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Analysis and optimization of mass percentage of zycoprint polymer and abrasives in achieving stability of suspension mixture in abrasive water jet machining

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Abstract. The suspension parameters are vital in the suspension-type abrasive water jet (AWJ) machining of several engineering materials, more so in difficult-to-cut materials, because it significantly influences the suspension stability and sedimentation behaviour of the suspension mixture and abrasive particle acceleration into the AWJs. The suspension stability and abrasive particle acceleration of the suspension-type AWJs are improved by using polymer additives. Hence, it is necessary to study the effect of suspension parameters (abrasive and polymer concentrations) on suspension stability. In this direction, the novel work reported in the paper analyses the stability of suspension by varying the mass percentage of abrasives (garnet and aluminum oxide (Al_2O_3)) (ω_a) and mass percentage of the zycoprint polymer (ω_p) in water by considering the Taguchi L_9 Orthogonal array (OA). The linear regression (LR) models for the percentage of suspension volume with garnet (V_s^G) and the percentage of suspension volume with Al_2O_3 (V_s^A), are developed. The JAYA algorithm is used to find the optimal combination of the suspension parameters, and its results are in close agreement with the findings from the LR results. The optimum setting of the suspension parameters for both, V_s^G and V_s^A, is 3% of ω_a and 0.80% of ω_p.

Keywords: Suspension / abrasives / water / jet / machining / garnets / aluminium / oxide / zycoprint / linear / regression / JAYA

1 Introduction

The challenges in machining several engineering materials, especially difficult-to-cut materials, demand rapid progress in machining technologies. The popularity of Abrasive water jet (AWJ) machining is rising due to its adaptable and flexible manufacturing capabilities [1,2]. In AWJ machining technology, suspension and injection jet methods are possible alternatives. While comparing the two, the first one can function with greater geometric accuracy and less angular error, causing smaller kerf taper ratios [3,4]. Suspension-type AWJ machining has significant advantages in energy management. These machines are extensively in use due to their versatile nature and ability to cut several metallic and non-metallic materials in the manufacturing sector. In the suspension-type AWJ machining technique, a suspension mixture (also called slurry) made of water, abrasives, and a polymer is prepared beforehand and directed through a nozzle at high pressures to form a fine jet. Several studies have been conducted on the suspension-type AWJ machining of different materials, viz., glass fibre-reinforced plastic composites [5,6], discontinuously reinforced Caryota urens fibre polyester composites [7], titanium alloy [8], mild steel [9], etc., as per Taguchi's L_9 orthogonal array (OA) to save the material cost, reduce the number of experiments and to evaluate the effect of respective process parameters on performance. Ramesha et al. [6] compared the effect of process parameters (namely Abrasive size, stand-off distance, abrasive concentration, and traverse rate) on kerf width and surface roughness while using the suspension-type AWJ technique for machining glass fibre-reinforced plastic composites. According to the authors, composite and conventional materials can be machined using a suspension-type AWJ process with reduced surface roughness and improved material removal. The authors suggested that suspension-type AWJ machining can produce better machining capabilities than abrasive water jet machining when a set of suspension parameters are optimized. Shetty and Hegde [7] recently attempted machining a discontinu-

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ously reinforced Caryota urens fibre polyester composites workpiece using a suspension-type AWJ process. The authors observed the effect of process parameters (water jet pressure, traverse rate, stand-off distance, abrasive flow rate, depth of cut, and abrasive size) on surface roughness using the Taguchi-based fuzzy logic model. The researchers claim that it is possible to machine the workpiece even at low water jet pressure (300 bar), resulting in minimum surface roughness. Dumbhare et al. [9] conducted the experimental test sequences as per Taguchi's L_9 OA to analyze the effect of machining parameters on the performance of ultra-high-pressure abrasive slurry jet machining of mild steel. The authors found that stand-off distance and traverse rate positively affect the surface roughness and kerf taper angle more than the abrasive flow rate after multi-objective optimization using the response surface methodology. The author recommended exploring the suspension parameters for machining in modern manufacturing industries. It is observed that most of the studies focused on several parameters such as hydraulic, nozzle, machining, and abrasive except suspension. It is found from the literature that the stability of the suspension mixture critically affects the performance of Suspension-type AWJ machining.

The suspension-type AWJ process is based on the direct-pumping system. In this system, the pre-mixed slurry is charged in a pressure vessel in which high-pressure water is pumped to pressurize the slurry. The direct-pumping systems are usually mixed with high-viscous additives (polymers) to suspend the storage vessel's abrasive particles and reduce their settling velocity. As per the latest review conducted by Sreekumar et al. [10], the polymers influence the suspension mixture's particles' resistance to sedimentation, which helps in maintaining the stability of the cutting process. The settling of the abrasives and the dispersive behaviour of the mix affect the suspension stability of the suspension mixture. The authors claim that selecting the proper polymer and its required concentration or mass percentage plays a vital role in holding the abrasive particles to avoid their settlement in the suspension mixture. Suspension-type AWJ machining with polymer additives has several benefits that are well-recognized by researchers, making it a hotspot of research in recent years. Louis et al. [11] claim that the polymer additives stabilize the suspension mixture in suspension-type AWJs. Due to these additives, the viscosity of the suspension mixture becomes four times higher than water. During the jet generation process in the suspension nozzle, the increased viscosity shifts the Reynolds number of the flow to lower values leading to an intensified abrasive particle acceleration, enhancing the material removal. Improved abrasive particle acceleration and suspension stability positively influence the cutting potential of abrasive suspension jets. The popular method used by previous researchers [12–14] to check the suspension stability of the suspension mixture is the "sedimentation method". An increase in polymer concentration at a specified limit enhances the performance of AWJ machining even at an increased distance of the nozzle from the workpiece and low water jet pressure.

