Original Article

Analytic framework on parameter ranking for hybrid TIG MAG arc welding of mild steel

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GRAPHICAL ABSTRACT

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ABSTRACT

Hybrid approach advocates combining two or more traditional technologies to overcome the limitations of the conventional practice. The devised Hybrid TIG MAG arc welding process with the help of an indigenous fixture overcomes the shortcomings of the conventional arc welding. The success of any hybrid technology depends on synergistic parameter interactions which demand a rigorous process control through parameter optimization. The devised process is controlled by 13 major parameters. Optimization of all the process controlling parameters is a resource consuming activity. This study manifests an analytic framework as a combination of hierarchical and networking decision making algorithms, which seeks input on parameter effects and their ranges arrived at through experimentation and gives a ranked or prioritized list of process controlling parameters as an output. The framework identifies 5 critical parameters responsible for the 62% of the parameter interactions which need to be optimized based on the application or the job at hand. The remaining 8 parameters responsible for the balance 38% of the parameter interactions have been stabilized through experimentation once for all process variations irrespective of the application or the job at hand. The study works on the merger of the process optimization and the process prioritization techniques.

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Introduction

Any conventional practice has its own advantages and limitations. Hybridization aims at clubbing two such practices into one in an attempt to overcome limitations at their individual levels.
reaping the joint benefits. Conventional arc welding practice deploys two process families based on the electrode consumption or the lack of it. The arc struck would either be with a consumable electrode or with a non-consumable electrode. The limitations of the conventional arc welding processes could be; arc instability, wider heat affected zones, defect prone metal transfer and the lack of preheating of the joint. The hybridization of the conventional processes by combining the two in a synergistic manner could well prove to be an answer to overcome the above limitations. For the metal joining of mild steel plates of up to 3 mm of thickness, Zhang et al. [1] and Wei et al. [2] have discussed process variants on the hybridization of the conventional metal joining practice. The literature pertains to the introduction of an additional non-consumable electrode to the consumable process. The elaboration also suggests a feasible introduction of two non-consumable electrodes to the conventional consumable electrode setup. The discussed variants deploy a single power source wherein the total heat input to the base metal has been reduced by the introduction of an additional non-consumable electrode to partially bypass the consumable electrode arc current. The newly introduced electrode with the bypass arc also aids in the detachment of the retained metal globule at the tip of the molten consumable electrode to enhance the metal transfer. Shi et al. [3] have discussed the pulsing of the above variants for the joining of the thin plates of the dissimilar metals using an intermetallic compound layer. This further reduces the heat input to the base material. Miao et al. [4] and Zhang et al. [5] have discussed another process variant which subject to access introduces the arcs from both sides of the weldment to increase the depth of weld penetration. Both the electrodes are powered through a current bypass from the single power source. For the metal joining of thicker plates wherein the rate of metal deposition carries significant weightage; Meng et al. [6], Kanemaru et al. [7], and Schneider et al. [8] have come up with the other hybrid variant with two separate power sources for the two separate arc welding torches of leading GTAW i.e. Gas Tungsten Arc Welding or TIG i.e. Tungsten Inert Gas Welding and the tailing GMAW i.e. Gas Metal Arc Welding or the MAG i.e. Metal Active Gas Welding. The requirement of the bypass current has been eliminated and the setup requires least tweaking to the existing conventional setup of arc welding. The available literature though suggests the need for the further process investigation with reference to the heat source positioning for the conceived hybridization. Sahasrabudhe and Ador Welding Ltd. [9] have come with schematics for the hybridization of the TIG and MAG arc welding processes as shown in Fig. 1a. As shown in the schematics, two separate power sources are deployed each for the leading TIG and the tailing MAG in tandem. Sahasrabudhe et al. [10] have studied the devised process for their parameter interactions vis-à-vis the process outcome in terms of the depth of the weld penetration, the transverse strength of the welded joint and the bead profile for the mild steel plates of 12 mm thickness. Hybridization as the name suggests is an attempt towards the common goal/s. This study hence deploys AHP and ANP in combination to arrive at the weightages of the factors and the alternatives respectively considering their interactions to reach the ANP super matrix which is then is raised to its higher powers by matrix multiplication to achieve a stabilized limit matrix with the intended prioritization. The matrices thus arrived during need to be validated for the consistency of the comparative scale. The standard used for the benchmarking is the Saaty’s eigenvector method and the associated random index tables based on his research of 1977 and the subsequent amendment to it in 2001. In this modelling, the values from the modified tables are used as per the order of the matrizied data. For the 3 × 3 matrix the random index used is 0.58 and for the matrix 13 × 13 the random index value of 1.56 is deployed while finding the consistency ratios for the pairwise comparison matrices. The matrices with consistency ratio values of <0.1 have been accepted for the subsequent computations.

