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Development of Microwave Hybrid Heating Welded Joints of Inconel-600 Superalloys using Grey Relational Analysis

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ABSTRACT:

Inconel-600 superalloys have a number of applications in space and aerospace sector due to its unique characteristics of high strength at elevated temperature, low weight, corrosion resistance and high wear resistance. However, due to these characteristics, Inconel-600 superalloy poses challenges in joining. Therefore, an attempt has been made to resolve these issues using microwave hybrid heating (MHH). The characteristics of the constituents of MHH process have large impact on the welded joint's strength. This paper examines the impact of control parameters on the ultimate tensile strength (UTS) and percentage elongation (EL) of Inconel-600 plates, which are welded via MHH. Design of experiments was carried out in accordance with Taguchi L_{16} orthogonal array (OA), taking in consideration of filler powder particle size (FPS), susceptor and separator. Multi-performance features were optimized via the effective utilization of Taguchi-based grey relational analysis (GRA) approach. ANOVA results show that the predominating factor to govern the joint strength is FPS followed by the susceptor and separator. The validation experiments are performed on the predicted optimized setting of process parameters. First level of FPS (30μm), second level of susceptor (Graphite) and second level of separator (SiC) were found as the optimized parametric settings.

KEYWORDS:

Welded joints; Grey relational analysis; Inconel-600; Microwave hybrid heating; Taguchi method; Tensile strength

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1. Introduction

Due to superior characteristics like excellent wear and corrosion resistance, mechanical properties and excellent oxidation resistance of Ni-based superalloys, such as Inconel-600, they have secured a position in space and aerospace industries, automobile, turbine and motor racing cars [1, 2]. Inconel-600 (Nickel-based superalloy) is a solid solution energized, when silicon and manganese are added into its nickel-chromium matrix. It is most commonly utilized in nuclear engineering, chemical power plants and marine industries. Diverse fusion welding methods such as EBW, GTAW and laser beam welding are used to weld nickel-based super alloys successfully [3, 4]. Almost all of these methods are developed in relation to academic research and technological advancement. On the other hand, mechanical characteristics get diminish because of the heat in this traditional procedure, which leads to substantial change in fusion zone microstructure and base metal [3, 5]. The cost is a matter for consideration in relation to maintenance and operating in traditional welding procedures. Hence, to overcome such limitation it is obligatory to develop some novel methods.

Excellent mechanical characteristics with ameliorated morphology can be obtained by microwave processing of advanced materials. This procedure is also very clean, economical, fast and at the same time consumption of power is very less as compare to other existing methods [6]. Walkiewicz et al [7] showed that metals can be heated proficiently in microwave oven, if used in fine powdered form. It is difficult to process the metals via microwave energy as it gets reflected, when incident on metals. As a result, spark is generated, which could destroy the microwave oven, if ignored. On the other hand, metals in bulk can be heated using Microwave Hybrid Heating (MHH) principle in an effective manner, where temperature is enhanced by incorporating susceptor, which is a microwave-absorbing substance. Metal-based materials are currently processed via microwave source in an effective manner by various investigators for joining and cladding applications. The processing of bulk materials was started back in the 2009 to join metals via microwave oven at home using hybrid heating methods [8]. The preliminary investigation was backbone for various researchers to investigate metallurgical and mechanical analysis of welded joints by utilizing MHH method [9-13].

Numerous optimization methods have been projected to set up the mathematical relationship amongst the performance characteristics and input control factors to generate the joint of preferred quality. Taguchi-based Grey Relational Analysis (GRA) is one of the standard methods utilized by many investigators to optimize multiple responses in a procedure. Many investigators used this method to a certain extent in a skillful manner to regulate partial data, uncertainty and other factors. Laksminarayanan and Balasubramanian [14] described the friction welding of aluminum alloy and corresponding optimization using Taguchi method. Ultimate Tensile Strength (UTS) of the welded joints was decided by the tool rotational speed. Lin [15] used GRA, Taguchi and neural network methods to optimize the input parameters for welded joints of Inconel-718 (GTA welding). Patel and Chaudhary [16] used GRA to study the impact of procedure parameters on the hardness of weld bead during MIG and TIG welding of AISI 1020 steel. Ilo et al [17] used Taguchi GRA to optimize multiple quality characteristics onto the hard face of mild steel.