The polymers are long-chained molecules that impart a viscoelastic fluid behaviour to the suspension mixture. There are various polymer additives during the Suspension-type AWJ machining of several materials, including SUPER-WATER/polyacrylamide (PAM) [15–17], Xanthan [16,18], polyox [19], carboxy methyl cellulose (CMC/cellulose gum) [16,17] and others. Recently, Wang et al. [20] studied the rheological properties of the suspension mixture with PAM and CMC used in suspension-type AWJs. The authors concluded that the abrasive does not influence the apparent viscosity of the slurry mixture. But the increased suspension stability will be a dominant factor in obtaining good-quality machined surfaces. Hence, the authors recommended studying the suspension stability and optimization of suspension parameters used in the suspension-type AWJ.

As per the recommendation by Sreekumar et al. [10], selecting a suitable polymer to get a stable suspension mixture is better. The polymers mentioned above have better suspension capability but cannot suspend the abrasive particles for an extended period. Therefore, they cannot be pre-mixed and stored. Hence, exploring the suspension stability of the suspension mixture using a polymer is necessary, which overcomes the above-said limitation. In this direction, a stable abrasive water suspension mixture is prepared in the current work using a polymer called 'zycoprint' (used by previous researchers, as mentioned in Tab. 1–serial numbers 1 and 8). There are several benefits of zycoprint polymer over other commercially available polymers [21]. It has a long-lasting ability to suspend abrasive particles and better suspension stability even at low concentrations (about 1%) to create a stable abrasive suspension mixture for experiments. Using the optimal quantity of the mass percentage of polymer (ω_p) to prepare the suspension mixture plays a vital role. Previous researchers have used various polymers with different mass percentages during suspension-type AWJ machining of several engineering materials, as summarized in Table 1.

The recent study conducted by Maurya et al. [33] focused on the performance analysis of the suspension-type AWJ machining of acrylonitrile butadiene rubber under room-temperature and cryogenic conditions. The authors used the zycoprint polymer and garnet abrasives to prepare the suspension mixture during machining, with a mass percentage of 0.8% and 3%, respectively but didn't explore its stability with the specific mass percentages. They used an anchor type agitator with a tangential impeller flow for preparing the suspension mixture. The authors were able to machine acrylonitrile butadiene rubber with good-quality slots using the mass percentages of zycoprint and garnet abrasives (0.8% and 3%, respectively) under cryogenic machining conditions. The experimental work in [33] validates the optimum mass percentages obtained in the present work. Even though relevant studies have been published on suspension-type AWJ machining by considering the several suspension parameters such as mass percentage of polymer and abrasive, type of abrasive, volume fraction of suspension agent, dispersant and particle size of

Table 1. Recommended mass percentage of polymers used by previous researchers during Suspension-type AWJ machining of several materials.

Sr. No.	Author (year)	Reference	Polymer name	Material machined	Recommended mass percentage of polymer, ω_p, %
1	Anjaiah and Chincholkar (2008)	[21]	Zycoprint	Glass	0.95–1.1
2	Wang et al. (2009)	[22]	PAM	Glass	0.6
3	Patel and Tandon (2013, 2017)	[23]	Gelatin	Mild steel	10–20
4	Amar and Tandon (2021)	[24]	Gelatin	Mild steel	20
6	Feng et al. (2017)	[25]	PAM	Mild steel	2.6, 3.3, 4.0 and 4.8
7	Qiang et al. (2019, 2020)	[26,27]	PAM	Stainless steel, Metal	10
8	Deepak and Devineni (2017)	[28]	Zycoprint	Ceramic	0.80
9	Wijk et al. (2019)	[29]	PEO	Glass	0.01–0.03
10	Wang et al. (2018)	[30]	PAM	Stainless steel	0.2–0.6
11	Kowsari et al. (2017)	[31]	PAM	Glass, Polymethyl methacrylate and ceramic	1
12	Kowsari et al. (2014)	[32]	PEO	Brittle and ductile materials	0.005

*PAM: polyacrylamide; CMC: carboxy methylcellulose; PEO: polyethylene oxide.

abrasive and many more, none of them focused on the reason behind selecting the prescribed mass percentage of polymer and abrasive.

