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Optimisation of weld-metal chemical composition from welding-flux ingredients: A non-pre-emptive goal programming approach

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Abstract: A non-pre-emptive goal programming (NGP) model for weld-metal chemical composition optimisation from welding-flux ingredients is proposed. The proposed model, which is the first multi-objective mathematical programming approach to welding-flux formulation, provides increased flexibility to the welding-flux formulator in several ways: (1) several conflicting objectives can be simultaneously considered, (2) the best compromise for welding-flux formulation can be achieved with minimal expenditure of resources and experimental efforts, (3) the welding-flux designer can explore various trade-off options, and (4) the lead time and cost of developing welding consumables can be drastically reduced. This paper has extended the work of Kanjilal and co-investigators by coupling it with the NGP optimisation technique so as to prescribe the welding-flux ingredient levels that will achieve optimum performance for the flux at minimum experimental efforts and cost. The feasibility and suitability of the model is illustrated with data from the literature.

Keywords: welding flux, weld-metal composition, non-pre-emptive goal programming, multi-objective optimisation, multi-response

Introduction

Weld-metal mechanical properties and metallurgical features depend on the chemical composition of the as-deposited weld metal. Service requirements and progress in steel technology constantly demand new developments in welding process and consumables to deposit the weld metal with chemical composition equivalent to that of the base metal. The chemical composition of the weld

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

is influenced by the composition of the base metal, filler metal and flux [1-5]. A common practice in welding-consumable design is to use a filler metal with the same composition with the base metal. However, in some situations such as joining of dissimilar metals or for economic reasons, it may be necessary that a cheaper filler metal with composition different from that of the base metal is used. In such situations, the flux ingredients and their respective proportions are carefully selected so that the welding process can deposit the weld metal with the required chemical composition. The first step in welding-consumable design is to determine the filler metal to be used. Once the choice of the filler metal is made, the next stage of welding-consumable design is the development of the welding flux that can be used with the filler metal to deposit the weld metal with chemical composition that meets service requirements.

The challenge confronting the welding-flux designer (WFD) is not trivial even when the filler metal has the same composition with the base metal. This is due to the complex interaction between the flux ingredients and the weld pool during the welding process. In addition, the flux is required to perform several other 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. Since filler metals are costly, it is cost-effective to use cheaper filler metals which may not have the same composition with the base metal. The required composition of the weld deposit is achieved by proper design of the welding flux. Often, the same type of filler metal is used to deposit the weld metal with different chemical composition through the manipulation of the flux composition. Hence it is possible to use the same type of filler metal to weld different base metals if the fluxes are designed to suit the welding of such metals. A well designed flux will reduce the cost of welding and enhance the productivity of the welding process.

The objectives a welding flux is expected to achieve are often mutually incompatible. The incompatibility arises because the improvement in one objective or quality characteristic can only be made to the detriment of one or more of the other quality characteristics. Compromises and balances are often provided and designed into the flux by the WFD such that as many as possible of the quality characteristics or desirable objectives are met. The traditional method employed by the WFD to achieve these compromises and balances is by lengthy trial-and-error experiments. The drawbacks of the conventional welding-flux design approach are many [6-7]: (i) there is usually a very long lead time because of the extensive experimental weld production and testing, (ii) it is costly because of the labour requirements and consumption of a considerable amount of costly materials and energy during the lengthy experiments, (iii) the welding flux developed by the conventional method has a random character and it is difficult to guarantee optimum formulation or determine the flux with the best compromise formulation, and (iv) the feasibility or otherwise of achieving a desired compromise formulation cannot be established until a lot of resources and efforts have been expended on trial-and-error experiments. These drawbacks have persisted in the state-of-the-art welding-flux design because of a paucity of multi-objective optimisation models in the welding-flux technology.