Methodology

The reference for this study is the inference drawn from the graphical representation of the parameter effects investigated through experimentation to form the pairwise comparison matrices of the factors and the alternatives to arrive at the weightages i.e. rankings of the process controlling parameters by using MCDM algorithms. The study uses the available data from Sahasrabudhe et al. [9,10] on the parameter effects and ranges for hybrid TIG-MAG arc welding.

Process description and challenges

The major challenge has been the understanding of the parameter interactions. The success of the hybridization lies in harnessing the synergy in process controlling parameters. The arcs proceed in tandem i.e. in a non-coaxial manner but need to interact in synergy into a common weld puddle. This could be achieved through the optimum heat source positioning. The mechanical aids have been developed as depicted in Fig. 1b which reflects an indigenous welding fixture with two separate machine mounted
straight shank welding torch assemblies. The hybrid arc welding fixture as depicted in Supplementary Material Fig. 1a and 1b not only clamps the heat sources but also aids in linear and angular adjustments to the torch during the experimentation. The welding fixture comprises of assembly of slides. The main slide is mounted on the drive mechanism which aids in the lateral movement of the entire assembly in the direction of the welding with the help of a tractor trolley as shown in Supplementary Material Fig. 1a. Two compound slides fitted onto the main slide aid the vertical movement of the assembly in the direction perpendicular to the direction of the welding. The two compound slides also carry the linear and angular scales on either side with a reading pointer. The compound slides in the front accommodate a gripper each for the torch holding. Two separate power sources and the fixture are automatically controlled with a remote arc initiation through a relay embedded in the control panel of the drive mechanism for the welding traverse. The control panel houses 42 V–50 Hz contactor to trigger the remote arc initiation.

Selection of process parameters and process responses

The conceived hybridization has identified 13 of the process controlling parameters as the key to the success of the process. The process outcome has been ratified with reference to the 3 process responses i.e. factors. The first of the identified factors has been the achieved weld bead profile as depicted in Supplementary Material Fig. 2a and 2b. Bead Profile (BP) is adjudged by the visual inspection on a 5 point qualitative scale. The 5 implies the best bead and the 1 implies the relatively inferior bead. The 5 point rating of the bead profile considers the bead profile without any visual defects as the best profile. The profiles with spatter and or the bead profiles with humping tendency i.e. a wayward or a camel back shape of the laid weld have been considered undesirable and hence have been rated lesser. The profile of the laid bead on plate also considers the heat affected zone distribution on the back of the plate as depicted in Supplementary Material Fig. 2b. The requisite bead profile also depicts the ripple marks of the weld metal.
solidification which happens to be another indication of a sound bead being considered for the rating of it. The achieved depth of weld penetration, WP, determined by ASTM E3: 2011/ASTM E-407-07e1/ASM H/B VOL9 procedures in mm as depicted in Supplementary Material Fig. 3a and the transverse tensile strength, TTS measured by ASTM E8 procedures in MPa (N/mm²) as depicted in Supplementary Material Fig. 3b are the other two process responses under consideration.