Ramesh and Suresha [18] utilized GRA to optimize the tribological parameters of carbon woven fabric protected epoxy hybrid composites with MoS_2 and Al_2O_3 fillers in powdered form. To evaluate the optimum process control factors for many responses such as coefficient of friction, wear rate and hardness, Taguchi-based GRA was used. Prasad et al [19] used pulsed current plasma arc welding to optimize the control factors of Inconel-625 having weld bead geometry. Padmanabhan et al [20] used GRA in TIG weld of AZ31B alloy to optimize the procedure control factors so as to achieve the tensile strength of joint up to maximum. Prasad et al [21] described the impact of input parameters on hardness, fusion zone grain size and UTS of Inconel-625 joints, which was generated by utilizing pulsed current plasma arc welding. The main purpose was to maximize the UTS and hardness, along with minimum grain size. Sharma et al [22] optimized the TIG welding parameters for the 202 Stainless Steel using NSGA-II. Shanmugarajan et al [23] used Taguchi GRA method to optimize the laser welded P92 steel so as to obtain the optimum set of control factors, which consist of focus plane position, welding speed and welding power. Welding speed was the main parameter trailed by laser power and focal length.

Dwivedi and Sharma [24] considered the impact of process control factors on MS MHH welded joint's tensile strength, which was obtained. The control factors - temperature, input power and exposure time were considered in the process. Hebbale and Srinath [25] established cobalt-based clad on AISI-420 steel via MHH to optimize the procedure control factors, which have a huge impact on erosive wear using Taguchi method. This proved the efficiency of GRA method to optimize the control factors of MHH welding. However, the optimization of predominant procedure control factors to weld the bulk metals MHH has not been stated yet. In this work, Taguchi-based GRA technique has been used for the optimization of procedure control factors - Filler Powder particle Size (FPS), susceptor material and separator material and find out which has great impact on the mechanical properties of Inconel-600 welded joints formed by utilizing MHH. UTS and percentage elongation (EL) of welded joints are chosen as output responses. The validation experiments are also conducted for confirmation of predicted results.

2. Experimentation

The welded joints were produced using a power level of 900 W, 2.45 GHz of a domestic microwave oven in an atmospheric condition without any assistance of clamping devices and shielding gas. Inconel-600 plates, having thickness of 6mm were welded via MHH by utilizing nickel-based powder as filler. After that EWAC powder was filtered so as to get four grades having average particle sizes of 30, 40, 50 and 60μm. Chemical composition of material is depicted in Fig. 1 using EDX analysis. Inconel-600 has chromium within, which enhance the foundation of oxide layer on the welded joint at elevated temperature. The presence of such oxide layer affects the wetting of interfacing surfaces, which is to be joined.

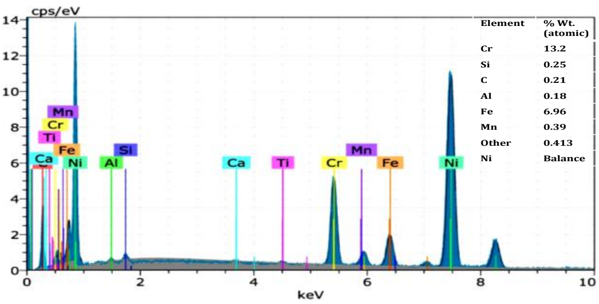

Fig. 1: EDX analysis of Inconel-600

The metal plates are placed in an alumina gasket to be welded by MHH. The alumina gasket is used to minimize the heat loss. The metal surfaces are cleaned and dried before welding. Masking was used to avoid direct contact of radiation with the metal plates. Susceptors are the materials that get heated when microwaves strike on it, as it can absorb the microwave. The heat produced will be transferred to the material which was targeted through traditional modes. Coal and SiC were chosen as susceptors. Nickel-based interface powder is blended with epoxy resin to make interface filler paste. This interface filler paste is used to fill the gaps between the two metal plates. A thin sheet used in between interface filler and susceptor, which is made up of refractory material is known as separator. Glasswool (GW) and graphite (Gr) were used as separators. This separator plate is placed over these to be welded parts and overall arrangement is covered by alumina gasket. When the temperature in the gap has reached the critical temperature, the microwave energy starts to be absorbed by the filler powder. This heating is completed by convectional and microwave heating. Therefore, it is a type of hybrid heating process.