The study on the optimum suspension parameters analysis to achieve stability of the suspension mixture before using it in the suspension-type AWJ machining process has not been reported in the published scientific literature. Therefore, the current work investigates suspension stability by varying the polymer and abrasive particle mass percentages using the sedimentation method. Achieving the suspension stability can help the custom manufacturing scenario in the Industry 4.0 concept. In custom manufacturing, the industries focus on creating small batches of specialized items made up of glass fibre-reinforced composites, elastomers, titanium alloy, nickel alloy, and many more for particular customers. Manufacturing of customized components with small lot sizes takes time and is un-economical to prepare by moulding methods. Hence, several industries and manufacturers are looking for modern manufacturing (green manufacturing) processes, like AWJ machining, to achieve a “lot size of one” in an affordable manner without delay. Hence, knowing the optimum setting of the suspension mixture before using it in AWJ machining of any engineering material, more so in difficult-to-machine material, leads to minimizing the pre-machining time and removing unnecessary hurdles. Providing the machined “lot size of one” at a lower price to the customer at the earliest will become possible and uplift the AWJ machining market in the manufacturing sectors.

The primary objective of the research paper is to prepare different suspension mixtures by varying the zycoprint polymer and abrasive concentrations as per the L_9 OA of the Taguchi method, preferred for the selected number of decision variables (3^2). The second objective is to develop the mathematical equations for the percentage of suspension volume (V_s) using linear regression (LR) modelling and validate them with the confirmatory test. The third objective is to use the JAYA algorithm to optimize suspension parameters.

2 Materials and methods

This section includes the details of polymer, abrasive particles and methodology used in the current work.

2.1 Zycoprint polymer

Zycoprint polymer is a copolymer of an ammonium salt and other ingredients like surfactants and paraffin oils. The zycoprint polymer solution at 1% concentration has a higher viscosity than the commercial polymer solution at 1.5% concentration [21]. The physical and chemical properties of the zycoprint polymer are shown in Table 2. The required volume (V_{polymer}) and mass ($\text{mass}_{\text{polymer}}$) of the zycoprint polymer are calculated using equations (1) and (2).

$$V_{\text{polymer}} = \frac{\text{mass}_{\text{polymer}}}{\rho_{\text{polymer}}}, \tag{1}$$

Table 2. Physical and chemical properties of the zycoprint polymer.

Properties	Description
Physical state	Liquid pourable dispersion
Colour	Creamish off-white
Odour	Paraffinic
pH	7–9
Freezing point	0 °C
Boiling point	100 °C
Flash point	>75 °C
Viscosity	500–6000 cP at 27–30 °C
Flammability	Not flammable
Specific gravity	1.06 ± 0.01 g/cc
Water solubility	Dispersible in water
Reactivity	Corrosive effects on metal are not anticipated
Harmful effects	Non-toxic
Density	1.05–1.07 g/ml

$$\text{mass}_{\text{polymer}} = \text{mass}_{\text{water}} \times \omega_p, \tag{2}$$

where ω_p (%) = mass percentage of the zycoprint polymer, ρ_{polymer} = density of the zycoprint polymer (1.05 g/ml) and $\text{mass}_{\text{water}}$ = mass of water (99.98 g).

2.2 Abrasive particles

The abrasive particle type, size, and shape significantly influence the suspension mixture [34]. The most commonly used abrasives in AWJ machining are garnet and aluminum oxide (Al_2O_3). Garnets with mesh size #80 (150 to 300 μm) can cut almost all material with a good surface finish [35]. The garnet and Al_2O_3 with mesh size #80 are selected to prepare the suspension mixture based on the findings from reported literature and the availability of resources. The quantity of the abrasives (garnet and Al_2O_3) required in the suspension mixture is calculated using equation (3)

$$\text{mass}_{\text{abrasive}} = \text{mass}_{\text{water}} \times \omega_a, \tag{3}$$

where ω_a (%) is the mass percentage of abrasive (garnet or Al_2O_3) and mass of the water ($\text{mass}_{\text{water}}$) is 99.98 g.

2.3 Slurry (suspension) preparation

The experiments are conducted to investigate the stability of the suspension mixture at different zycoprint concentrations, with sediments being in static conditions. The suspension mixture is prepared in a 100 ml beaker by adding the required amount of zycoprint to 100 ml of water and stirring it at a low speed of 30 rev/min for 10 min using a cylindrical glass tube type of mixer to get a homogeneous mixture. Then, the required amount of the abrasive (garnet or Al_2O_3) is added to the mixture and mixed for 3 min. Further, the prepared mixture is kept aside for 2 h to get maximum sedimentation at the bottom of the beaker. Finally, the suspension ability of the different combinations of the mixtures prepared is compared in terms of the percentage of suspension volume (V_s) to obtain the best combination.

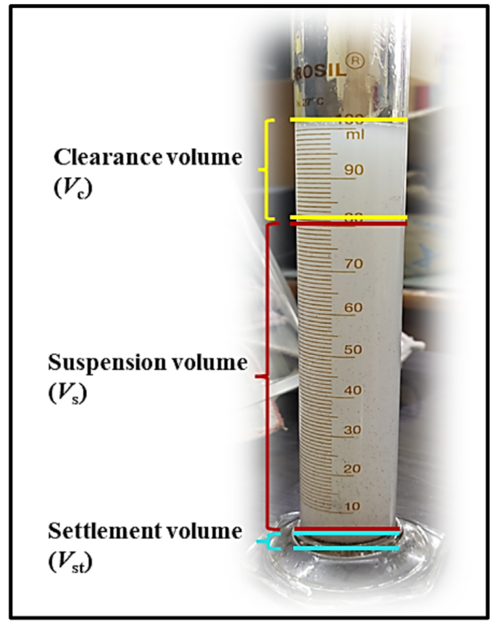

Fig. 1. Pictorial representation of clearance, suspension, and settlement volumes.