Recently, Kanjilal et al. [8] proposed a methodology of developing analytical models for the prediction of the weld-metal chemical composition from welding-flux ingredient levels using data from experiments conducted according to a type of design-of-experiment (DoE) method known as

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

mixture experiments. Regression models for the prediction of oxygen, manganese, nickel, silicon and sulphur contents as a function of flux ingredient levels were proposed. The models can only predict the values of individual responses when the levels of flux ingredients are chosen. In practice, the WFD is interested in determining the flux ingredient levels that optimise all the responses or quality characteristics simultaneously and not individually. For instance, he may wish to achieve predetermined target values for some responses while at the same time he may also want to maximise desirable responses and minimise undesirable ones. The WFD therefore needs modelling tools that can handle multiple objectives and also assist him in exploring various trade-off options in order to be able to determine the best compromise for flux formulation. Goal programming is a versatile multi-objective optimisation modelling tool that has found wide-scale applications in various industries and in other areas of arc-welding technology except in welding-flux design where such applications are scanty [9]. This study seeks to extend the work of Kanjilal et al. [8] by coupling it with the non-pre-emptive goal programming (NGP) technique for the determination of flux ingredient levels that give the best compromise for flux formulation. As far as we know, NGP applications to the welding-flux design have not appeared in the open literature. In the following section we describe the systematic procedure a WFD can follow in the application of NGP to welding-flux design. Next, numerical examples are solved using data from the work of Kanjilal and co-investigators to illustrate the application of goal programming to welding-flux design.

The Proposed NGP Approach

The key conditions for the application of the NGP methodology are: (a) all the response variables defining the quality of the welding flux depend on the same set of predictor variables and (b) prediction equations that describe the relationship between the response variables and the predictor variables can be assumed over the domain of interest. The procedure for developing such response equations is beyond the scope of this paper. The procedure has been described elsewhere [6-8]. Once these conditions are met the procedure outlined below may be followed to arrive at the flux formulation that will give the best balance between the responses. The procedure is in two phases. Phase I is the determination of the feasible solution space and feasibility while phase II is the development and solution of the NGP model.

Phase I: Determination of the solution space and feasibility

The WFD needs to know the solution space so that the feasibility or otherwise of achieving the desired performance level for the welding flux can be known early. The steps the WFD may follow are:

Step 1: The WFD determines, for each of the responses, the minimum and maximum values, $f_i^{\min}(x)$ and $f_i^{\max}(x)$ respectively, within the experimental domain by solving equations (1a and 1b) below.

$$Minimise, \eta_i = f_i(x)$$

subject to: (1a)

$$x \in C_s$$

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

$$Maximise, \eta_i = f_i(x)$$

subject to: (1b)

$$x \in C_s$$

where

η_i = response i, for each $i \in I$

$f_i(x)$ = regression equation/function for response *i*, for each $i \in I$

x = n-dimensional decision/predictor variables

C_s = set of feasible constraints

$f_i^{\min}(x)$ = minimum value of the regression equation for response *i*, for each $i \in I$

$f_i^{\max}(x)$ = maximum value of the regression equation when solved individually for response *i*, for each $i \in I$

I = set of responses, quality characteristics or objectives

Step 2: The WFD writes the values of $f_i^{\min}(x)$ and $f_i^{\max}(x)$ for each $i \in I$. The solution space is defined by $\left[f_i^{\min}(x), f_i^{\max}(x)\right]$ and any point within or on the boundary is theoretically feasible.

Step 3: The WFD writes the desired or target value, T_i, for each $i \in I$ and compares them with their respective $\left[f_i^{\min}(x), f_i^{\max}(x)\right]$ interval. If the T_i values for all $i \in I$ fall within or on the boundary of the solution space, then it is feasible to achieve the needed flux with the present flux ingredients. If one or more of the T_i values fall outside the solution space, then it is not feasible for the WFD to achieve the desired flux with the present flux ingredients without some changes.

Step 4: If it is feasible to achieve the desired flux, the WFD proceeds to Phase II. Otherwise he goes back to experiments and makes necessary changes such as the addition of ferroalloys, addition or substitution of flux ingredients or any other actions based on experience and principles of metallurgy.

Phase II: Development and solution of the NGP model

It is not feasible to achieve all the target values simultaneously because of the conflicting nature of the quality characteristics. Therefore, there will be deviations from the target values of the quality characteristics. The deviations are undesirable and should be minimised. The unwanted deviations are assigned weights according to their relative importance to the WFD and then minimised as an Archimedian sum. The basic approach of NGP consists of the following steps [10]:

Step 1: The WFD assigns weights, w_i^+ and w_i^-, to each quality characteristic's deviation (d_i^+ and d_i^-), where w_i^+ and w_i^- are the respective weights for the positive and negative deviations from the target value of response i for each $i \in I$ ($w_i^+ = w_i^-$ if positive and negative deviations are weighted equally), and d_i^+ and d_i^- are the respective positive and negative deviations from the target value of response i for each $i \in I$. The weights w_i^+ and w_i^- take the value zero if the minimisation of the corresponding deviation is not important to the WFD.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