Tensile tests are performed on the microwave welded Inconel-600 superalloy. All the tests have been performed on universal testing machine (Hitech make). Tensile test has been performed at strain rate of 0.008 mm/s. The specimens are developed as per ASTM E8 standard. For each experimental setting, two tests are performed for maintaining the statistical accuracy during the analysis. After performing the tensile tests, the morphology of specimen is investigated by scanning electron microscopy (SEM). The SEM micrographs are captured by Zeol make scanning electron microscope at 20 kV. Those results of fabrication, mechanical testing and SEM analysis are published elsewhere and not form as the scope of this paper.

3. Methodology

Fig. 2 represents the process flow of methodology adopted in this work. All the experiments are planned as per Taguchi GRA method [26, 27]. The trials were carried out as per Taguchi L16 Orthogonal Array (OA), by taking three factors into consideration such as interface filler powder size "FPS" (4 levels) and susceptor "Sus" (2 levels) and separator "Sep" (2 levels) in accordance with Table 1. The responses selected for present work are EL and UTS of the MHH welded joints. Table 2 gives the experimental design array and corresponding test results. The quality attributes of Taguchi method are lower the better and higher the better type. During the analysis in Taguchi method, the signal to noise (S/N) ratio plays a pivotal role. Larger value of S/N ratio is preferred. Once the experiments were conducted as per Taguchi OA, the analysis is made for single response optimization.

Table 1: Process parameters and their levels

Process parameter	Level 1	Level 2	Level 3	Level 4
FPS (μm)	30	40	50	60
Sus	GW (1)	Gr (2)	-	-
Sep	Coal (1)	SiC (2)	-	-

To optimize the multiple quality performances in a single time, GRA is used. This is a mathematical approach by which response mean values (or S/N ratios) are analyzed and processed in a systematic manner as defined by Deng et al [28, 29]. The process parameters are analyzed by a grey grade system. Data normalization or pre-processing is a process by which the responses are normalized according to the nature of their characteristics such that the normalised response is in between 0 and 1. The following relations are used for higher the better and smaller the better type quality characteristics [8, 30, 31] respectively,

$$U_i^*(k) = \frac{U_i(k) - \min\ U_i(k)}{\max\ U_i(k) - \min\ U_i(k)} \quad (1)$$

$$U_i^*(k) = \frac{\max\ U_i(k) - U_i(k)}{\max U_i(k) - \min\ U_i(k)} \quad (2)$$

Where, $U^*_i(k)$ = Normalized value of response characteristic. $U_i(k)$ = Mean value of response characteristic corresponding to experimental run. k = 1, 2 for first and second response characteristic respectively. i = 1, 2, 3…, n for trial run 1 to n.

Table 2: Experimental L16 array and corresponding results

S. No	FPS	Sus	Sep	UTS	%EL
1	30	1	1	648	34
2	30	1	2	667	27
3	30	2	1	653	33
4	30	2	2	679	31
5	40	1	1	642	40
6	40	1	2	661	36
7	40	2	1	650	37
8	40	2	2	668	33
9	50	1	1	629	47
10	50	1	2	643	43
11	50	2	1	633	44
12	50	2	2	656	39
13	60	1	1	616	52
14	60	1	2	632	47
15	60	2	1	625	48
16	60	2	2	637	44

