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Fuzzy-TOPSIS Model for Optimization Hot Corrosion Resistance of Inconel718 Coated by Yttrium-doped Aluminizing-Siliconizing Process

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ABSTRACT

The objective of this study is to find out the optimum hot corrosion resistance and hardness for Inconel718 coated by simultaneous yttrium-doped aluminizing-siliconizing process. The hot corrosion parameters selected for the experiments are Na_2SO_4, NaCl, and V_2O_5. The optimization is carried out by choosing three input parameters at two levels. Multi objective optimization technique, TOPSIS optimization approach is used for maximizing the hot corrosion resistance (minimizing hot corrosion rate Kp),and hardness. ANOVA is performed to investigate the more influencing parameters on the multiple performance characteristics. It also helps to calculate percentage contribution of each parameter. Finally, accuracy of optimization was confirmed by conducting confirmations. Results indicate feasibility of TOPSIS analysis in continuous improvement in hot corrosion resistance.

Keywords: ANOVA, Taguchi concept, TOPSIS, Hot corrosion, orthogonal array

INTRODUCTION

Nickel-base super alloys Inconel718 are widely employed in the aerospace industry; in particular in the hot sections of gas turbines engines, due to their high-temperature strength, however, these alloys may not be able to meet both the high temperature strength requirements and high temperature corrosion resistance simultaneously for longer life. So, protective coatings are used to counter the latter. Hot corrosion may be defined as an accelerated corrosion, resulting from the presence of salt contaminants such as Na_2SO_4, NaCl, and V_2O_5 that combine to form molten deposits, which damage the protective surface oxides. Hot corrosion occurs when metals are heated in the temperature range 700-900^{o}C in the presence of sulphate deposits as a result of the reaction between sodium chloride and sulphur compounds in the gas phase surrounding the metals . The behavior of high temperatures has been significant in the improvement of society for many countries. Structural equipment in many high technology areas has to be operating under severe circumstances of temperatures, pressure and corrosive environment. Consequently, materials degradation at high temperature is a severe trouble in several industries. Gas turbines in airplane, fossil fuelled power plants, refiners, and petrochemical industries, and heating elements for elevated heat furnaces are examples where corrosion reduces their life, considerably affecting the efficiency. Coal is a compound and comparatively polluted fuel that contains varying quantity of sulphur and a considerable fraction of non-combustible mineral constituents, commonly called ash. The vast scientific literature available is evidence that corrosion and deposits on the firesides of boiler surfaces or in gas turbines represent important

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problems. Metals and alloys may experience accelerated oxidation when their surfaces are coated by a thin film of fused salt. High temperature degradation is one of the main failure modes of hot-sections components in the gas turbines, so understanding corrosion and wearing down by fly ashes and unburned carbon particles are the man trouble to be solved in these applications. Therefore, the increase of high temperature oxidation (Hot Corrosion) protection systems in industrial turbines is a very important topic from both engineering and an economic perspective [1, 2].

The development of a surface oxide scale limits the degradation of a pure metal or alloy in a hot oxidizing environment. The addition of reactive elements which have a high affinity for oxygen (such as Y, Ce, Hf) may further improve the oxidation resistance through various effects [3]:

- Promotion of the selective oxidation of an element which forms a stable oxide of low diffusivity (such as Al_2O_3 and SiO_2).
- Reduction of the growth rate of oxide scale.
- Inhibition of scale failure (i.e. through thickness cracking and scale/substrate interfacial decohesion).