The 13 process parameters i.e. alternatives identified through experimentation are namely; ‘TS’ (torch separation) i.e. the distance between the torch sleeves which separates the two heat sources in mm in the horizontal direction to achieve the electromagnetic isolation; ‘AS’, the arc separation i.e. the distance in mm in the horizontal direction between the two electrode tips of the interacting arcs to achieve the electromagnetic synergy; ‘Lt’, the arc length for TIG electrode i.e. the electrode tip to workpiece distance in mm in the vertical direction; ‘It’, the arc current for

![Bead Profile vs. S TAm TAt Fm Vm It](image)

**Fig. 2.** Bead profile vs energy balance and arc positioning parameters [9,10].

![Bead Profile vs. Fm Gt Gm S TS AS It Vm](image)

**Fig. 3.** (a) Investigation on bead profile for arc energy, arc shielding and arc separation (b) Investigation on weld penetration vs arc shielding parameters [9,10].
TIG in Ampere; ‘Vm’, arc voltage MAG in Volt; ‘Gt’, the shielding gas flow rate for TIG in l/min; ‘Gm’, the shielding gas flow rate for MAG in l/min; ‘E0m’, Electrode stick out MAG in mm i.e. length of electrode protruding out of the consumable sleeve which is exposed to the leading TIG arc; ‘E0t’, Electrode stick out TIG i.e. the length of electrode in mm which is protruding out of the consumable sleeve at the torch end which is directed towards the tailing MAG wire in tandem; ‘TAm’, the torch angle of MAG to the vertical to the direction of welding in degree; ‘TAt’, the torch angle TIG to the normal to the direction of welding in degree; ‘Fm’, the rate of MAG wire feed in m/min of the self-adjusting arc which in turn governs the arc current for MAG and ‘S’, the welding traverse i.e. speed of the welding in m/min effected by the tractor trolley to welding fixture. The Parameters and Responses are weighed for their relative importance within themselves and with each other using the decision making algorithms of AHP and ANP in combination. The relative importance by pairwise comparison has been arrived at on a 5 point scale. The 5 implies the pair under consideration shares a significant relative importance on the process outcome. The 1 implies the pair under consideration together has no significant role towards the process outcome. If the dominating one of the compared pair gets a weightage of 3, the relatively insignificant of the two under consideration gets the reciprocal of 3 as its weightage for the comparison.

Results

This section reflects the outcome of the experimentation and the inferences drawn to arrive at the parameter ranges. The section also elaborates outcome of the analytic framework for the parameter ranking. The section is the output of the above mentioned methodology with reference to the reviewed literature.

