Machining performance analysis of Al 7075/ferrochrome metal matrix nanocomposite using uncoated carbide insert towards environmental sustainability

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Abstract. Aluminium metal matrix composites are profoundly utilized in the aerospace, automobile, and marine sectors owing to their enhanced mechanical qualities, such as a high strength-to-weight ratio and corrosion resistance. This work focuses on analysing the influence of various machining parameters, specifically cutting speed, feed rate, and depth of cut, on noise emission and hardness during the turning process of Al7075 reinforced with 5 wt.% Fe-Cr composites. The studies were conducted on a CNC lathe using uncoated carbide insert employing a Taguchi L_9 orthogonal array. At run 5, with a cutting speed of 110 m/min, a feed rate of 0.1 mm/rev, and a depth of cut of 0.3 mm, a greater noise level (79.5 dB) was obtained. The maximal hardness of 167 HV was reached at run no. 3 (cutting speed: 60 m/min, feed rate: 0.15 mm/rev, and depth of cut: 0.3 mm). The ANOVA findings indicated that cutting speed significantly influences both noise emission and hardness. Multiple linear regression models for both Ne and H are found to be significant as R^2 approaches 1 with p-value <0.05 and obtained optimal parameters through desirability approach. The research findings provide insights for improving machining performance during the turning of AMMC composites.

1 Introduction

Aluminum metal matrix composites (AMMCs) have wide range of applications in aerospace, automobile sectors and marine owing to their outstanding features, particularly their superior strength compared to weight, corrosion resistance and optimum formability. Hardness and noise emissions are two of the key parameters which profoundly affects the operational performance and manufacturing of these materials. Hardness, which reflects how well a material resists localized plastic deformation, is an important measure of its mechanical strength and overall durability of the material. Noise, in the context of material science, is often a by-product of a material's internal structural changes and dynamic behaviour under stress [1]. The generation and propagation of acoustic signals during deformation and failure

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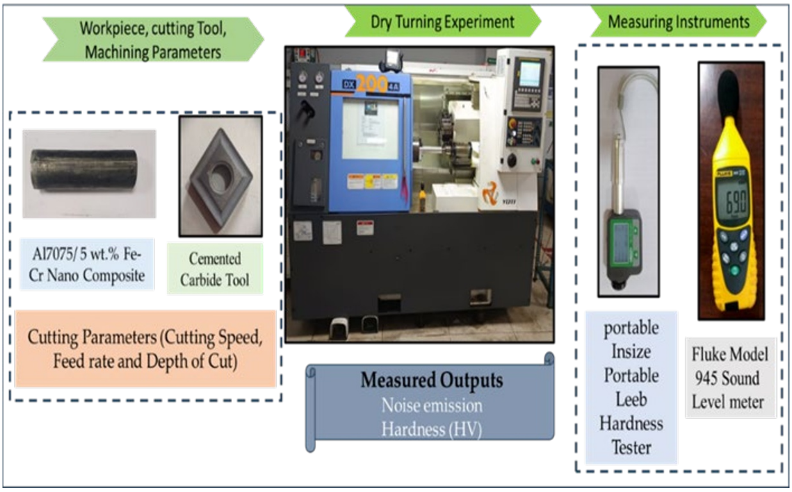
process, can provide valuable insights into the material's microstructural integrity [2]. Understanding acoustic behaviour is crucial for developing non-destructive testing methods and for monitoring the structural health of components in real-time such as crack initiation and propagation, twinning and phase transformation [3, 4]. The correlation between hardness and noise emission is significant to understand and optimize product design and applications of AMMCs in industrial systems. Undesirable noise generation by dynamic contacts, friction and wear on components like brake systems in automotive, landing mechanism in aerospace industry and other high speed rotating assemblies can not only indicate underlying damage but also contribute to environmental noise pollution, affecting human comfort and regulatory compliance. Hence, study of noise emission characteristics alongside hardness can provide holistic insights into developing composites that perform efficiently while maintaining operational quietness. James et al. [5] fabricated and examined the characterization like Vickers micro hardness of Al6061 reinforced with ZrO2 and Al2O3 and discovered a 70% increase in hardness from the base alloy. Rajesh A M and Mohammed Kaleemulla [6] synthesized Al7075 with various volume fraction of SiC and alumina (Al2O3) and discovered that at 10% of both reinforcement gives highest Vickers hardness number to the composite. Parswajinan et al. [7] experimented on aluminum alloy reinforced with four different compositions of SiC and carbon nanotubes and tested hardness in Brinell hardness scale. Narayan and Rajeshkannan [8] evaluated the hardness of pure aluminum and their composites using different cooling methods, including sinter-forged furnace cooling, sinter-forged water cooling, homogenous sinter-forged furnace cooling, and homogenous sinter-forged water cooling. Kumar et al. [9] synthesized Al7075 with ZrC to sought out mechanical characteristics of the composite and optimize the wear process through using Taguchi method. The authors measured the hardness of the composite using both Brinell and Vickers tests and found that it increased with ZrC content up to 9%. However, further addition of reinforcement led to a decrease in hardness, likely due to cluster formation at higher concentrations. Subramanian et al. [10] fabricated aluminium metal matrix composite reinforced with various volume fraction 3.5% and 7% of SiC and discovered maximum Vickers hardness value of 111VHN at 7% SiC at a weight of 1000 kgf. Prakash and Irudayaraj [11] fabricated aluminium metal matrix composite reinforced with ZrC and fly ash and discovered its hardness properties peaks at 9% ZrC and 3% fly ash reinforced AMMCs at 172 HV. Liu et al. [12] attempted optimizing tool life during Al/SiCp composite milling by analysing acoustic emission sources during machining. Several researchers in recent have studied the behaviour of noise emission and acoustic emission for composite materials [13-15].