Reactive-Element (RE) additions may be providing either as metallic or oxide dispersed components in bulk alloy, or as surface produced by coating. They are used predominantly with Cr_2O_3- and Al_2O_3-forming alloys to resist aggressive environment [4]. V.Provenzano and coworkers [5].Proposed a model of mechanical keying due to the formation of oxide pegs rich in active elements, the role of these peg being to anchor the oxide scale to the coating alloy. It was found that the addition of yttrium prevents the sulfur segregation to the alloy/scale interface, either by reacting with sulfur to form stable sulfides or by tying up the sulfur by segregation to internal oxides surfaces [6]. Thus, the addition of small amount of reactive element [Y,Ce, La, Hf, Zr, Th] to an alloy resulted in substitution improvements in the adherence of their oxide scales during thermal cycling [7]. Previous work [8,9,10,11,12,13,14], has shown that such reactive element additions are effective in improving the high temperature corrosion of Nickel and Iron-base alloys by improving the resistance of protective scales to spallation. It was found that the scale formed on germanium -free alloy is typically convoluted or wrinkled and poorly adherent, the germanium -containing alloy produces a flat and adherent oxide. In recent years germanium has become the most commonly used of these reactive elements. The amount of the reactive element needed to produce the beneficial effect is small, (typically 1wt. % or less). Heat-resisting alloys depend on the formation of a protective oxide on the metal surface to limit section loss by oxidation. Generally, this protective oxide is Alumina (Al_2O_3), silica (SiO_2) or Chromia Cr_2O_3. In practice, the most common way that a protective oxide fails is by exfoliation or spalling from the metal surface. This spallation may be induced by stresses arising from the oxide growth process itself, strains resulting mechanical flexing of the component in the service, or from stresses arising from thermal cycling because of the difference in the coefficients of thermal expansion of the oxide and the metal. Spallation of oxide may involve fracture in the oxide adjacent to the metal surface, fracture in the metal immediately below the interface, or by separation at the interface itself. In the last case, failure involves not only the magnitude of the stresses, but also a consideration of the interfacial adhesion.

This paper attempts to optimization the hot corrosion resistance of Inconel718 coated by simultaneous yttrium-doped aluminizing-siliconizing process using decision- making (MCDM) method, technique for order preference by similarity to ideal solution TOPSIS and fuzzy-based Taguchi approach .

Topsis Method

This study uses the TOPSIS technique. A positive ideal solution increases the advantage requirements or features and reduces the cost requirements or features, whereas a negative ideal solution increases the cost requirements or features and reduces the advantage requirements or features. The TOPSIS approach is determined through the following steps: [15]

1- Determine the stabilized decision matrix. The stabilized value is measured as follows:

$r_{ij} = x_{ij}\sqrt{\sum_{i-1}^{m} x_{ij}^2}$ i =1, 2, ..., m and j = 1, 2, ..., n, m=number of columns and n=number of rows .

2. Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as follows:

$$v_{ij} = r_{ij} \times w_j \quad \text{i =1, 2,..., m and j = 1, 2, ..., n.} \qquad \dots (1)$$

Where w_j is the weight of the j^{th} criterion or attribute and

$\sum_{j=1}^{n} w_j = unity$, i.e. summation of responses weight equal to (1)

3- Determine the ideal (A^*) and negative ideal (A^-) solutions.

$$A^* = \{(\max_i v_{ij} \mid j \in C_b), (\min_i v_{ij} \mid j \in C_c)\} = \{v_j^* \mid j = 1,2,...,m\} \qquad (2)$$

$$A^- = \{(\min_i v_{ij} \mid j \in C_b), (\max_i v_{ij} \mid j \in C_c)\} = \{v_j^- \mid j = 1,2,...,m\} \qquad (3)$$

4- Calculation of the separation measures of responses using the m-dimensional Euclidean distance. The separation measures of each alternative (performance cjarateristics) from the positive ideal solution (S_i^*) and the negative ideal solution (S_i^-) , respectively, are as follows:

$$S_i^* = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^*)^2}, j = 1,2,...,m \qquad (4)$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^-)^2}, j = 1,2,...,m \qquad (5)$$

5- Calculation of the relative closeness to the ideal solution for responses (RC_i^*). The relative closeness of the alternative A_i (ideal) with respect to A^* (Negative ideal) is defined as follows:

$$RC_i^* = \frac{S_i^-}{S_i^* + S_i^-}, i = 1,2,...,m \qquad (6)$$

6- Rank the preference order of the performance characteristics.