2.4 Percentage of suspension volume (V_s)

The suspension mixture's stability is evaluated as the suspension volume (V_s) percentage, as shown in equation (4)

$$V_s(\%) = \left[1 - \left(\frac{V_{\text{st}} + V_c}{V_t}\right)\right] \times 100, \tag{4}$$

where V_{st} = 'settlement volume' (volume of abrasive particles settled at the bottom of the beaker in 'ml'), V_c = 'clearance volume' (volume of the mixture at the topmost portion, having negligible abrasives in 'ml'). V_t = 'total volume' of the suspension mixture (total volume of the beaker) in 'ml.' The settlement and clearance volumes are measured by visual inspection, as shown in Figure 1. In this work, the total volume of the suspension mixture is constant at 100 ml, viz., $V_t = V_c + V_s + V_{\text{st}} = 100$ ml. Larger the V_s (%), lesser is the precipitation of the abrasive particles, the better is the dispersion effect and the slurry suspension stability. Therefore, the focus of the present work is to maximize the V_s (%) and attaining the preset limit of 100%.

2.5 Design of experiments (DoE)

The Full factorial experimental design considers numerous runs, which is expensive. Utilizing Taguchi's approach will reduce costs, time, and resource usage. The dominant suspension parameters were chosen based on the literature

Table 3. Details of suspension parameters and their levels used in the suspension preparation.

Suspension parameters	Symbol	Units	Level_1	Level_2	Level_3
Mass percentage of polymer	ω_p	%	0.70	0.75	0.80
Mass percentage of garnet/Al_2O_3	ω_a	%	3	5	7

[17,21–32]. The ranges of suspension parameters selected for the experimentation were tested in the preliminary suspension mixture preparation trials. The experimental runs were constructed using Taguchi's L_9 OA, which allows for a smaller number of runs needed than the conventional central composite design used along with response surface methodology. Table 3 details the suspension parameters and levels used for the experimental design to prepare a suspension mixture using garnet and Al_2O_3. The percentage of suspension volume (V_s) is considered a response variable.

2.6 Linear regression (LR) modelling

The regression equations, for V_s^G and V_s^A, are developed using the LR modelling technique, where V_s^G = percentage of suspension volume with garnet as abrasive, and V_s^A = percentage of suspension volume with Al_2O_3 as abrasive [36]. The closeness of the predicted responses to the experimental responses is measured by the 'adjusted R^2 (Adj. R^2)' and 'predicted R^2 (Pred. R^2)'. The LR model is considered a good one if the Adj. R^2 is closer to 1, and the difference between the Adj. R^2 and Pred. R^2 is less than 0.2.

The LR model developed for V_s^G (refer to equation (5)) offers a good fit with Adj. R^2 and Pred. R^2 of 0.7171 and 0.5295, respectively. The value of Adj. R^2 is in reasonable agreement with the Pred. R^2, as the difference between the two, is less than 0.2. Similarly, the LR model developed for V_s^A (refer to Eq. (6)) also offers a good fit with high values of Adj. R^2 and Pred. R^2 of 0.9267 and 0.8435, respectively. The value of Adj. R^2 is in reasonable agreement with the Pred. R^2, as the difference between the two, is less than 0.2.

$$V_s^G = 100 + 10 \times \omega_p - 2.458 \times \omega_a, \tag{5}$$

$$V_s^A = -127.7 + 578 \times \omega_p - 0.0833 \times \omega_a - 367 \times \omega_p \times \omega_p. \tag{6}$$

The main effect plots obtained during the analysis of developed LR models are used to analyze the effect of suspension parameters (ω_p and ω_a) on the mean of V_s^G and V_s^A and to determine the optimal levels of the suspension parameters corresponding to the maximum suspension volumes (V_s^G and V_s^A). The effect of the significant interaction term between the ω_p and ω_a on the V_s^G and V_s^A is explored using contour plots. The software Minitab (2019Minitab® 19.1.1 (64-bit)) is used to generate Taguchi's L_9 OA and develop the LR model.

2.7 Single-objective optimization

In the problem under consideration, each response equation (Eqs. (5) and (6)) is considered the objective function of the optimization problem. The objective is to maximize the percentage of suspension volume. This case is a single-objective optimization problem (SOOP), as each objective function (Eqs. (5) and (6)) is to be optimized individually. The popular 'JAYA algorithm' is used for optimizing V_s^G and V_s^A due to its simple concept and better performance than other advanced metaheuristic algorithms [37]. The pseudo-code of the JAYA algorithm is presented below (see page 6). The variables in bold represent matrices.