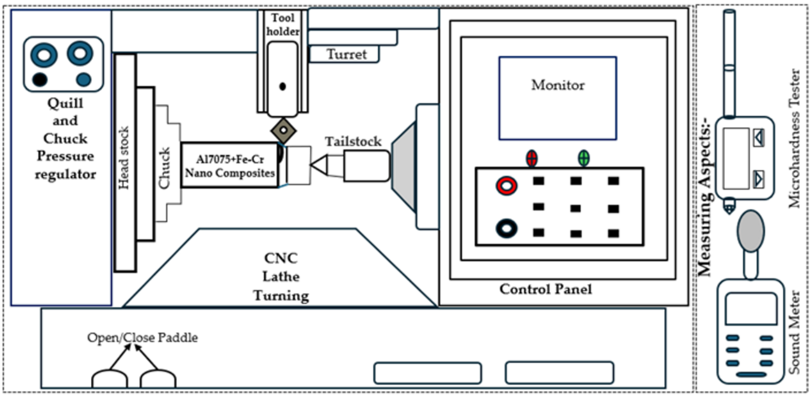
Conventional MMCs are usually reinforced with single-phase ceramics such as SiC, TiC, Al2O3 etc whereas nanocomposites used in the study is novel stir-ultrasonication-squeeze cast Al7075 matrix with industrial waste byproduct ferrochrome slag at nanoscale as the reinforcement which consists of multiphase ceramic particles like Al2O3, MgO and SiO2 etc that finds the novelty of the investigation. The machinability is expected to be improved due to uniform distribution of the Fe-Cr nanoparticles which prevents crack propagation and formation of smooth continuous ductile chips that yields less abrasive wear and desirable surface quality. As observed, limited literatures are found on the machinability aspects of metal matrix nanocomposites, but machining behaviour of Al7075 nanocomposite reinforced with ferrochrome slag is almost absent and brings the novelty of the investigation. Machinability is poor due to hard ceramic reinforcements in the aluminium matrix and its mixing distribution and thus worthy of investigation. Therefore, appropriate process parameters are utmost essential for potential application in industries. Therefore, the present studies deal with machining performance assessment of Al7075 metal matrix nanocomposite reinforced with ferrochrome slag using economical uncoated tungsten carbide cutting tools under dry environment in context to the measurement of noise emission and microhardness followed by analysis through main effects plot, interaction plots, analysis of variance (ANOVA), prediction models and multi-response parametric optimization.

2 Experimental procedures

In this research, a cylindrical workpiece of Al7075 + 5 wt.% Fe-Cr composite 47.9 mm diameter and 100 mm length was utilized for machining operation using CNC lathe machine (Jyoti DX 200) FANUC controller as shown in Figure 1 (a). The turning tests are performed by utilizing WIDIA cemented uncoated carbide cutting tool under dry condition. The turning parameters, like cutting speed (60, 110, 160 m/min), feed rate (0.05, 0.1 and 0.15 mm/rev) and depth of cut (0.1, 0.2 and 0.3 mm) were chosen as input and hardness and noise emission are chosen as output parameters. The Design of Experiment was carried out using the Taguchi L_9 orthogonal array approach. The analysis of noise emission was conducted using Fluke Model 945 Sound Level meter. Furthermore, the hardness was measured using portable Insize Portable Leeb Hardness Tester (Basic Type) HDT-L41 as shown in Figure 1 (a). The schematic setup for the turning operation has also been shown in Figure 1 (b).



(a)



(b)

Fig. 1. (a) Machining operation set up for Al7075/Ferrochrome metal matrix nanocomposite (a) Experimental, and (b) Schematic.