Linguistic Variables Expressed in TFN (Triangular Fuzzy Numbers)

The extension of the TOPSIS method in the fuzzy environment can be achieved by expressing the weights of the criteria and the ratings as linguistic variables. A linguistic variable is a variable whose values are linguistic terms. The concept of linguistic variable is very useful in dealing with situations which are too complex or too ill-defined to be reasonably described in conventional quantitative expressions (Zadeh, 1975). According to many authors, the linguistic variables can be expressed in positive triangular fuzzy numbers as shown in Table 1 [16].

Table (1): Linguistic variables

Linguistic variables for the importance weight of each criterion	
Very low (VL)	(0.1,0,0)
Low (L)	(0.3,0.1,0.1)
Medium low (ML)	(0.5,0.3,0.3)
Medium (M)	(0.7,0.5,0.5)

Medium high (MH)	(0.9,0.7,0.7)
High (H)	(1,0.9,0.9)
Very high (VH)	(1,1,1)

The Taguchi Method

The Taguchi approach is more effective method than traditional design of experiment methods such as factorial design, which is resource and time consuming. It is correct to point out also limitations of the Taguchi method. Most critical drawback of the Taguchi method is that it does not account higher order interactions between design parameters. Only main effects and two factor interactions are considered. Taguchi methods, developed by Dr. Genichi Taguchi, are based on the following two ideas

– Quality should be measured by the deviation from a specified target value, rather than by conformance to preset tolerance limits;

– Quality cannot be ensured through inspection and rework, but must be built in through the appropriate design of the process and product.

In the Taguchi method, two factors such as the control factor and the noise factor are considered to study the influence of output parameters. The controlling factors are used to select the best conditions for a manufacturing process, whereas the noise factors denote all factors that cause variation. The signal-to-noise (SN) ratio is used to find the best set of design variables. Usually, the SN ratio is calculated for finding the individual and combined effect of the factors and the large value is considered as the optimal . According to the performance characteristics analysis, the Taguchi approach is classified into three categories:

– Nominal-the-Better (NB),
– Higher-the-Better (HB),
– Lower-the-Better (LB).

In the following Higher -the-Better (LB) approach is employed in order to maximize the objective functions. The SN ratio is calculated as follows [17]:

$$SN_i = -10log\left(\frac{1}{N_i}\sum_{k=1}^{N_i}\frac{1}{y_k^2}\right) \qquad (7)$$

where i , k , N_i stand for experiment number, trial number and number of trials for experiment i , respectively.The results obtained from the Taguchi Method can (should) be validated by the confirmation tests. The validation process is performed by conducting the experiments with a specific combination of the factors and levels not considered in initial design data.