In the process of implementation of GRA, after the normalization of data next steps are deducing the deviational sequence, calculation of grey coefficient and grey grade. The value of deviational sequence, $\text{б}_{0i}(k)$, is obtained after comparing it with reference value (i.e. 1),

$$\text{б}_{0i}(k) = \left| U_0^*(k) - U_i^*(k) \right| \quad (3)$$

Where, $\text{б}_{0i}(k)$ = Difference between the reference value, $U_0^*(k)$ and experimental value, $U_i^*(k)$. The grey coefficients (ɧ) are evaluated for each response variable corresponding to each experimental setting using,

$$\text{ɧ}_i^*(K) = \frac{\text{б}_{min} + Ø.\text{б}_{max}}{\text{б}_{0i}(k) - Ø\,.\text{б}_{max}(k)} \quad (4)$$

For giving equal importance to all responses, the value of deviational sequence identification coefficient, Ø, is set to 0.5. The value of grey grade (ɳ) is calculated using [29] the following,

$$\text{ɳ}_i = \frac{1}{n}\sum_{k=1}^{n} \text{ɧ}_i(k) \quad (5)$$

Where, ɳ_i is the grey grade for the i[th] experiment and n is the number of response characteristics.

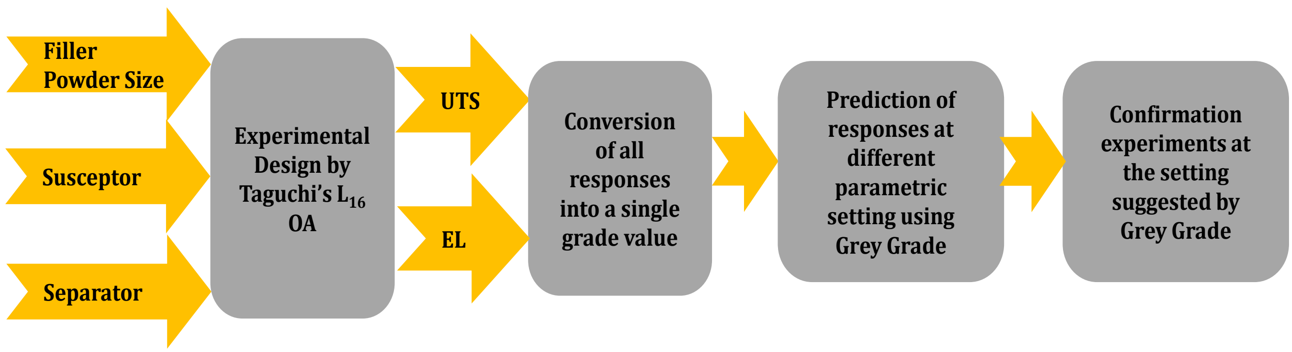

Fig. 2: Process flow of methodology

4. Results and discussion

4.1. Effect of input parameters on UTS and EL

The analysis of variance (ANOVA) of UTS and EL is given in Table 3(a) and Table 3(b) respectively. It is clear from the statistical analysis that FPS, Sus and Sep parameters play an influential role on UTS. The FPS has the major contribution of 62.89% followed by separator (29.96%) and susceptor (5.5%). The ANOVA of EL shows that FPS has the major contribution of 84.21% followed by separator (10.13%) and susceptor (5.17%). For both the UTS and EL responses, the P-value of all process parameters is less than 0.05. The P-value of all interaction terms are greater than 0.05. Therefore, interaction terms do not play significant role for the investigation of UTS and EL. The coefficient of determination (R^2) and adjusted R^2 for UTS and EL are within acceptable thresholds.

The % contribution of each parameter is arrived by dividing the sum of squares (SS) of parameter to the total SS value. The value of Mean of Squares (MS) for a process parameter is assessed by dividing the SS value by its degree of freedom (DF) value. Table 4 shows the response table for mean values of UTS and EL. UTS is assessed using larger the better type quality attribute. EL is assessed using lower the better type quality attribute. Therefore, FPS at level 1, susceptor at level 2 (Gr) and separator at level 2 (SiC) suggests as the best combination for UTS and EL responses.