Step 2: The WFD constructs the goal constraints of the problem as:

$$f_i(x) + d_i^- - d_i^+ = T_i \quad (2)$$

Step 3: The WFD determines the deviational variable(s) to be minimised for each response. The four possibilities are the following. If $f_i(x) \geq T_i$, then solutions that fall below T_i are undesirable. Hence negative deviations (d_i^-) are to be minimised. Similarly, if $f_i(x) \leq T_i$, then minimize d_i^+ and if $f_i(x) = T_i$, minimise both d_i^+ and d_i^-. If $T_{Li} \leq f_i(x) \leq T_{Ui}$, then minimise d_{Li}^- and d_{ui}^+, where T_{Li} and T_{Ui} are the respective lower and upper limits while d_{Li}^- and d_{ui}^+ are the negative and positive deviations from the respective lower and upper limits.

Step 4: The WFD writes the complete NGP model to minimise the weighted sum of the unwanted deviations, subject to the technological and goal constraints as:

$$Minimise, asum = \sum_{i \in 1} (w_i^- d_i^- + w_i^+ d_i^+)$$

subject to: (3)

$$f_i(x) + d_i^- - d_i^+ = T_i$$
$$x \in C_s$$

where 'asum' is the achievement function or the Archimedian sum of the deviations.

Step 5: The WFD uses the appropriate algorithm or software to solve the problem.

Application of the Proposed Methodology

This section illustrates how the proposed NGP methodology can be integrated with the models of Kanjilal et al.[8] to establish feasibility and prescribe the flux ingredient levels that give the best balance between the conflicting objectives. Kanjilal and co-investigators developed prediction models for manganese, silicon, sulphur, oxygen and nickel contents in the weld deposit as a function of flux ingredient levels for submerged arc welding of C-Mn steel. The empirical models are shown in Table 1. 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 composition of the base metal and filler wire is given in Table 2 while the flux formulations as per the mixture experiment design are given in Table 3.

Constraints

The constraints of the NGP model are lower and upper limits of the flux ingredients:

$$15 \leq x_{CaO} \leq 35 \quad (4)$$
$$10 \leq x_{MgO} \leq 32.40 \quad (5)$$
$$10 \leq x_{CaF_2} \leq 40 \quad (6)$$
$$8 \leq x_{Al_2O_3} \leq 40 \quad (7)$$

where, x_{CaO}, x_{MgO}, x_{CaF_2} and $x_{Al_2O_3}$ are the respective proportions of CaO, MgO, CaF_2 and Al_2O_3 in the flux. These proportions in the Kanjilal experiments always sum up to 80% of the flux composition.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

The balance (20%) was made up of SiO_2, Fe-Mn, Ni and bentonite, all of which are of constant amounts throughout the experiment (Table 3). Hence there is an additional constraint given by:

$$x_{CaO} + x_{MgO} + x_{CaF_2} + x_{Al_2O_3} = 80 \quad (8)$$

Table 1. Prediction equations for the chemical elements in the weld deposit

Element	Prediction equation
Manganese content	$f_{Mn}(x) = -0.0244x_{CaO} + 0.059x_{MgO} + 0.0012x_{CaF_2} + 0.0024x_{Al_2O_3} - 0.0004x_{CaO}x_{MgO} + 0.0012x_{CaO}x_{CaF_2} + 0.0013x_{CaO}x_{Al_2O_3} - 0.0013x_{MgO}x_{CaF_2} - 0.0014x_{MgO}x_{Al_2O_3} - 0.0002x_{CaF_2}x_{Al_2O_3}$
Silicon content	$f_{Si}(x) = 0.0107x_{CaO} + 0.0520x_{MgO} + 0.0083x_{CaF_2} + 0.0128x_{Al_2O_3} - 0.0011x_{CaO}x_{MgO} - 0.0001x_{CaO}x_{CaF_2} - 0.00008x_{CaO}x_{Al_2O_3} - 0.0012x_{MgO}x_{CaF_2} - 0.0013x_{MgO}x_{Al_2O_3} + 0.0002x_{CaF_2}x_{Al_2O_3}$
Sulphur content	$f_S(x) = 0.00312x_{CaO} + 0.00471x_{MgO} + 0.00181x_{CaF_2} + 0.0022x_{Al_2O_3} - 0.00015x_{CaO}x_{MgO} - 0.00007x_{CaO}x_{CaF_2} - 0.00008x_{CaO}x_{Al_2O_3} - 0.00009x_{MgO}x_{CaF_2} - 0.00011x_{MgO}x_{Al_2O_3} - 0.00002x_{CaF_2}x_{Al_2O_3}$
Oxygen content	$f_{O_2}(x) = 63.305x_{CaO} - 12.42x_{MgO} + 6.457x_{CaF_2} + 16.775x_{Al_2O_3} - 0.945x_{CaO}x_{MgO} - 1.557x_{CaO}x_{CaF_2} - 2.061x_{CaO}x_{Al_2O_3} + 0.835x_{MgO}x_{CaF_2} + 0.767x_{MgO}x_{Al_2O_3} + 0.378x_{CaF_2}x_{Al_2O_3}$
Nickel content	$f_{Ni}(x) = -0.0776x_{CaO} + 0.0556x_{MgO} - 0.0181x_{CaF_2} - 0.0058x_{Al_2O_3} + 0.0006x_{CaO}x_{MgO} + 0.0030x_{CaO}x_{CaF_2} + 0.0026x_{CaO}x_{Al_2O_3} - 0.0015x_{MgO}x_{CaF_2} - 0.0018x_{MgO}x_{Al_2O_3} + 0.0004x_{CaF_2}x_{Al_2O_3}$

Source: Kanjilal et al. [8]

Table 2. Base metal and filler wire composition

Element	Carbon (wt.%)	Manganese (wt.%)	Silicon (wt.%)	Sulphur (wt.%)	Phosphorus (wt.%)	Nickel (wt.%)	Oxygen (ppm)	Nitrogen (ppm)
Base metal	0.22	0.77	0.25	0.03	0.02	-	350	50
Filler wire	0.10	0.56	0.05	0.02	0.01	-	380	60

Source: Kanjilal et al. [8]

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

Table 3. Flux formulations determined by mixture design and results of the experiments

Sample No.	Mixture variables composition (wt %)				Constant composition (wt %)					Measured responses from experiments				
	CaO	MgO	CaF_2	Al_2O_3	SiO_2	Fe-Mn	Fe-Si	Ni	Bentonite	Mn (%)	Si (%)	S (%)	O (ppm)	Ni (%)
P1	15.00	15.00	10.00	40.00	10.0	4.0	3.0	1.0	2.0	0.560	0.340	0.042	560	0.21
P2	15.00	15.00	40.00	10.00	10.0	4.0	3.0	1.0	2.0	0.520	0.210	0.042	570	0.11
P3	15.00	32.40	10.00	22.60	10.0	4.0	3.0	1.0	2.0	0.620	0.280	0.040	520	0.20
P4	15.00	17.00	40.00	8.00	10.0	4.0	3.0	1.0	2.0	0.470	0.170	0.034	500	0.17
P5	15.00	32.40	24.60	8.00	10.0	4.0	3.0	1.0	2.0	0.600	0.248	0.044	530	0.27
P6	35.00	15.00	10.00	20.00	10.0	4.0	3.0	1.0	2.0	0.670	0.229	0.028	380	0.24
P7	17.00	15.00	40.00	8.00	10.0	4.0	3.0	1.0	2.0	0.488	0.270	0.040	490	0.32
P8	35.00	15.00	22.00	8.00	10.0	4.0	3.0	1.0	2.0	0.580	0.200	0.028	480	0.29
P9	29.60	32.40	10.00	8.00	10.0	4.0	3.0	1.0	2.0	0.690	0.260	0.027	330	0.23
P10	35.00	27.00	10.00	8.00	10.0	4.0	3.0	1.0	2.0	0.540	0.193	0.034	480	0.31
P11	24.43	23.14	24.43	8.00	10.0	4.0	3.0	1.0	2.0	0.700	0.120	0.021	300	0.50
P12	15.67	15.67	40.00	8.66	10.0	4.0	3.0	1.0	2.0	0.601	0.150	0.037	350	0.34
P13	25.92	24.36	10.00	19.72	10.0	4.0	3.0	1.0	2.0	0.620	0.160	0.016	320	0.30
P14	23.40	15.00	24.40	17.20	10.0	4.0	3.0	1.0	2.0	0.748	0.258	0.031	300	0.78
P15	19.87	32.40	14.86	12.87	10.0	4.0	3.0	1.0	2.0	0.800	0.370	0.020	320	0.59
P16	15.00	22.36	24.92	17.72	10.0	4.0	3.0	1.0	2.0	0.507	0.200	0.024	600	0.05
P17	35.00	19.00	14.00	12.00	10.0	4.0	3.0	1.0	2.0	0.595	0.273	0.015	470	0.33
P18	22.67	21.63	21.63	14.07	10.0	4.0	3.0	1.0	2.0	0.517	0.160	0.023	540	0.29