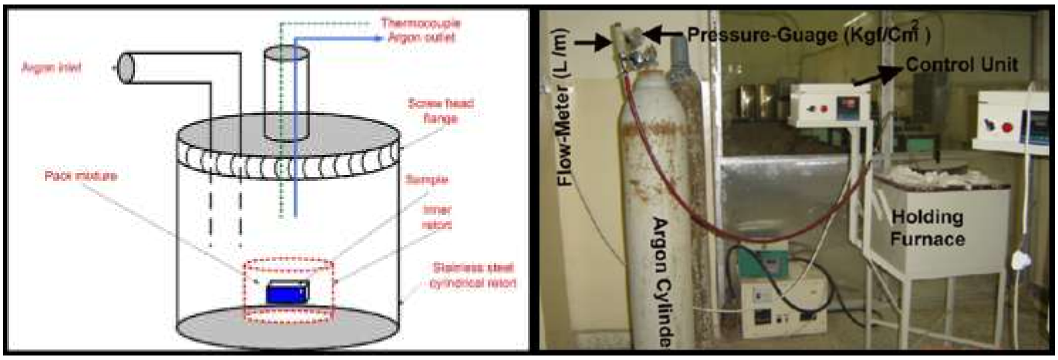
Experimental Procedure

Coating System

The experimental procedure was conducted by using samples of inconel718. The spectrochemical investigation of materials are provided in Table (2) , Specimens were cut into pieces forms with measurements (20mm× 20×mm×5mm) with little opening of 2mm dimension was drilled in each example for having. All areas, such as the sides were subjected to wet ground using 120, 220, 320, 600, 800, and 1200 grit silicon carbide paperwork. These Specimens were then washed with water, degreased with acetone, and then ultrasonically washed for 30 moments using ethanol as a medium. After drying, the Specimens were held in polyethylene zip-lock bags. The sizes of all Specimens were determined. The pack mixture for aluminum-silicon diffusion covering composed of 16 Wt.% Al powdered (50-60 µm in compound size) as an aluminium resource, 6 Wt.%Si powdered (50-60 µm in compound size) as a silicon resource, 2Wt.% NaF and 2Wt.%NaCl as activator and the remainder was silica-powder (70-120 µm in compound size). All package powders were sieving by sieving technique and 1Wt.% of the pack silica was changed by yttrium . The Specimens were placed in a enclosed stainless-steel round retort of 50mm in a diameter and of 80mm in a height. The external retort has a part pipe through which argon gas goes up. K-Type adjusted thermocouple was placed through the cover of the external retort for recording actual heat range near inner retort. Pack cementation procedure was performed at 1050 ^{o}C for 6 hr. under an Ar environment. After coating, the Specimens were ultrasonically washed, and weighted. A coating thickness of 65-66 μ was obtained bythe diffusion coating time of 6 hr. at 1050 ^{o}C.The apparatus used for pack cementation is shown in Figure 1 .

Table(2) :Chemical composition of Inconel718(Weight Basis)

C	Si	Cu	Fe	Mn	Ti	Al	Cr	Ni	Mo	Co
0.024	0.08	0.05	Bal	0.07	0.88	0.43	16.4	51.70	0.03	0.05



(a) Pack Cementation retort (b) Pack Cementation Furnace

Figure(1):Apparatus used for pack cementation

Hot Corrosion Test

For hot corrosion tests, Na_2SO_4, NaCl, and V_2O_5 powders were selected as a corrosive salts. Specimens were placed with each of these salts until a total covering bodyweight of 5 mg/cm^2 was achieved according to A. Anderson et. al procedure [2] .The samples were measured and weighted first , then placed on a hot coated warmed to 110^{o}C. An air gun applied on the soaked aqueous – salt solutions in air spray and a cover of fine sodium contaminants established on the samples areas after the spray resolved and the h2o disappeared. The procedure was recurring until the dry contaminants were placed up to 5 mg/cm2. Hot corrosion test was conducted in a fixed air at temperature range (800^{o}C-900^{o}C) for 50 hr. at 5 cycles in a automated pipe heater. After examining the samples were washed in an ultrasound bath, first in distilled water and then in ethanol. They were then weighted on a digital balance to determine the change in weight.

Table(3): Experimental factor and two levels

Factor		Symbol	Level Code		Unit
			Low	High	
1.	Na_2SO_4	A	20	30	%Wt.
2.	NaCl	B	20	30	%Wt.
3.	V_2O_5	C	20	30	%Wt.

Selection of procedure factors has significant impact on the hot corrosion resistance. Table 3 shows independent controllable process variables, which were identified based on their significant effect on hot corrosion resistance to carry out the experiments.

The hot corrosion resistance can expressed in terms of parabolic oxidation rate (K_P) which can be determined from weight gain/area (mg/cm^2) vs time (number of cycles) plots as shown in Figure1 (top plot) where the (K_P) value was determined at run order (1) . The weight gain square (mg^2/cm^4)vs time (number of cycles) plot is shown in Figure1 (bottom plot) to establish the rate law for the hot corrosion. It is observed from the graph that coated system at run order (1) follow nearly parabolic rate law. The parabolic rate constant K_p was calculated by linear least-square algorithm to a function in the form of [15]:

$$(W/A)^2 = K_p\, t \qquad \dots (8)$$

Where *W/A* is the weight gain per unit surface area (mg/cm^2) and t indicates the number of cycles representing the time of exposure. The parabolic rate constants for coated system in molten salts under temperature range (800-900^oC) were calculated on the basis of 10 cycle's data and are reported in Table 4.Microhardness testing of oxide layers is employed by precise diamond indenter with 1 kgf load. The dwell time is kept at 10 s while the speed of indentation is set at 50 µm/s. An average of at least five hardness values for each sample is reported in Table 4. With aid of using "(Larger-the-better approach)," for hardness and using "(Smaller-the-better approach),'' for hot corrosion rate Kp, the experimental results have been normalized , then the normalized responses for both hardness and corrosion rate are converted into linguistic variables as listed in Table 5.