Table 3(a): ANOVA for UTS

Source	DF	SS	p	MS	F	P
FPS	3	2835.19	62.89	945.06	97.14	0.002
Sus	1	248.06	5.5	248.06	25.50	0.015
Sep	1	1350.56	29.96	1350.56	138.82	0.001
FPS*Sus	3	1.69	0.04	0.56	0.06	0.979
FPS*Sep	3	36.19	0.8	12.06	1.24	0.432
Sus*Sep	1	7.56	0.17	7.56	0.78	0.443
Res. Error	3	29.19	0.64	9.73		
Total	15	4508.44	R^2: 99.35%; Adj R^2: 96.76%			

Table 3(b): ANOVA for EL

Source	DF	SS	p	MS	F	P
FPS	3	636.188	84.21	212.063	122.64	0.001
Sus	1	18.062	5.17	18.062	10.45	0.048
Sep	1	76.562	10.13	76.563	44.28	0.007
FPS*Sus	3	17.687	0.09	0.229	3.41	0.170
FPS*Sep	3	0.187	0.02	0.062	0.04	0.989
Sus*Sep	1	1.562	0.08	0.563	0.90	0.412
Res. Error	3	5.187	0.3	1.729		
Total	15	755.438	R^2: 99.31%; Adj R^2: 96.57%			

Table 4: Response table for UTS and EL

Level	UTS			EL		
	FPS	Sus	Sep	FPS	Sus	Sep
1	661.8	642.3	637.0	31.25	40.75	41.88
2	655.3	650.1	655.4	36.50	38.63	37.50
3	640.3	-	-	43.25	-	-
4	627.5	-	-	47.75	-	-
Delta	34.3	7.9	18.4	16.50	2.13	4.38
Rank	1	3	2	1	3	2

Fig. 3 depicts the variation of UTS with respect to input parameters. It is evident that with the increase of FPS, the UTS of the specimen decreases. When the FPS varies from 30µm to 60 µm, the UTS is decreased from 661.8 MPa to 627.5 MPa. The main reason for this reduction is the inter-binding strength due to fine particles. Another factor for favouring the 30 µm size is the heating rate. The heating rate is dependent on the conductivity of material used in the joint which in turn lies on the skin depth characteristic of powder. Smaller the skin depth, larger will be the conductivity of material. It is also evident from Fig. 3 that graphite susceptor and SiC as separator in the MHH gives the maximum UTS value. This is due to graphite by nature being a carbonaceous material; it exhibits a high value of dielectric loss factor. Therefore, graphite susceptor absorbs large amount of microwave energy and provides a good strength to the joint. The UTS of the sample is high in case of SiC separator as compared to coal, due to better heating characteristics. The warm-up time in case of SiC is low, hence a high heating rate is achieved in shorter duration. However, when coal is used as a separator, it burns very early and converted into ash, which may cause insufficient heating and decreases the UTS of the welded joint.

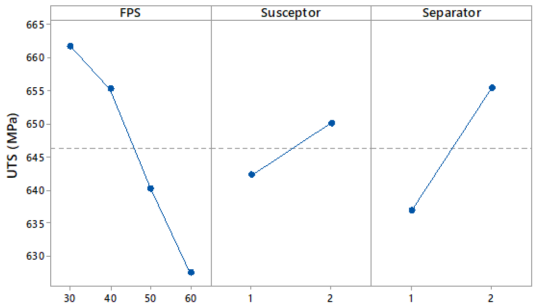

Fig. 3: Variation of UTS with respect to input parameters

Fig. 4 depicts the effect of process parameters on EL. It is observed that low level of FPS, Gr as susceptor and SiC as separator suggests lowest EL. The smaller particle size i.e. fine particles in the weld produces a sound quality joint due to which the EL is small. From Fig. 4, it is also clear that the performance of Gr susceptor and SiC separator is better as compared to GW susceptor and coal separator. When compared GW, Gr susceptor has high dielectric loss factor, which increases the heat absorption capacity of material and reduces the EL. Due to better heating qualities of SiC, using it as a separator in the welded joint gives minimum EL due to maximum strength.