The JAYA algorithm is implemented through the customized MATLAB (R2020a) programs on an Intel i5 2.11 GHz processor and 8GB RAM laptop. The JAYA algorithm is run for six different combinations of population size (PS) and the number of generations (*MaxGen*), as shown in Table 4.

3 Results and discussion

The experiments are conducted as per L_9 OA. Table 5 gives the details of all nine combinations of suspension parameters and the corresponding values of the response variables determined by experimentation.

The analysis of variance (ANOVA) of the LR model is used to check the linear and interaction effects of the polymer and the abrasive concentrations on the percentage of suspension volume (V_s^G and V_s^A). The ANOVA test of the LR model is conducted at a 95% confidence interval. Therefore, the variables with probability value (p-value) $\leq$0.05 are considered significant.

3.1 LR results for the percentage of suspension volume (V_s^G) with Garnet as the abrasive

From the LR results for the percentage of suspension volume (V_s^G) with Garnet as abrasive (refer to Tab. 6), it could be observed that 77.98% of the variation in the response variable is caused by the mass percentage of abrasive (garnet) (ω_a). Hence, the contribution of $\boldsymbol{\omega}_a$ on the regression model is more than the mass percentage of the polymer (ω_p). The p-value of the linear term ω_a (0.003) is less than 0.05. Hence, the mass percentage of abrasive (Garnet) (ω_a) proves significant. Figure 2 shows the main effect plot (a) and contour plot (b) for V_s^G. The ω_p is considered in the LR model because it is an

Inputs: pop, $nVar$, $MaxGen$

pop = size of population
$nVar$ = number of design variables
$\boldsymbol{L} = [L_j]$; $j = 1$ to $nVar$; [Row matrix with lower limits of variables]
$\boldsymbol{U} = [U_j]$; $j = 1$ to $nVar$; [Row matrix with upper limits of variables]
$MaxGen$ = Maximum number of generations or iterations: termination criteria
Outputs: f_{opt}, x_{opt}
f_{opt} = Optimum cost
x_{opt} = Optimum solution
Step 1: Create the initial population matrix $\boldsymbol{x} = [x_i]$, $i = 1$ to pop
Step 2: Find the fitness $\boldsymbol{f} = [f_i]$ such that $f_i = \varphi\,(x_i)$
Step 3: Initialize $gen = 1$
while ($gen < MaxGen$)
a. Find the best and the worst solution
$f_{best} = \max\,(\boldsymbol{f})$
$f_{worst} = \max\,(\boldsymbol{f})$
b. Pick the best solution $x_{best} = x_i$ corresponding to best fitness f_{best}
Pick the worst solution $x_{worst} = x_i$ corresponding to worst fitness f_{worst}
c. Update the population $\boldsymbol{x}$ as $\boldsymbol{xx}$ by using the equation
$xx_i = x_i + r_1 * (x_{best} - |\,x_i\,|) - r_2 * (x_{worst} - |\,x_i\,|)$
d. Modify the solutions in the updated population such that they satisfy the limits $\boldsymbol{L}$ and $\boldsymbol{U}$
$\boldsymbol{xn}$ = modify ($\boldsymbol{xx}$)
e. Find the fitness $\boldsymbol{fn}$ of the modified population $\boldsymbol{xn}$
$\boldsymbol{fn} = [fn_i]$ such that $fn_i = \varphi\,(xn_i)$
f. Choose the best solution candidates from $\boldsymbol{x}$ and $\boldsymbol{xn}$
if ($fn_i > f_i$)
$f_i = fn_i$
$x_i = xn_i$ corresponding to fn_i
end if
g. Choose the best cost f_{opt} from $\boldsymbol{f}$
$f_{opt} = \max\,(\boldsymbol{f})$
$x_{opt} = x_i$ of $\boldsymbol{x}$ corresponding to f_{opt}
h. $gen = gen + 1$
end while
Step 4: print f_{opt} , x_{opt}

N.B. The variables in bold represent matrices.

Table 4. Selected conditions for the JAYA algorithm.

Condition number (CN)	**Conditions**	
	Population size (PS)	Number of generations (*MaxGen*)
CN_1	10	20
CN_2	15	20
CN_3	10	40
CN_4	15	40
CN_5	10	60
CN_6	15	60

Table 5. The suspension parameters and their corresponding responses for nine experimental runs.

Suspension parameters			Response variable	
			Garnet (#80)	Al_2O_3 (#80)
Sr. No.	ω_p (%)	ω_a (%)	V_s^G (%)	V_s^A (%)
1	0.70	3	99.5	97.5
2	0.70	5	98.5	97
3	0.70	7	87	96.5
4	0.75	3	97.5	99.5
5	0.75	5	96	99
6	0.75	7	90	99.5
7	0.80	3	99.5	100
8	0.80	5	98.5	99.5
9	0.80	7	90	100

Table 6. ANOVA results of the LR model for the percentage of suspension volume V_s^G and V_s^A.