Table (4): Design matrix and their response

Run Order	A	B	C	Vickers microhardness	K_P ($10^{-10} mg^2/cm^4\, s^{-1}$)
1	1	1	1	1010	1.3322
2	1	1	1	1027	4.7911
3	1	2	2	957	6.4321
4	1	2	2	1033	2.1054
5	2	1	2	1039	7.3001
6	2	1	2	1041	3.8432
7	2	2	1	922	4.1761
8	2	2	1	910	8.3512

Table (5):Experimental results for responses in terms of linguistic termsusing L8 orthogonal array

Run Order	A	B	C	Vickers microhardness	K_P ($10^{-10} mg^2/cm^4\, s^{-1}$)
1	1	1	1	EH	M
2	1	1	1	L	VH
3	1	2	2	VL	L
4	1	2	2	H	VH
5	2	1	2	VL	EH
6	2	1	2	M	EH
7	2	2	1	H	VL
8	2	2	1	EL	EL

Microstructure and X-Ray Diffraction

The microstructure of specimens exposed to hot corrosion was analyzed using optical microscopic. X-Ray generator with Cu- K_α rays at 40 KV and 20 mA was used. The X-Ray is produced by X-rays-diffractometer, type Philips (pw 1840) (using scanning- rate of 6^o (2 θ) for each moment) . The sensor is shifted through an position of 2θ =10 to 80 degree. The XRD was performed at S.C. Geological Survey and Mining.

Results and Discussions

Assignment of weights to the performance characteristics are based on experience of engineers, customer's requirements and their priorities. In the present work equal importance is given for both microhardness and hot corrosion rate Kp. Therefore $W1$ &$W2$ = 0.5.Then, the values for (The normalized decision matrix and the criteria weights) are multiplied to obtain the weighted normalized matrix for all performance characteristics. The ideal (best-A+) and negative ideal (worst-A-) solutions are calculated using "(2)," and "(3)," respectively as listed in Table 6.

Table (6): Ideal and positive ideal value for response

Response	A+	A-
Microhardness	0.239215	0
Hot Corr. Rate Kp	0.292976	0

Using "(4)," and "(5)," the separation measures(S+ and S-) of each criterion from the ideal and negative ideal solutions are computed as shown in Table 7 .The relative closeness coefficient (RC) value for each combination of performance characteristics has been calculated by "(6)," as shown in Table 8.

Table (7): Separations measures

Exp.No.	S+	S-
1	0.309513879	0.139394701
2	0.089572132	0.289418315
3	0.209570536	0.272817279
4	0.233706339	0.219532981
5	0.009782982	0.368560299
6	0.12085059	0.294704855
7	0.258869054	0.189325397
8	0.239215246	0.292975596

Table (8): Closeness coefficients values

Exp.No.	RC	SN
1	0.310519	-10.1582
2	0.763656	-2.34205
3	0.565556	-4.95049
4	0.484364	-6.29656
5	0.974143	-0.22755
6	0.709183	-2.98483
7	0.422418	-7.48515
8	0.550509	-5.18472

The quality of each factor on the quality features can be examined using SN ratios and the quality results are described and analyzed according to complete mean principles of test trial outcomes (matrix-design outcomes) or SN ratios .The best possible comparative nearness coefficient (RC) value for each mixture of microhardness and hot corrosion rate can be measured by means of complete mean principles of matrix-design outcomes. Another requirement in the computation of the best possible principles is to determine the optimum levels. The optimum levels can be determined by analyzing two different quantities of a control factors according to the results from the mixtures generated by the orthogonal array of matrix-design outcomes. The levels of control factors were determined as Na_2SO_4 at level 2, NaClat level 1and V_2O_5 at level2 and *SN* graphics of these levels were used for the evaluation as shown in Figure2.