Source: Kanjilal et al. [8]

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

Determination of solution space and feasibility

For manganese content in the weld deposit, the $\left[f_{Mn}{}^{\min}(x), f_{Mn}{}^{\max}(x)\right]$ values are determined as follows:

$$Minimise, (f_{\mathrm{Mn}}(x)) = -0.0244x_{\mathrm{CaO}} + 0.059x_{\mathrm{MgO}} + 0.0012x_{\mathrm{CaF_2}} + 0.0024x_{\mathrm{Al_2O_3}} - 0.0004x_{\mathrm{CaO}}x_{\mathrm{MgO}} + 0.0012x_{\mathrm{CaO}}x_{\mathrm{CaF_2}} + 0.0013x_{\mathrm{CaO}}x_{\mathrm{Al_2O_3}} - 0.0013x_{\mathrm{MgO}}x_{\mathrm{CaF_2}} - 0.0014x_{\mathrm{MgO}}x_{\mathrm{Al_2O_3}} - 0.0002x_{\mathrm{CaF_2}}x_{\mathrm{Al_2O_3}}$$

subject to constraint equations (4)-(8) (9)

and

$$Maximise, (f_{\mathrm{Mn}}(x)) = -0.0244x_{\mathrm{CaO}} + 0.059x_{\mathrm{MgO}} + 0.0012x_{\mathrm{CaF_2}} + 0.0024x_{\mathrm{Al_2O_3}} - 0.0004x_{\mathrm{CaO}}x_{\mathrm{MgO}} + 0.0012x_{\mathrm{CaO}}x_{\mathrm{CaF_2}} + 0.0013x_{\mathrm{CaO}}x_{\mathrm{Al_2O_3}} - 0.0013x_{\mathrm{MgO}}x_{\mathrm{CaF_2}} - 0.0014x_{\mathrm{MgO}}x_{\mathrm{Al_2O_3}} - 0.0002x_{\mathrm{CaF_2}}x_{\mathrm{Al_2O_3}}$$

subject to constraint equations (4)-(8) (10)

Similarly, the $\left[f_i^{\min}(x), f_i^{\max}(x)\right]$ for Si, S, O and Ni are determined to establish the feasible solution space.

Development and solution of the NGP model

Suppose the WFD wants a flux that will deposit a weld metal with the composition in Table 4.

Table 4. Desired weld-metal composition

Element	Mn (%)	Si (%)	S (%)	O (ppm)	Ni (%)
Amount desired	0.760	≥ 0.200	≤ 0.035	$250-350$	0.460

We consider two welding-flux design situations:

(i) All deviations are of equal importance to the WFD (Example 1);
(ii) Some deviations are of greater concern to the WFD than others (Example 2).

Example 1: All deviations are of equal concern to the WFD. Hence all the deviations are assigned equal weights ($w_i^+ = w_i^- = 1$) for each $i \in I$. The goal constraints of the problem may be stated as (Tables 1 and 4):

$f_{Mn}(x) + d_{Mn}{}^- - d_{Mn}{}^+ = 0.760$ (manganese content goal constraint) (11)

$f_{Si}(x) + d_{Si}{}^- - d_{Si}{}^+ = 0.200$ (silicon content goal constraint) (12)

$f_S(x) + d_S{}^- - d_S{}^+ = 0.035$ (sulphur content goal constraint) (13)

$f_{O_2}(x) + d_{LO_2}{}^- - d_{LO_2}{}^+ = 250$ (oxygen content lower-bound goal constraint) (14)

$f_{O_2}(x) + d_{UO_2}{}^- - d_{UO_2}{}^+ = 350$ (oxygen content upper-bound goal constraint) (15)

