_3}} - 0.00737\mathrm{X_{CaF_2}X_{Al_2O_3}} \tag{23}$$

2.1 THE CONSTRAINTS

The proportions of CaO, MgO, CaF_2 and Al_2O_3 in the Kanjilal experiments always sum up to 80% of the flux composition. The balance (20%) was made up of SiO_2, Fe-Mn, Ni and bentonite, all of which are of constant amounts throughout the experiment. The constraint can be written as

$$X_{CaO} + X_{MgO} + X_{CaF_2} + X_{Al_2O_3} = 80 \tag{24}$$

The technological constraints are

$$15 \leq X_{CaO} \leq 35 \tag{25}$$

$$10 \leq X_{MgO} \leq 32.40 \tag{26}$$

$$10 \leq X_{CaF_2} \leq 40 \tag{27}$$

$$8 \leq X_{Al_2O_3} \leq 40 \tag{28}$$

2.2 PROBLEM STATEMENT

The problem of the welding flux design can be written as
Max f_{AF}
Min f_{GBF}

Max f_{PF}
Min f_{FASP}
Min f_{SPF}
Max f_{YS}
Max f_{UTS}
Max f_{CIS}
s.t

$$\begin{gathered} 15 \leq X_{CaO} \leq 35 \\ 10 \leq X_{MgO} \leq 32.40 \\ 10 \leq X_{CaF_2} \leq 40 \\ 8 \leq X_{Al_2O_3} \leq 40 \\ X_{CaO} + X_{MgO} + X_{CaF_2} + X_{Al_2O_3} = 80 \\ X_{CaO}, X_{MgO}, X_{CaF_2}, X_{Al_2O_3} \geq 0 \end{gathered} \tag{29}$$

3.0 DISCUSSION OF RESULT

The model was run by using lingo 14 software on a dell 4gigabyte ram, 2.5GHz quad core processor. The model was run by optimising each objective separately subject to the constraint to determine the ideal points and flux formulations. The payoff table obtained is shown below;

Table 1; Payoff table for the criteria

	Acicular ferrite (%)	Grain boundary ferrite (%)	Polygonal ferrite (%)	Ferrite with aligned second phase (%)	Side plate ferrite (%)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Charpy impact strength (Joules)
Acicular ferrite	**44.5**	35.1	12.8	8.7	8.8	390	582	33.3
Grain boundary ferrite	42.2	**21.4**	18.3	7.8	10.5	392	532	27.9
Polygonal ferrite	8.4	39.7	**33.7**	3.9	19.7	274	406	7.6
Ferrite with aligned second phase	10.1	39.9	32.1	**3.5**	19.9	266	409	7.6
Side plate ferrite	43.9	35.7	13.5	8.9	**8.6**	393	579	33.5
Yield strength	42.6	31.3	17.72	7.9	10.4	**393**	536	27.7
Ultimate tensile strength	44.3	35	12.7	8.8	9	387	**583**	32.9
Charpy impact strength	44.2	35.5	13.2	8.8	8.6	393	581	**33.5**

Ideal points in bold, nadir points underlined.

The payoff matrix (Table 1) shows a conflict between different objectives. The diagonal values in bold represent the ideal point while the underlined values represent the nadir point. A look at the ideal values and the index values of the objectives in the same column shows that the ideal value of a particular objective is not equal to the index value for another objective except for two cases where these values were equal. In case of maximisation problems, the index values were lower while that of minimisation problems, the index values were higher. The ideal value (maximum value) of the yield strength and the corresponding index value of the charpy impact strength on the same column, and the ideal value (minimum value) of side plate ferrite and the corresponding index value of the charpy impact strength were identical (The ideal value of the charpy impact strength was also identical to the index value of the side plate ferrite). The exceptional cases showed that the objectives were partly complementary and complementary for charpy impact strength-yield strength and side plate ferrite-charpy impact strength respectively. This means that an improvement in side plate ferrite also improves the charpy impact strength.

The effect of the complementary objectives was that an increase in charpy impact strength reduces the side plate ferrite content and vice versa (The charpy impact strength was maximised and the side plate ferrite minimised). This means the two objectives are not conflicting and it is required to drop one of these objectives. The side plate ferrite was dropped from the model and the seven other objectives were used to solve the model. The weights for the seven criteria determined using AHP is shown below;

Table 2: weights of each criterion determined using AHP

Criteria	Weights
Acicular ferrite	0.22
Grain boundary ferrite	0.027
Polygonal ferrite	0.066
Ferrite with aligned second plate	0.026
Yield strength	0.24
Ultimate tensile strength	0.22
Charpy impact strength	0.20

The model was solved on lingo 14 using two cases, case 1 considered the criteria to be of equal weights while case 2 considered the criteria to be of different weights. The weight in table 2 was used in case 2. The result is shown below;

Table 3: The flux formulation and achievement level on each criterion under L_1, L_2 and L_∞