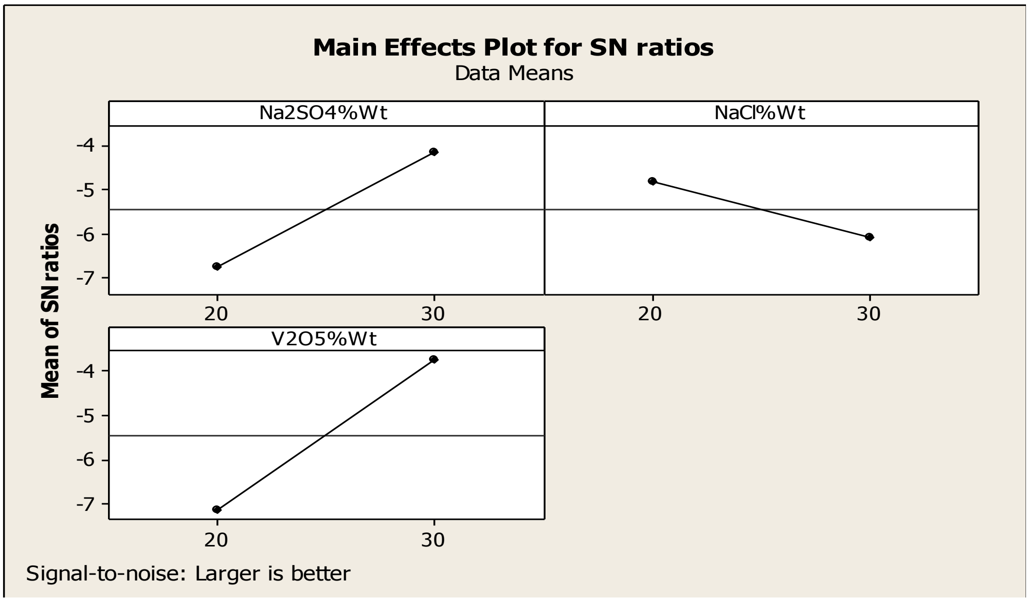


Figure (2): Response plot for closeness coefficient

In this study, ANOVA (Analysis of Variance) was used to evaluate the results of Na_2SO_4, NaCl and V_2O_5. ANOVA is a statistical method used for identifying the contribution (%) of individual interactions of all control factors. In this research, the share distributions of each control factor were used to look at the corresponding results on the quality features. The conducted trial plan was analyzed at a level of confidence of 95%. ANOVA principles that belong to trial results for the efficiency features are shown in table 9. The significance of control factors in ANOVA is determined by comparing *F* value of each control factor and*F*0.05 value from table. According to the results of table 9, NaCl had a larger effect (42.2%) on the performance characteristics, followed by V_2O_5 with a ratio of 35.55 %.

Table (9) : ANOVA table

Source	DF	Seq SS	Adj SS	Adj MS	F	%Contrib
Na_2SO_4%Wt	1	0.03511	0.03511	0.03511	0.94	22.24
NaCl%Wt	1	0.06661	0.06661	0.06661	1.78	42.20
V_2O_5%Wt	1	0.05611	0.05611	0.05611	1.50	35.55
Error	4	0.14935	0.14935	0.03734		
Total	7	0.30719				

The final step of the Taguchi method is the verification assessments performed for analyzing the standard features. The model used in the verification assessments is determined with the total impact generated by the control aspects. The standards are is equal to to the sum of each individual impact. The maximum top quality attribute was obtained by considering the significant aspects within the analyzed the best possible combination.The S/N rate at the best possible level of all responses has been determined by the following formula [17]:

$$\mu_{opti} = \mu_m + \sum_{i=1}^{p} (\mu_i - \mu_m) \qquad \dots (9)$$

Where μ_m is the average value of the SN-ratio of all responses in all experimental runs μ_i is the value of the SN ratio corresponding to optimum level and p is the number of factors. Table 10 shows the comparison of the experimental results for the optimal conditions (A2B1C2) with predicted results for optimal (A2B1C2). The comparison again shows the good agreement between the predicted and the experimental values as shown in table 10.

Table (10) : Confirmation results.