Source	DoF*	Seq. SS*	Contribution	Adj. SS*	Adj. MS*	F*- ratio (obtained)	F*-ratio (critical)	*p*-value	Remarks
					V_s^G				
Model	2	146.542	78.79%	146.542	73.271	11.14	F (2,8) = 4.46	0.010	Significant
Linear	2	146.542	78.79%	146.542	73.271	11.14	F (2,8) = 4.46	0.005	Significant
ω_p	1	1.500	0.81%	1.500	1.500	0.23	F (1,8) = 5.32	0.650	Insignificant
ω_a	1	145.042	77.98%	145.042	145.042	22.05	F (1,8) = 5.32	0.003	Significant
Error	6	39.458	21.21%	39.458	6.576				
Total	8	186.000	100.00%						
					V_s^A				
Model	3	13.8889	95.42%	13.8889	4.6296	34.71	F (3,8) = 4.07	0.001	Significant
Linear	2	12.2084	83.88%	2.0242	1.0121	7.59	F (2,8) = 4.46	0.023	Significant
ω_p	1	12.0417	82.73%	1.8575	1.8575	13.93	F (1,8) = 5.32	0.014	Significant
ω_a	1	0.1667	1.15%	0.1667	0.1667	1.25	F (1,8) = 5.32	0.314	Insignificant
Square	1								
$\omega_p \times \omega_p$	1	1.6806	11.55%	1.6806	1.68056	12.60	F (1,8) = 5.32	0.016	Significant
Error	5	0.6667	4.58%	0.6667	0.1333				
Total	8	14.5556	100%						

*DoF: Degree of freedom; Seq. SS: Sequential sum of squares; Adj. SS: Adjusted sum of squares; Adj. MS: Adjusted mean square; *F*-ratio: Fisher's- ratio.

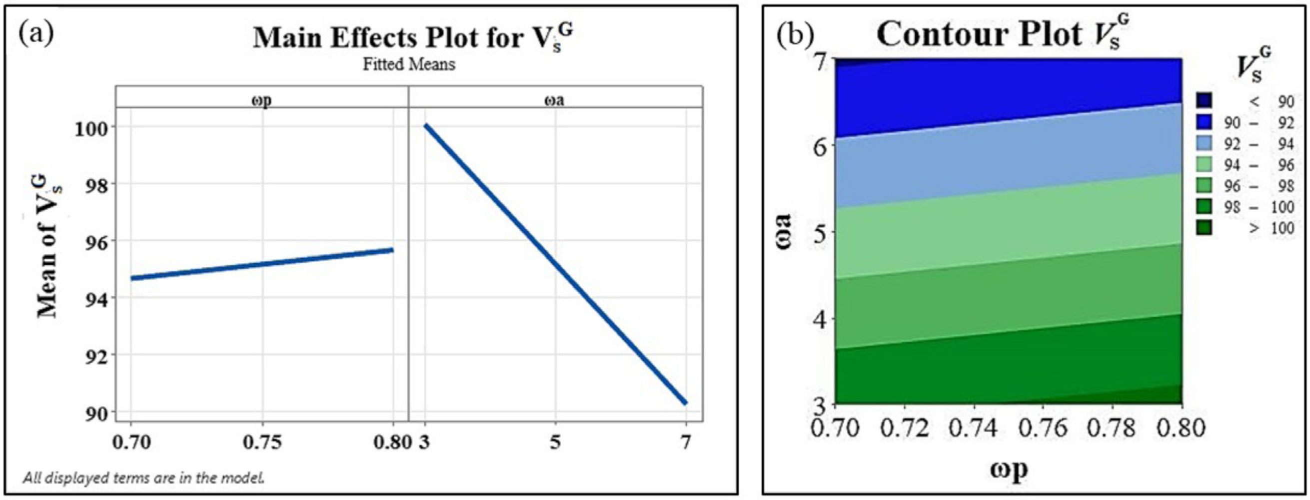

Fig. 2. (a) Main effects and (b) contour plots for V_s^G.

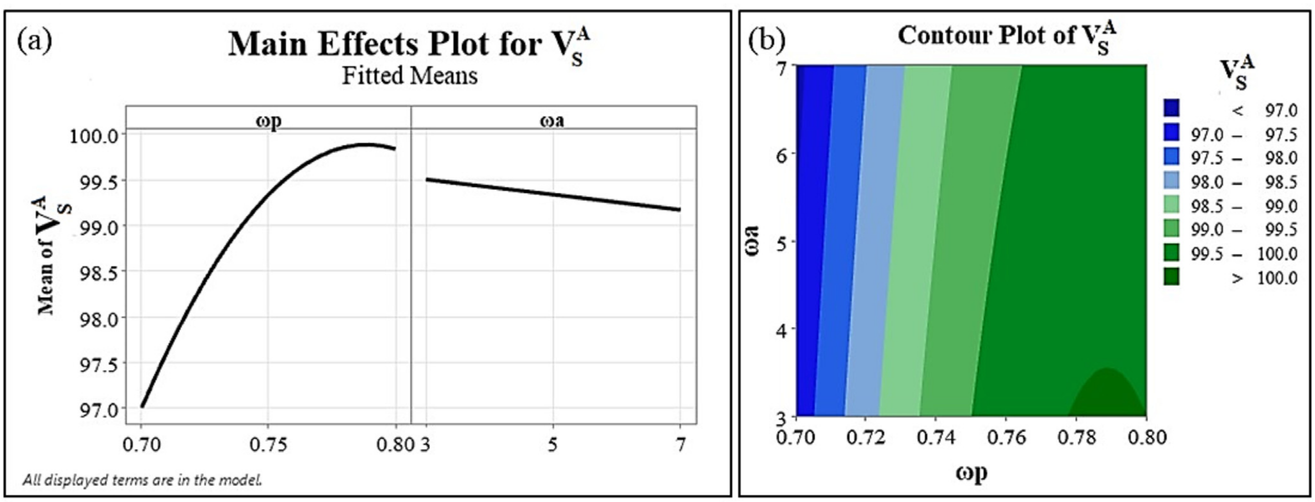

Fig. 3. (a) Main effects and (b) Contour plots for V_s^A.