$f_{Ni}(x) + d_{Ni}{}^- - d_{Ni}{}^+ = 0.460$ (nickel content goal constraint) (16)

It is required that the Mn content be 0.760; therefore, deviations above and below the target are unwanted and must be minimised. Si content above 0.200 is acceptable to the WFD but values below

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

the lower limit are not desirable and must be minimised. Sulphur content in the weld must not exceed 0.035; therefore, deviation above this value is minimised. For oxygen, deviations above the upper limit and below the lower limit are minimized, while for Ni both the positive and negative deviations are minimised. The complete NGP model to minimise the Archimedian sum of the unwanted deviations is:

$$Minimise, asum = d_{Mn}^{-} + d_{Mn}^{+} + d_{Si}^{-} + d_{S}^{+} + d_{LO_2}^{-} + d_{UO_2}^{+} + d_{Ni}^{-} + d_{Ni}^{+}$$

subject to: (17)

technological constraints (the constraint equations (4)-(8))

goal constraints (the constraint equations (11)-(16))

Example 2: The WFD wants to achieve the same weld-metal content as in example 1 but the deviations are not of equal concern to him. Many methods exist by which the WFD may assign weights to the deviations to reflect his concern. In this study, the pairwise comparison method is used (Table 5) [11]. The normalised scores (weights) from Table 5 are:

$w_{Mn}^{-} = 0.30$, $w_{Mn}^{+} = 0.06$, $w_{Si}^{-} = 0.17$, $w_{S}^{+} = 0.26$, $w_{LO_2}^{-} = w_{UO_2}^{+} = 0.02$, $w_{Ni}^{-} = 0.15$ and $w_{Ni}^{+} = 0.02$

The NGP model is:

$$Minimise, asum = 0.3.d_{Mn}^{-} + 0.06d_{Mn}^{+} + 0.17d_{Si}^{-} + 0.26d_{S}^{+} + 0.02d_{LO_2}^{-} + 0.02d_{UO_2}^{+} + 0.15d_{Ni}^{-} + 0.02d_{Ni}^{+}$$

subject to: (18)

technological constraints (the constraint equations (4)-(8))

goal constraints (the constraint equations (11)-(16))

Table 5. Pairwise comparison of deviations for weight determination

Deviation	d_{Mn}^{-}	d_{Mn}^{+}	d_{Si}^{-}	d_{S}^{+}	$d_{LO_2}^{-}$	$d_{UO_2}^{+}$	d_{Ni}^{-}	d_{Ni}^{+}	Total score (t)	Normalised score $t/T = Weight$
d_{Mn}^{-}	_	2	2	2	2	2	2	2	14	0.30
d_{Mn}^{+}	0	_	0	0	1	1	0	1	3	0.06
d_{Si}^{-}	0	1	_	0	2	2	1	2	8	0.17
d_{S}^{+}	0	2	2	_	2	2	2	2	12	0.26
$d_{LO_2}^{-}$	0	0	0	0	_	0.5	0	0.5	1	0.02
$d_{UO_2}^{+}$	0	0	0	0	0.5	_	0	0.5	1	0.02
d_{Ni}^{-}	0	1	0	0	2	2	_	2	7	0.15
d_{Ni}^{+}	0	0	0	0	0.5	0.5	0	_	1	0.02
								Grand total (T)	47	1.00

Note: Scores for WFD's relative concern: high concern = 2; moderate concern = 1; equal concern = 0.5; less concern = 0

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

Discussion

The models were solved with the Lingo 11 software. The ranges of chemical composition possible for each of the elements in the weld metal within the experimental domain define the feasible solution space, which is presented in Table 6, while the NGP result for flux formulation that gives the best balance between the elements is presented in Table 7. Any weld-metal composition that falls within this range is achievable with the filler wire. The appropriate welding-flux ingredient levels are determined by solving the NGP model. The WFD need not embark on extensive and expensive experiments when it is required that a consumable that will deposit the weld metal with different composition be made provided such composition falls within the feasible solution space.

The capability to establish feasibility is a great advantage of this methodology because of the cost saving in terms of time, labour, materials and energy. In the case of the conventional welding-flux design approach, the feasibility or otherwise of achieving the desired flux performance level is not easy to ascertain until a lot of time, labour and resources have been expended on trial-and-error experiments. For the case under study, the feasible solution space can be identified with only 18 experiments (Tables 3 and 6). The WFD can know how far a given desired composition deviates from the feasible solution space in situations where the desired weld-metal composition does not fall within the feasible solution space. This knowledge can serve as a useful guide for the WFD in determining the next line of action.