		Ideal points	**Case 1 (Equal weights)**			**Case 2 (Different weights)**		
	Flux Ingredients		**L_1 = 0.3**	**L_2 = 0.04**	**L∞ = 0.07**	**L_1 = 0.04**	**L_2 = 0.005**	**L∞ = 0.05**
Flux Formulation	X_{CaO} (%)		26.99	28.32	35	27.98	28.38	33.32
	X_{MgO} (%)		10	10	11.23	10	10	10
	X_{CaF_2} (%)		25.4	10	18.41	10	10	12.97
	$X_{Al_2O_3}$ (%)		17.6	31.68	15.36	32.02	31.62	23.71
Performance criteria	Acicular ferrite (%)	44.5	42.2	44.1	28.5	44.2	44.1	36.6
	Grain boundary ferrite (%)	21.39	31.7	35.5	40.6	35.4	35.6	38.6
	Polygonal ferrite (%)	33.7	18.1	13.3	24	13.2	13.3	18.5
	Ferrite with aligned second phase (%)	3.5	7.8	8.8	7.1	8.8	8.8	8.4
	Side plate ferrite (%)	8.6	10.3	8.6	12.7	8.6	8.6	10.2
	Yield strength (MPa)	393	391	393	350	392	393	379
	Ultimate tensile strength (MPa)	583	535	580	501	581	580	544
	Charpy impact strength (Joules)	33.5	28.5	33.5	21.5	33.5	33.5	28.5

3.1 CASE 1: CRITERIA ARE OF EQUAL IMPORTANCE

For the this scenario, the flux formulation under L_1 will be chosen if the welding flux designer considers all distances from the ideal point to be of equal importance and the formulation L∞ will be chosen if only the largest deviation count. The flux formulation under L_2 will be chosen if the welding flux designer weighs each deviation in proportion to its magnitude (Adeyeye and Oyawale, 2010). The flux formulation under L_1 was 26.99% of CaO, 10% of MgO, 25.4% of CaF_2 and 17.6% of Al_2O_3. For L_∞, it was 35% of CaO, 11.23% of MgO, 18.41% of CaF_2 and 15.36% of Al_2O_3 and for L_2 the flux formulation was 28.32% of CaO, 10% of MgO, 10% of CaF_2 and 31.68% of Al_2O_3. The welding flux designer can also calculate the response of each objective under L_1 and L_∞ since all compromise solution are bounded by L_1 and L_∞ (Gan et al. 1996). Table 12 shows the achievement level of each objective under L_1, L_2 and L_∞.

It was shown from Table 3 that under L∞ the acicular ferrite content was 28.5% and the corresponding yield strength, ultimate tensile strength and charpy impact strength were 350MPa, 501MPa and 21.5 joules respectively while the achievement under L_2 and L_1 with acicular ferrite content of 44.1% and 42.2% respectively showed an increase in the mechanical properties of the weld. The corresponding values for the yield strength, ultimate tensile strength and charpy impact strength were 393MPa, 580MPa and 33.5 joules and 391MPa, 535MPa and 28.5 respectively. This is in agreement with Kanjilal et al. (2005) and Hunt et al (1994) that the microstructures primarily consisting of acicular ferrite provide optimal weld metal mechanical properties, both from a strength and toughness point of view. It was also known that the welded metal and acicular ferrite have a high dislocation density which combined with the small grain size of the acicular ferrite produces a considerable high yield and tensile strength (da Trindade Filho et al., 2004).

3.2 CASE 2: CRITERIA ARE OF VARYING DEGREE OF IMPORTANCE

In real life, criteria are not of equal importance. Here, the welding flux designer considers all criteria to be of different weights. The flux formulation under L_1 was 27.98% of CaO, 10% of MgO, 10% of CaF_2 and 32.02% of Al_2O_3. For L_∞, it was 33.13% of CaO, 10% of MgO, 12.97% of CaF_2 and 23.71% of Al_2O_3 and for L_2 the flux formulation was 28.38% of CaO, 10% of MgO, 10% of CaF_2 and 31.62% of Al_2O_3. The response of each objective under L_1 and L_∞ was calculated since all compromise solutions are bounded by L_1 and L_∞ (Gan et al. 1996). Table 12 also shows the response of each objective under L_1, L_2 and L_∞.

From Table 12, L_1 and L_2 achievement levels were closest to the ideal when compared to L_∞. Under $L\infty$ the acicular ferrite content was 36.6% and the corresponding yield strength, ultimate tensile strength and charpy impact strength were 379MPa, 544MPa and 28.5 joules respectively. The achievement under L_2 was 44.1% of acicular ferrite content with an improvement in the mechanical properties (yield strength = 393MPa, ultimate tensile strength = 580MPa and charpy impact strength = 33.5 joules) of the weld and the achievement under L_1 with 44.2% of acicular ferrite content also showed good mechanical properties (yield strength = 392MPa, ultimate tensile strength = 581MPa and charpy impact strength = 33.5 joules) of the weld. The achievement level under L_∞ showed the highest concentration of side plate ferrite, grain boundary ferrite and polygonal ferrite when compared to the other two metrics for both scenarios. The achievement level under L_1 and L_2 were the closest to the ideal. This showed the best value in mechanical property.

4.0 CONCLUSION

Compromise programming model has been proposed for welding flux development for submerged arc welding. The approach is useful for determining the best compromise flux formulation when various conflicting performance criteria are considered. The weld metal responses such as microstructural and mechanical properties in submerged arc welding have been optimized. The proposed method eliminates the problem experienced by the traditional welding flux development to give the best balance among several conflicting quality criteria. The welding flux designer can use different weight structures to explore trade-off options before choosing the formulation that best suits his needs. This approach is also useful for identifying complementary and conflicting criteria.

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