Parameter interactions and parameter ranges

The process parameters have been divided into few common segments as ‘arc positioning parameters’ which include arc length, electrode stick-outs, torch angles, arc separation and torch separation; ‘arc shielding parameters’ which include gas flow rates and ‘arc energy parameters’ which include arc currents, arc voltage and the speed of the welding. The segmentation has been done for the simplicity of judging their correlation with reference to their collective impact on the hybrid arc welding process outcome. The arc positioning parameters are supposed to provide the mechanical assistance in maintaining the synergy in arc interaction. The arcs in the conceived hybrid arc welding are supposed to act in tandem i.e. in a non-coaxial manner. The optimum arc positioning with the help of the indigenous welding fixture makes the arc unite in a common weld pool owing to the anticipated electromagnetic drag which overcomes the requirement of developing a co-axial head to contain the participating arcs. The arc energy parameters, as the name suggests are responsible to maintain the balance in the arc energies for the desired electromagnetic synergy for the hybridization to sustain. The arc shielding parameters maintain the protective mixed gas atmosphere around the interacting arcs of one active i.e. of CO₂ for MAG and the other inert i.e. of Argon for TIG. The common path of the arc plasma between the interacting arcs is the result of the synergistic interaction of the
arc shielding parameters in unison with the arc energy parameters. The inert gas shield of Argon aids the ionization to maintain an effective arc pressure and the active gas shield of CO₂ provides the high thermal conductivity for the effective weld penetration. The major of the process controlling parameters have been depicted in Supplementary Material Fig. 4. Sahasrabudhe et al. [9,10] have studied arc positioning parameters through a set of experiments alongside the arc energy parameters for their collective impact on the process outcome in terms of the bead profile and the depth of weld penetration. As shown in Fig. 2 Bead Profile has been mapped against the arc energy and arc positioning parameters. The graphical representation suggests bead profile for a medium welding traverse of 0.6 m/min with arc voltage at 22 V and the arc currents in balance i.e. in the ratio 1:1 (TIG at 225A and MAG electrode wire feed rate at 12 m/min) seemed optimum for the MAG torch held almost normal in the direction of welding and the TIG torch being fed in at an angle from beneath the depositing electrode leading the direction of the welding. Interacting parameters stack up to reflect their common optimum for the bead profile achievement as depicted in the graphical representation of the data. The MAG power source is a constant voltage power source, the rate of filler wire feed hence controls the arc current. The arc voltage of MAG hence has no role to play in the achievement of the weld penetration but the profile of the weld i.e. the width of the bead being laid. The iteration in Supplementary Material Table 1 hence considers the highest 'D'epth/ 'W'idth ratio of the achieved penetration for the parameter interactions depicted in Fig. 2. The tabulated data further vindicates the results and optimizes the TIG torch angle to 30° for the common optimum considering the achievement in the weld penetration. Sahasrabudhe et al. [9,10] have also investigated on arc shielding parameters for their collective impact on the weld penetration and the bead profile. As shown in Fig. 3a the arc shielding parameters are investigated with the varying arc energy and arc separation for the collective impact on the bead profile. As depicted in Fig. 3a the common optimum for the arc energy parameters in line with the previous iteration reconfirms the effect of MAG arc voltage on the improvement in the bead profile which improves at higher arc voltage with the arc currents in a balance. For a TIG arc current in the range of 250A the increase in rate of MAG electrode feed towards 12 m/min balances the arc currents for the continuous improvement in the process outcome. The weld traverse is also expected to be in the higher order to match the increase in the arc energies for the balanced heat input to the base material for minimizing the heat affected zone. The torch separation virtually had no role whatsoever in the bead formation and is seen dominated by the arc separation. The arc separation seemed to aid the optimum outcome for wider distances at higher arc energies. Fig. 3a and b depict investigation on arc shielding parameters with the common optimum arrived at with reference to the bead profile and the depth of weld penetration respectively with the rest of the parameters in the ranges of the common optimum being arrived in the previous iterations. Fig. 3a and b represent the similar common optimum for gas flow rates of around 10–12 L/min for argon shielding of TIG and 8–10 L/min of CO₂ for MAG shielding. The Argon beyond the optimized range adds no value to the process outcome. The CO₂ beyond the arrived optimum seems to interfere with the ionization of plasma along the arc bridge. For the lower
arc energies as shown in Fig. 4a, for the TIG arc current being held at 200A which has been found just sufficient to aid the electromagnetic drag necessary for the hybridization, the equivalent arc current balance with the lower order MAG wire feed rates of 9 m/min demands the narrower arc separations of up to 9 mm at a relatively slower welding traverse of 0.45 m/min. In line with these iterations Fig. 4b depicts the range for the TIG arc length in unison with the other process controlling parameters. The graphical representation suggests 2 mm or arc gap happens to be the optimal for the desired arc pressure to maintain the electromagnetic drag on the trailing deposition. Beyond, the TIG has the tendency to strike an arc with the tailing electrode wire instead which is undesirable from the hybridization point of view. Fig. 5a depicts the investigation on the arc positioning parameters with reference to the depth of weld penetration. For the arc currents in balance, the MAG electrode stick-out of 15 mm seemed to provide the better process outcome for the TIG arc length of 2 mm and arc separation of 12 mm. This arc positioning proved universal in the subsequent experimentation. The graphical representation in Fig. 5b depicts the investigation on the arc current balance with reference to the depth of weld penetration. The representation of the data suggests so long as the increase in the TIG arc current is being held in a balance with the increase in the MAG electrode wire feed rate the depth of the weld penetration shows a continuous improvement. The arc current balance once lost reflects a decline in the process outcome. The TIG arc current has been varied from 200 to 3000A. For TIG arc current of up to 250A with the MAG wire feed rate of beyond 15 m/min the electromagnetic drag assistance of the leading TIG arc becomes weaker in comparison of the tailing MAG deposition and the process outcome deteriorates. For the further increase in TIG arc current of up to 300A, the process outcome improves when the arc currents balance at the MAG wire feed rate of 18 m/min which is irrespective of the arc voltage deployment. The MAG arc voltage plays a crucial role in deciding the bead profile but has no significance in the achievement of the depth of weld penetration. The transverse tensile strength of the joints has been investigated with reference to the arc energy parameters. Fig. 6a for simple square butt joint depicts the better process outcome so long as the arc currents are in a balance. Similarly in Fig. 6b for the investigation on arc energy for transverse tensile strength of the 60° V joint wherein the TIG arc current of 300A is held constant; the MAG wire feed rate of 18 m/min with the equivalent current balance seemed to provide the better process outcome.