Table 6. Feasible solution space

Element	Lower limit	Upper limit
Mn	0.453 %	0.762 %
Si	0.175 %	0. 374 %
S	0.024 %	0.049 %
O	249 ppm	633 ppm
Ni	0.104 %	0.615 %

The NGP model solutions are presented in Table 7. Without any further experiments the flux levels that will give the best balance between the various chemical elements are established. In example 1, where all deviations are equally weighted, the flux formulation that will give the best balance or compromise between the elements is 28.45% CaO, 32.40% MgO, 10.00% CaF_2 and 9.15% Al_2O_3 (Table 7). Manganese target is underachieved by 2.0% while sulphur content is 5.7% above the target value. Oxygen content is within the specified range (250-350 ppm). Nickel target in weld metal is achieved exactly while silicon content value is at an acceptable level.

In the case of example 2, where the negative deviation from the manganese content target is of the highest concern to the WFD and is assigned the highest weight, the manganese target is achieved, unlike in example 1 where it is underachieved by 2.0%. The corresponding welding-flux formulation is 26.43% CaO, 32.40% MgO, 10% CaF_2 and 11.17% Al_2O_3. Positive deviation from the sulphur content target is next in terms of the concern of the WFD with a corresponding weight of 0.26. The positive

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 347-359

Table 7. NGP model solution for flux formulation

Element	Target value	NGP model value		Deviation						Best compromise for welding-flux formulation (%) from NGP model	
				Case 1			Case 2			Example 1	Example 2
		Case 1 (equal weights)	Case 2	(-ve)	(+ve)	(%)	(-ve)	(+ve)	(%)		
Mn	0.760	0.745	0.760	0.015	-	2.0	0.0	0.0	0.0	CaO (28.45)	CaO (26.43)
Si	≥ 0.200	0.370	0.365	0.0		0.0	0.0		0.0	MgO (32.40)	MgO (32.40)
S	≤ 0.035	0.037	0.036		0.002	5.7		0.001	2.9	CaF_2 (10.00)	CaF_2 (10.00)
O	250-350	299	284							Al_2O_3(9.15)	Al_2O_3(11.17)
Ni	0.460	0.460	0.486	0.0	0.0	0.0	0.0	0.026	5.7		

deviation from the sulphur content target decreases from 5.7% in example 1 to 2.9% in example 2. The nickel content target is achieved in example 1 while in the case of example 2, there was a positive deviation of 5.7%. Because of the mutual incompatibility of the objectives, it is not possible to improve one quality characteristic without negatively affecting one or more of the other quality characteristics. When nickel content target is achieved in example 1, the manganese content is underachieved, while in example 2 the manganese content target is achieved but the nickel content target is overachieved. The NGP approach provides flexibility to the WFD, who can use different weight structures for the deviations from the targets to explore various trade-off options before choosing the one that best meets his needs.

Apart from weld-metal chemical composition optimisation, NGP method may also be useful in other multiple-objective welding-flux design situations. The determination of welding-flux ingredient levels that will achieve the desired values of acicular ferrite, polygonal ferrite, bainite and grain boundary ferrite contents in the weld-metal microstructure, or give the desired balance between mechanical properties such as yield strength, tensile strength, Charpy impact strength, hardness and elongation are such examples.

Conclusions

The NGP approach for multi-response optimisation of weld-metal chemical composition from welding-flux ingredients is proposed. The major conclusions are:

● It is feasible for the WFD to simultaneously consider many mutually incompatible responses or objectives with the NGP method.

● If all the responses depend on the same set of predictor variables and the models that capture the relationship between the response and predictor variables can be assumed over the experimental

domain, then the proposed methodology can be used to determine the best balance between the responses.

● The proposed methodology can be used to establish the feasible solution space and the feasibility or otherwise of achieving the desired performance level of the welding flux before a lot of resources are expended on experiments.

● The random character of the welding flux developed by traditional approach is eliminated because the NGP model ensures that the flux that gives the best balance between the objectives of the WFD is formulated.

● The WFD can use different weight structures to explore trade-off options before choosing the formulation that best suits his needs.

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