individual term and main suspension parameter, even though it is insignificant. The individual terms (ω_p and ω_a) are used for the practical usage of the equation [38,39]. From the main effect plot (refer to Fig. 2a), it is observed that the increase in ω_p from 0.7 to 0.8% increases the average V_s^G by about 1%. The maximum percentage of suspension volume (V_s^G) is observed from the main effect plot and contour plot (refer to Fig. 2b) at 0.80% of ω_p and 3% of ω_a.

3.2 LR results for the percentage of suspension volume (V_s^A) with Al_2O_3 as the abrasive

From the LR results for the percentage of suspension volume (V_s^A) with Al_2O_3 as abrasive (refer to Tab. 6), it could be observed that the linear terms cause 83.88% of the variation in the response compared to the 11.55% significance exhibited by the squared term. Hence, the contribution of linear terms to the response variable is more. But the p-value of the linear terms ω_a (0.314) is greater than 0.05. Hence, the mass percentage of abrasive (Al_2O_3) (ω_a) proves insignificant. The p-value of the linear terms ω_p (0.014) is less than 0.05. Hence, the mass percentage of polymer (ω_p) proves to be significant. In square terms, the p-value of $\omega_p \times \omega_p$ is 0.016 (significant), even though their percentage of contribution is only 11.55%. Hence, only a large change in the mass percentage of polymer (ω_p) brings a difference in the response, which is evident from the medium significance percentage (11.55%) of the square term of ω_p. Figure 3 shows the main effect plot (a) and contour plot (b) for V_s^A. The ω_a is considered in the LR model because it plays a major role in the suspension preparation, even though it is insignificant. It can be seen from the main effect plot (refer to Fig. 3a) and contour plot (refer to Fig. 3b) between the mass percentage of Garnet

Table 7. Validation experiments for the percentage of suspension volume (V_s^G and V_s^A).

Confirmatory tests (CT)	Suspension parameters		Response variables					
			Garnet (#80)			Al_2O_3 (#80)		
	ω_p (%)	ω_a (%)	V_s^G (%)_ Experimental	V_s^G (%)_ model	% Error	V_s^A(%)_experimental	V_s^A(%)_model	% Error
CT1	0.73	3.5	99.5	98.697	0.807	98	98.374	0.004
CT2	0.74	4	99	97.568	1.446	98.5	98.718	0.002
CT3	0.76	4.5	97	96.539	0.475	99	99.226	0.002
CT4	0.78	6	95	93.052	2.051	99	99.357	0.004
CT5	0.79	6.7	93	91.431	1.687	100	99.317	0.007
Mean % error							1.293	0.019

Table 8. Performance of the JAYA algorithm.

Condition number (CN)	Opt_PPs_JAYA*			
	Garnet (#80)		Al_2O_3 (#80)	
	ω_p (%)	ω_a (%)	ω_p (%)	ω_a (%)
CN_1	0.80	3	0.78	3
CN_2	0.80	3	0.78	3
CN_3	0.81	3	0.79	3
CN_4	0.81	3	0.79	3
CN_5	0.82	3	0.79	3
CN_6	0.82	3	0.79	3

*Opt_PPs_JAYA = Optimum suspension parameters achieved by the JAYA algorithm.

(ω_a, %) and mass percentage of polymer (ω_p, %) that the maximum percentage of suspension volume (V_s^A) is observed at 3% of ω_a and 0.80% of ω_p.

3.3 Results of the developed linear regression (LR) models for the percentage of suspension volume V_s^G and V_s^A

The developed LR model for V_s^G provides a good fit with Adj. R^2 and Pred. R^2 of 0.7171 and 0.5295, respectively. The average percentage error of prediction between 9 experimental and predicted values is 0.046%. It is observed from equation (5) that the positive coefficient of the mass percentage of polymer (ω_p) of the developed LR model indicate that as its value increase, the mean of the percentage of suspension volume (V_s^G) also tends to increase. But at the same time, the negative coefficient of the mass percentage of abrasive (Garnet) (ω_a) indicate that as its value increase, the mean of the percentage of suspension volume (V_s^G) tends to decrease.