Analytic framework

The study with the above modelling considerations on the parameter interactions has in the first phase of the framework followed the hierarchical algorithm to arrive at the priority vectors, PV for the 3 of the desired process responses vis-à-vis 13 identified process parameters. In the first phase of the analytic framework the hierarchical priority vectors for the process responses as shown in from Tables 1–3 derive the pairwise comparisons of the parameters based on the modelling considerations as depicted in the graphical representation of the data of the parameter

![Graph](image)

**Fig. 6.** Investigation on joint strength vs arc energy for (a) Simple square butt (b) 60° V [9,10].
interactions and their ranges. The study in the second phase of the framework follows the networking algorithm to arrive at the priority vectors for each of the 13 of the identified process parameters against the 3 of the desired process responses. The networked priority vectors as shown in Table 4 infer the pairwise comparison on the criticality of every identified parameter towards the process outcome against the experimental findings on the parameter interactions. This phase considers the interdependence of the factors and the alternatives since is critical for any hybrid technology which involves the highest order of the parameter interactions vis-à-vis the desired process outcome. The third phase of the framework merges the arrived priority vectors from the first two phases into a super matrix as shown in Table 5. This is a metricized data of combination of the algorithms which not only considers the hierarchical dependence but also the networked interdependence of the factors and the parameters. The super matrix is weighed into

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Super Matrix a Merger of Hierarchical (1st 3 columns) a PVs with Networked (1st 3 rows) b PVs.

Networked PV a, Priority Vectors for Parameter Interactions. b depicted in Table 6 is the prioritized list of parameters based on their criticality towards the desired process outcome. The output of the framework as a limiting matrix which is iterated to deliver the parameter prioritization by vector rankings. The output of the framework as depicted in Table 6 is the prioritized list of parameters based on their criticality towards the desired process outcome.

Discussion

Parameter effects

The torch separation has been dominated by the arc separation for their collective impact on the process outcome. The arc separation seems influencing the synergy in arc interaction and hence directly affects process outcome in all forms. The TIG arc length which governs the leading arc pressure is responsible in maintaining the electromagnetic drag necessary for the hybridization and directly affects the depth of weld penetration and hence the strength of the welded joint. The welding traverse governs the time for the heat dissipation, slower the traverse wider is the heat affected zone. The faster travels are preferred with the higher arc energies for the effective depth to width ratio of the weld penetration. The slower arc travels are preferred with the lower arc energies for the desired depth of weld penetration with a wider deposition area. The welding traverse at a given