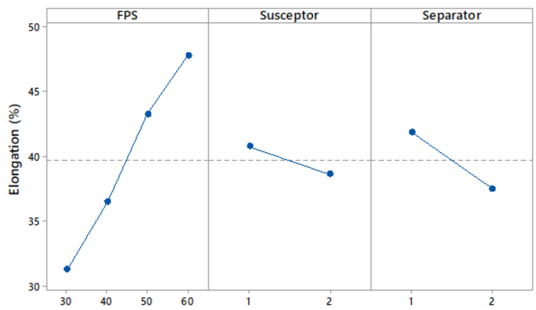

Fig. 4: Variation of EL with respect to input parameter

4.2. Optimization using GRA

Multiple performances can be collectively optimized using GRA after converting number of responses into single response. As per the first step of grey procedure, data preprocessing or normalization is performed, in which all the quality characteristics (i.e. UTS and EL) are converted in to 0 and 1 using Eqns. (1) and (2). UTS and EL respectively are assessed using "higher the better" and "lower the better" quality types. Once the data is normalized, the next step is adopted for obtaining the deviational sequence as per Eqn. (3), in which obtained normalized value is subtracted from reference value (i.e. 1). The grey coefficients are evaluated according to Eqn. (4), where each response is given equal contribution by using identification coefficient value as 0.5. The grey grade is evaluated using Eqn. (5) by averaging the grey coefficients of UTS and EL. Table 5 represents the normalized value, deviational sequence, grey coefficient and grade evaluated from the mean values of results.

Table 5: Normalization, Deviational Sequence, Grey coefficient and Grade

S. No	Normalization		Deviational sequence		Grey coefficient		Grade	Ranking
	UTS	EL	UTS	EL	UTS	EL		
1	0.5079	0.7200	0.4921	0.2800	0.5040	0.6410	0.5725	6
2	0.8095	1.0000	0.1905	0.0000	0.7241	1.0000	**0.8621**	2
3	0.5873	0.7600	0.4127	0.2400	0.5478	0.6757	0.6118	4
4	1.0000	0.8400	0.0000	0.1600	1.0000	0.7576	**0.8788**	**1**
5	0.4127	0.4800	0.5873	0.5200	0.4599	0.4902	0.4750	9
6	0.7143	0.6400	0.2857	0.3600	0.6364	0.5814	0.6089	5
7	0.5397	0.6000	0.4603	0.4000	0.5207	0.5556	0.5381	8
8	0.8254	0.7600	0.1746	0.2400	0.7412	0.6757	**0.7084**	**3**
9	0.2063	0.2000	0.7937	0.8000	0.3865	0.3846	0.3856	14
10	0.4286	0.3600	0.5714	0.6400	0.4667	0.4386	0.4526	10
11	0.2698	0.3200	0.7302	0.6800	0.4065	0.4237	0.4151	12
12	0.6349	0.5200	0.3651	0.4800	0.5780	0.5102	0.5441	7
13	0.0000	0.0000	1.0000	1.0000	0.3333	0.3333	0.3333	16
14	0.2540	0.2000	0.7460	0.8000	0.4013	0.3846	0.3929	13
15	0.1429	0.1600	0.8571	0.8400	0.3684	0.3731	0.3708	15
16	0.3333	0.3200	0.6667	0.6800	0.4286	0.4237	0.4262	11

Once the grey grades are obtained, these values are assumed as responses and solved by Taguchi's method by considering the "larger the better" type quality attribute. This is due to the fact that larger value of grade is always preferred and suggests the best optimal setting of input parameters. The ANOVA of grade values are analyzed and given in Table 6. It is evident from the analysis that maximum contribution for the evaluation of grade i.e. simultaneous optimization of UTS and EL is FPS (69.33%) followed by separator (20.69%), interaction terms of FPS and separator (6.66%) and susceptor (2.54%). These are due to P-value less than 0.05. However, for other interaction terms the P-value is greater than 0.05 and has non-significant effect on the evaluation of grade. It is clear from Table 7 (response table for grey grade mean value) and Fig. 5 (S/N) that first level (30µm) of FPS, second level of susceptor (Gr) and second level of separator (SiC) gives the optimum of grey grade. The largest value of grey grade corresponds to the optimum setting of process parameters at which the maximum UTS and minimum EL are obtained.