The developed LR model for V_s^A also offers a good fit with high values of Adj. R^2 and Pred. R^2 of 0.9267 and 0.8435, respectively. The average percentage error of prediction between 9 experimental and predicted values is 0.394%. It is observed from equation (6) that the positive coefficient of the mass percentage of polymer (ω_p) of the developed LR model indicate that as its value increase, the mean of the percentage of suspension volume (V_s^A) also tends to increase. But at the same time, the negative coefficient of the mass percentage of abrasive (Al_2O_3) (ω_a) and square term of mass percentage of polymer (ω_p) indicate that as their values increase, the mean of the percentage of suspension volume (V_s^A) tends to decrease.

The average percentage of errors in both cases, V_s^G and V_s^A, are less than 5%. It indicates a close match of experimental and predicted values percentage of suspension volume [40,41]. Hence, it suggests that the developed LR models are acceptable for predicting the response variables (V_s^G and V_s^A).

3.4 Confirmation test results

The developed LR models (Eqs. (5) and (6)) are validated with further experiments, as shown in Table 7. The values of suspension parameters selected for the confirmatory test are in the range of levels mentioned in Table 3. The percentage error (% error) for each confirmatory test is calculated using equation (7) [42], and their results are

Table 9. Comparison between the optimum combination of suspension parameters obtained using the JAYA algorithm and LR model.

Avg_Opt_PPs_JAYA*				Opt_PPs_LR*			
Garnet (#80)		Al_2O_3 (#80)		Garnet (#80)		Al_2O_3 (#80)	
ω_p (%)	ω_a (%)	ω_p (%)	ω_a (%)	ω_p (%)	ω_a (%)	ω_p (%)	ω_a (%)
0.81	3	0.789	3	0.80	3	0.80	3

*Avg_Opt_PPs_JAYA = Average optimum suspension parameters achieved by the JAYA algorithm; Opt_PPs_LR = Optimum suspension parameters obtained from the main effect plot of the LR model.

depicted in Table 7. The confirmation experimental test values of V_s^G and V_s^A are in agreement with the calculated model values, as the mean % error for Garnet and Al_2O_3 are 1.293 and 0.019, respectively.

$$\%\,\text{Error} = \left|\frac{V_s\text{\_experimental} - V_s\text{\_model}}{V_s\text{\_experimental}}\right| \times 100. \quad (7)$$

3.5 Results of single-objective optimization

Table 8 demonstrates the optimum suspension parameters and their corresponding optimum response variables obtained using the JAYA algorithm after considering the conditions mentioned in Table 4. The combined optimum suspension parameters obtained from the average JAYA algorithm results of all condition numbers and LR model results are incorporated in Table 9. The optimization results of the JAYA algorithm are close to the best parameter combinations ($\omega_p = 0.80$ and $\omega_a = 3$ for both garnet and Al_2O_3), evident from the contour plots in Figures 2b and 3b.

4 Conclusions

The suspension mixture's stability is vital in the Suspension-type AWJ machining process. The mass percentage of polymer and abrasives are critical parameters of the suspension mixture. The settling of abrasive particles and the dispersive behaviour of the mix affect the suspension stability of the suspension mixture. The larger the percentage of suspension volume ($V_s(\%)$) lesser is the precipitation of the abrasive particles, the better is the dispersion effect and slurry suspension stability. Hence, it is crucial to analyze the suspension stability of the suspension mixture using a zycoprint polymer which has a long-lasting ability to suspend abrasive particles. In this vein, the current research work is attempted. The essential highlights of the novel work include finding the optimal combination of the suspension mixture composition and obtaining the mixture's stability are discussed here.

It is found from the experimental runs that in the case of Garnet, the maximum $V_s^G(\%)$ is observed at (3% of ω_a, 0.70% of ω_p) and (3% of ω_a, 0.80% of ω_p). Whereas, in the case of Al_2O_3, the maximum $V_s^A(\%)$ is observed at (3% of ω_a, 0.80% of ω_p) and (7% of ω_a, 0.80% of ω_p). The statistical results obtained from the ANOVA of the developed LR models show that the *p*-values of the models are significant for garnet and Al_2O_3. The developed LR models and confirmatory test are in agreement with the experimental results, as the mean % errors for garnet and Al_2O_3 are 1.293 and 0.019, respectively. The optimum value of the suspension parameter ω_a is towards the lower level (i.e., Level_1 (3%)), and ω_p is towards the higher level (i.e., Level_3 (0.80%)) to achieve maximum suspension volumes ($V_s^G = 99.5\%$ and $V_s^A = 100\%$) obtained from the main effect plots of the LR models. These results are in close agreement with the JAYA algorithm results. The study recommended that achieving the maximum stability of the suspension mixture is possible by considering the suggested settings of the suspension parameters while using it in the Suspension-type AWJ machining process.

In applying the Industry 4.0 features, the manufacturing sectors can benefit from the suggested optimum suspension parameters obtained by the current work in the suspension-type AWJ process to cut several difficult-to-machine materials (such as glass fibre-reinforced composites, titanium alloy, nickel alloy, polymers, etc.). Further investigation is recommended by considering the process parameters (such as hydraulic, nozzle, machining, abrasive, and work material) along with the stated optimal suspension parameters to study the fluid dynamics of the suspension-type AWJs. Exploring the abrasive particle settlement velocity for different abrasives and their respective concentrations is also recommended for future work so that it can be pre-mixed and stored for an extended duration.

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