Table 4
Networked PV a Priority Vectors for Parameter Interactions. b

| TS | TTS | WP | BP | PV a | AS b | TTS | WP | BP | PV a | Vm b | TTS | WP | BP | PV a |
|----|-----|----|----|------|------|-----|----|----|------|------|-----|----|----|------|
| TTS | 1.00 | 0.50 | 2.00 | 0.31 | TTS | 1.00 | 0.50 | 2.00 | 0.29 | TTS | 1.00 | 2.00 | 0.50 | 0.30 |
| WP | 2.00 | 1.00 | 2.00 | 0.49 | WP | 2.00 | 1.00 | 4.00 | 0.57 | WP | 0.50 | 1.00 | 0.33 | 0.16 |
| BP | 0.50 | 0.50 | 1.00 | 0.20 | BP | 0.50 | 0.25 | 1.00 | 0.14 | BP | 2.00 | 3.00 | 1.00 | 0.54 |
| E0T c | TTS | WP | BP | PV a | Gt f | TTS | WP | BP | PV a | TAt b | TTS | WP | BP | PV a |
| TTS | 1.00 | 0.50 | 3.00 | 0.32 | TTS | 1.00 | 0.50 | 2.00 | 0.30 | TTS | 1.00 | 2.00 | 0.50 | 0.31 |
| WP | 2.00 | 1.00 | 4.00 | 0.56 | WP | 2.00 | 1.00 | 3.00 | 0.54 | WP | 0.50 | 1.00 | 0.50 | 0.20 |
| BP | 0.33 | 0.25 | 1.00 | 0.12 | BP | 0.50 | 0.33 | 1.00 | 0.16 | BP | 2.00 | 2.00 | 1.00 | 0.49 |

Table 5
Super Matrix a Merger of Hierarchical (1st 3 columns) a PVs with Networked (1st 3 rows) b PVs.

| TS | TTS | WP | BP | TS | AS | Lt | It | Vm | Gt | Gm | EOm | EOT | TAM | Tat | Fm | S |
|----|-----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|----|----|
| TTS | 1 | 0 | 0 | 0.31 | 0.29 | 0.27 | 0.27 | 0.30 | 0.30 | 0.61 | 0.49 | 0.34 | 0.31 | 0.20 | 0.30 | 0.16 |
| WP | 0 | 1 | 0 | 0.49 | 0.57 | 0.61 | 0.61 | 0.16 | 0.54 | 0.27 | 0.31 | 0.54 | 0.20 | 0.49 | 0.54 | 0.59 |
| BP | 0 | 0 | 1 | 0.20 | 0.14 | 0.12 | 0.12 | 0.54 | 0.16 | 0.20 | 0.12 | 0.49 | 0.31 | 0.16 | 0.25 |
| TS | 0.14 | 0.16 | 0.13 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AS | 0.08 | 0.09 | 0.07 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| It | 0.12 | 0.15 | 0.11 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vm | 0.12 | 0.18 | 0.14 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gt | 0.03 | 0.03 | 0.03 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gm | 0.02 | 0.02 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EOm | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EOT | 0.05 | 0.05 | 0.06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| TAM | 0.04 | 0.03 | 0.04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Tat | 0.06 | 0.05 | 0.06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Fm | 0.11 | 0.11 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |

a 1st three columns reflect the priority vectors drawn from the hierarchical process.
b 1st three rows reflect the priority vectors drawn from the networked process.
deposition rate decides the amount of weld metal deposition which not only influences the profile of the weld but also the strength of the joint. The MAG electrode wire feed decides the current requirement for the depositing arc. The wire feed rate in balance with the leading TIG arc current aids hybridization and maintains the synergy in arc interaction with a sustained spray mode of metal transfer. This in effect governs the defect free laying of the weldment and directly influences the quality of the weldment. The MAG arc voltage on the other hand doesn’t influence the arc energy and has no impact on the depth of weld penetration but on the profile of the weld being laid which is in line with the literature by Schneider et al. [8]. Higher arc voltages are preferred hence for the single pass laying of the welded joints for the effective weld fusion at the joint walls along the length of the weld. The TIG arc length governs the arc pressure in achieving the desired depth of weld penetration and also governs the effective ionization of the arc plasma in achieving the electromagnetic drag responsible for the spray mode of metal transfer for the defect free metal joining. The TIG torch angle seemed to mechanically assist the generation of the electromagnetic drag on the MAG torch being held at normal in the direction of welding. Experimentally arrived torch angles assumed universal values holding good for all arc energy ranges. The arc inclinations except for their mechanical assistance to the electromagnetic drag have had no direct influence on the process outcome. So is the electrode stick-out of the MAG which controlled the length of depositing electrode being exposed to the leading TIG arc assisted the arc current balancing. The longer stick-out has been observed to lead to spatter which deteriorated the leading TIG arc assisted the arc current balancing. The TIG arc current seemed to help in achieving the depth of weld penetration which is also in agreement with the literature Schneider et al. [8].

**Model outcome**

The model outcome ranks the identified 13 of the process controlling parameters as depicted in Table 6. The ranking suggests the arc energy parameters happen to be more impactful over the other parameter segments. The arc separation is the only positioning parameter which makes it to the top of the rankings otherwise. This implies the top 5 parameters need to be optimized based on the application. The case could be the application specific as for the metal joining or surface processing. The case could also be job specific owing to the due consideration to the sectional thickness to be joined. The rest of the 8 parameters with their collective impact on the process have been found stabilized through experimental iterations. Their ranges once arrived at could hold good for the possible arc energy permutations and combinations with reference to the desired process outcome. The model outcome is quite in agreement with the literature of Schneider et al. [8] which also lists the similar top few critical parameters with reference to the achieved bead profile and the depth of weld penetration. This analytic framework a step further, accommodates more parameters, total 13, buckets them into three based on their purpose and then ranks them in the order of their critical importance towards the success of the conceived process hybridization. Sahasrabudhe et al. [9,10] have attempted to optimize the arc energy parameters vis-à-vis arc separation with the arrived presets for the rest of the parameters. The response surface methodology has been utilized to optimize only the critical parameters for the welding of mild steel plates of 12 mm thickness for the desired process outcome. The results seem in congruence with the ranking of the parameter criticalities towards the process outcome. The model outcome suggests 38% of the parameters carry 62% of the critical importance towards the desired process outcome and they need to be optimized with reference to the application or the job in hand. The remaining 62% of the parameters which are responsible for 38% of the interactions could be stabilized through experimental iterations without going in for the resource consuming optimization techniques once for all irrespective of the application or the job at hand.

**Conclusions**

The major challenge in the implementation of the any hybrid technology happens to be in maintaining the synergy in interactions of their respective process controlling parameters. While the hybrid technology is being applied to the industrial need, it needs extensive optimization of the participating parameters for their collective impact on the process outcome. This study has been a successful attempt in a parameter sort for the critical ones needing the application or job specific optimization and for the ones which could be stabilized through experimental iterations. The metal joining otherwise needs exhaustive set of experiments to be designed for the due consideration to the entire list of process controlling parameters. The metal joining by arc as well involves radiation hazards which don’t allow longer exposures. The devised analytic framework would aid in future exploration in the domain of the hybrid TIG MAG arc welding process. The usage of parameter interaction profiles in conjunction with the decision making models has been found effective. This framework merges the parameter optimization methodology with the parameter prioritization algorithms for the more effective process control. The proved Pareto of interacting parameters to its advantage could save time on the level of process optimization. The devised analytic framework
could be extended to the allied hybrid process studies featuring extensive parameter interactions.

**Conflict of interest**

The authors have declared no conflict of interest.

**Compliance with Ethics Requirements**

This article does not contain any studies with human or animal subjects.

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**Appendix A. Supplementary material**

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jare.2018.03.001.

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