	Initial Conditions	Optimal parameters	
		Prediction	Experiment
Setting levels	A1B1C1	A2B1C2	A2B1C2
SN ratio	-10.1582	-3.00961	-3.332

According to Taguchi's forecast, SN rate for RC becomes 3.00961, compared to that of confirmatory research, which acquired a value of -3.332. So, a good quality characteristic has enhanced using the maximum establishing. Typical microstructure of the scales formed on alloy is shown in Figure 3. It is evident that the scales formed on the alloy were complex, depending strongly on hot corrosion parameters. They generally consisted of an outer layer of mostly$NiCr_2O_4$and minor amounts of Fe_2O_3 .XRD is a graph plotted between Intensity and diffraction angle 2θ to identify the phases present in the scale formed. X-ray diffract grams of the scale formed on the oxidized specimens are shown in Figure 4. The major phases identified in superni718 (INCONEL) are $Fe_2O_3$and $NiCr_2O_4$ which provide oxidation resistance.

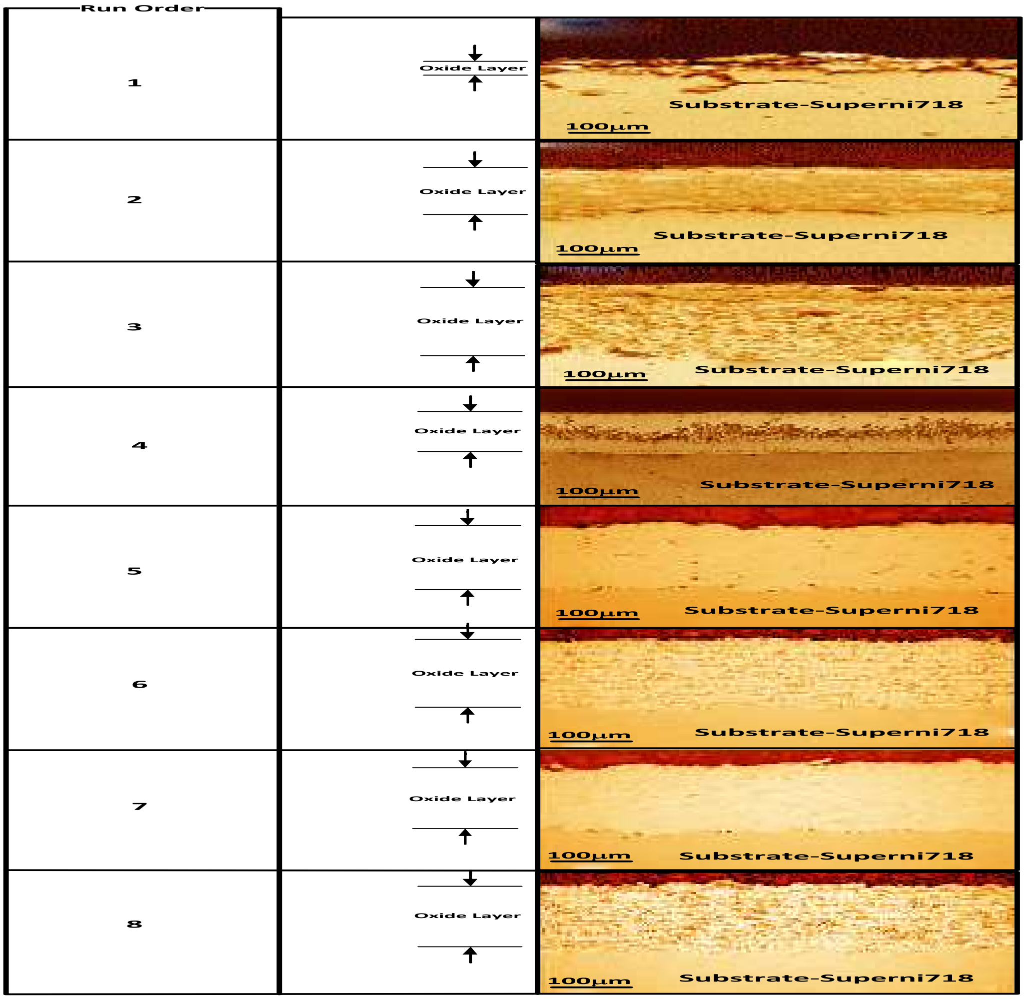
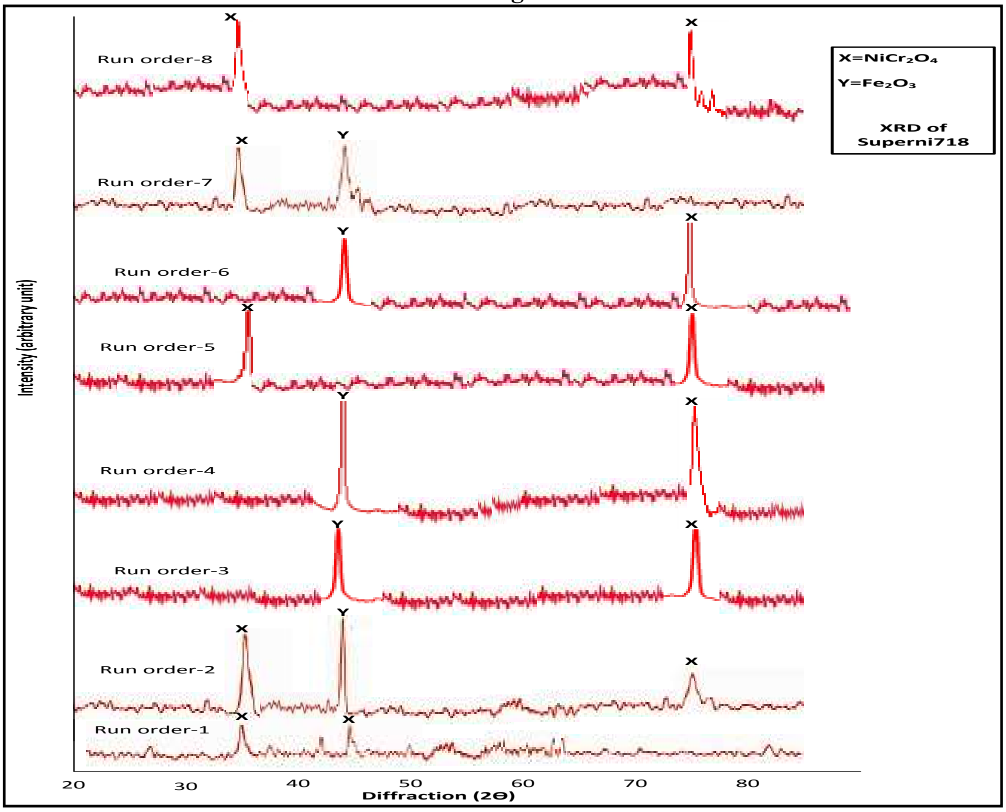


Figure (3): Light optical microscope (LOM) microstructure (Cross-Section View) of Supereni718 coated with Y-doped aluminizing-siliconizing after hot corrosion test according to design matrix



Figure(4):XRD patterns of Supereni718 coated with Y-doped aluminizing-siliconizing

CONCLUSIONS

Based on the present study, the following conclusions can be drawn:

1- The optimization of hot corrosion parameters by TOPSIS, Taguchi approach and fuzzy logic was found to be successful.

2- Based on ANOVA results, it has been proved that TOPSIS, Taguchi approach and fuzzy logic analyses were accurate techniques to optimize the hot corrosion resistance and hardness of coated inconel718 under hot corrosion environments.

3- The optimal parameters combination was determined as A2B1C2 .

4- The predicted results were checked with experimental results and a good agreement was found with 90.32%

5- This work demonstrates the method of using Taguchi-based Fuzzy/TOPSIS methods for optimizing the hot corrosion parameters for multiple response characteristics.

Therefore the present investigation findings along with various mathematical models for fuzzy-TOPSIS-Taguchi will provide effective guideline to select parameter settings for achieving desired hot corrosion resistance and hardness of coated inconel718 under hot corrosion environments during application.

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