Table 6: ANOVA for grey grade

Source	DF	SS	p (%)	MS	F	P
FPS	3	0.287611	69.33	0.095870	261.04	0.000
Sus	1	0.010518	2.54	0.010518	28.64	0.013
Sep	1	0.085823	20.69	0.085823	233.69	0.001
FPS*Sus	3	0.001785	0.43	0.000595	1.62	0.351
FPS*Sep	3	0.027673	6.66	0.009224	25.12	0.013
Sus*Sep	1	0.000321	0.08	0.000321	0.87	0.419
Res. Error	3	0.001102	0.27	0.000367		
Total	15	0.414832				

Table 7: Response table for grade

Level	FPS	Sus	Sep
1	0.7313	0.5104	0.4628
2	0.5826	0.5616	0.6092
3	0.4493		
4	0.3808		
Delta	0.3505	0.0513	0.1465
Rank	1	3	2

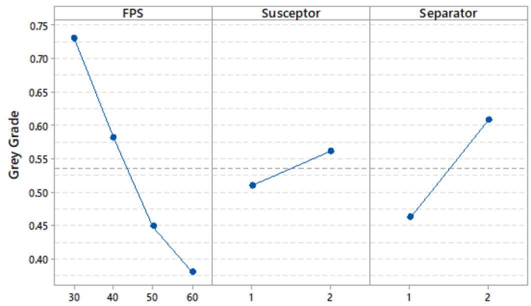

Fig. 5: Variation of Grade value with respect to process parameter

4.3. Validation test

After obtaining the optimized setting of input parameters by grey analysis, the next step is to validate the setting and investigate the values of responses i.e. UTS and EL. After that the optimized value of process parameters is compared with other parametric settings which exhibit grade value nearby maximum grade value. It is evident from Table 5 that the experimental run number 2 represents grade value (0.8621) which is nearby the maximum grade value (run number 4). After that trial run number 8 shows grade value (0.7084). Thus, these two settings of run number 2 and 8 are compared with the optimized grade value (0.8889). After performing validation experiments, an improvement of 0.0101 in grey grade value is observed, see Table 8. Validation experiments are performed at this setting for three times and the mean of this is depicted in Table 8. It was found that there is a close agreement between the predicted value and experimental results.

Table 8: Validation experiments for optimized setting

S. No.	UTS	%EL	Grade
$(FPS)_{30}(Sus)_{Gr}(Sep)_{SiC}$	679	31	0.8788
$(FPS)_{30}(Sus)_{GW}(Sep)_{SiC}$	667	27	0.8621
$(FPS)_{40}(Sus)_{Gr}(Sep)_{SiC}$	679	31	0.7084
$(FPS)_{30}(Sus)_{Gr}(Sep)_{SiC}$	682	32	0.8889

5. Conclusions

In present work, the effect of process parameters on UTS and EL are evaluated using Taguchi method for the welded joints developed on Inconel-600 superalloy by MHH using nickel powder as interface filler. The multiple performance characteristics optimization was performed using GRA. After implementation of Taguchi method, it was found that nickel powder as filler interface has the maximum influence (62.89%) followed by separator (29.96%) and susceptor (5.5%) on the UTS. The optimized setting for UTS is 30μm FPS, Graphite susceptor and SiC separator. It was found after ANOVA that FPS (84.21%) has maximum influence on EL followed by separator (10.13%) and susceptor (5.17%). From the analysis, it is clear that the minimum EL is obtained for 30μm FPS, Glass wool susceptor and SiC separator. It has been observed from the GRA that grade is influenced by FPS (69.33%) followed by separator (20.69%), interaction terms of FPS and separator (6.66%) and susceptor (2.54%). Grey grade suggests that 30μm FPS, Graphite susceptor and SiC separator process parameters gives an overall optimized value of UTS and EL. The experimental values are in close agreement with the values predicted from the GRA.

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