3 Results and discussion

The brief discussion on experimental results is analyzed as follows:

During machining, higher noise level influences negatively on operator's health and environment i.e. stress level, hearing problem, headaches and difficulties in communication etc and thus needs to be controlled using appropriate cutting tool, geometry and environments for better societal and environmental sustainability. Noise emission during machining of MMCs have been found to be in the range of 68.3dB-79.5dB which are within the range of acceptable limit of human hearing i.e. 85dB (Table 1) as per the National Institute for Occupational Safety and Health (NIOSH) and thus found to be environmentally sustainable and graphically shown in Figure 2 as higher noise level can cause health issues in humans. This may be attributed due to the minimization of friction and power consumption during machining under dry environment. Noise emission increases with cutting speed, feed and depth of cut due to increase of impact energy/power consumption and vibration during machining and due to friction at the chip-tool and work-tool interface as seen from the main effects plot Figure 3 (a) where increasing trend is higher in case of cutting speed parameter. Because of the increase of cutting speed, severe plastic deformation for formation of chips and forces evolved to cause vibration during machining that may lead to chatter and severe noise at very high cutting speed and thus negatively influences the surface quality. Also, high temperature evolved at higher cutting speed causes thermal softening/over-tempering of work material at the shear zone and reduces materials microhardness and strength in the surface layer. However, due to strain hardening, microhardness increases at the surface layer particularly at low to medium cutting speed as observed in the main effects plot. The high temperature during turning may cause agglomeration of nanoparticles in the nanocomposites thus altering the effect of reinforcements and microstructural properties at the surface and affects the microhardness. Most significant parameter for noise emission during turning has been found to be the cutting speed as $p<0.05$ at 95% confidence level as revealed from the analysis of variance study Figure 3 (b) with 49.45% contribution followed by marginally federate as p-value is 0.053. Depth of cut is insignificant on Ne. Multiple linear regression model Eq-1 of Ne has been found to be significant because of higher R^2 value (86.62%) and p-value < 0.05. Model adequacy has also been checked through normal probability plot and pareto standardized effects and proved to be significant as revealed from Figure 4 (a-b). The residuals are distributed normally and lie on the straight line from the normal probability plot (Figure 4a) and thus found to be the goodness of the fit of the model developed. Also, pareto chart of the standardized effects (Figure 4b) of model reveals that cutting speed and feed have the highest statistically significant as it crosses the reference line of 2.571.

$$\text{Noise emission (Ne)} = 62 + 0.0584\ v + 43.9\ f + 16.22\ d \ldots\ldots\ldots\ldots \quad (1)$$
$$R^2 = 86.62\ \%,\ R^2\ (adj) = 78.59\ \%,\ p<0.05$$

Similarly, micro-hardness evolution after the machining due to plastic deformation is shown in Table 1 and Figure 2 with ranges from 160-167HV. From main effects plot (Figure 5a), reduction of micro-hardness is noticed at higher cutting speed for ease of machining and may be attributed due to the formation of thinner chips and less chip reduction coefficients. Micro-hardness increases with feed and depth of cut. Due to higher cutting temperature at higher cutting speed range, it softens the work material and reduces the materials microhardness and improves the machinability. Cutting speed and depth of cut influence on micro-hardness is higher with 66.11 % and 30.91% respectively at 95% confidence level as shown in ANOVA Table (Figure 5b). Multiple linear regression model Eq-2 of H has been found to be significant because of higher R^2 value (98.52%) and p-value < 0.05. Model adequacy has also been checked through normal probability plot and pareto standardized effects and proved to be significant as revealed from Figure 6 (a-b). The residuals are distributed normally and lie on the straight line from the normal probability plot (Figure 6a) and thus found to be the goodness of the fit of the model developed. Also, pareto chart of the standardized effects (Figure 6b) of model reveals that cutting speed, feed and depth of cut have the highest statistically significant as it crosses the reference line of 2.571 with higher effect of cutting speed.

$$\text{Micro-hardness (H)} = 163.878 - 0.04\ v + 8\ f + 13.67\ d \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$
$$R^2 = 98.52\ \%,\ R^2\ (adj) = 97.64\ \%,\ p<0.05$$

The prediction error (%) for both noise emission and microhardness have been calculated for all 9 nuns with formula as [I (Experimental - Predicted) I / Experimental]x100. The prediction errors for both Ne and H are found to be in the range of 0.13-3.24 and 0.00-0.25 respectively with mean % of error for both Ne and H are 1.24 and 0.11 respectively which are well below 5% as shown in Table 2 and shows the reliability of the prediction model developed. Mult-response optimization of process parameters has been carried out through desirability approach and found to be v: 100.404 m/min, f: 0.05 mm/rev and d: 0.1 mm with composite desirability (D) of 0.7324 as shown in Figure **7** where values of Ne and H at optimal conditions are 71.67 dB (desirability, d=0.69897) and 161.628 HV (desirability, d=0.76739) respectively. The experimental verification at optimal settings has been carried out and the responses Ne and H are found to be 72.65dB and 161.2HV respectively. The percentage of error between experimental and optimal values are 1.34% and 0.26% respectively for both Ne and H which are less than 5% and thus found to be effective and reliable in the multi-response optimization process.

Table 1. Taguchi L_9 experimental design and responses.

Run	Input parameters			Responses	
	v, m/min	f, mm/rev	d, mm	Ne, dB	H, HV
1	60	0.05	0.1	68.3	163.5
2	60	0.1	0.2	72.7	164.9
3	60	0.15	0.3	77.05	167.0
4	110	0.05	0.2	73.75	162.2
5	110	0.1	0.3	79.5	164.4
6	110	0.15	0.1	77.56	161.7
7	160	0.05	0.3	78	162.0
8	160	0.1	0.1	78.96	160.0
9	160	0.15	0.2	78.6	161.4

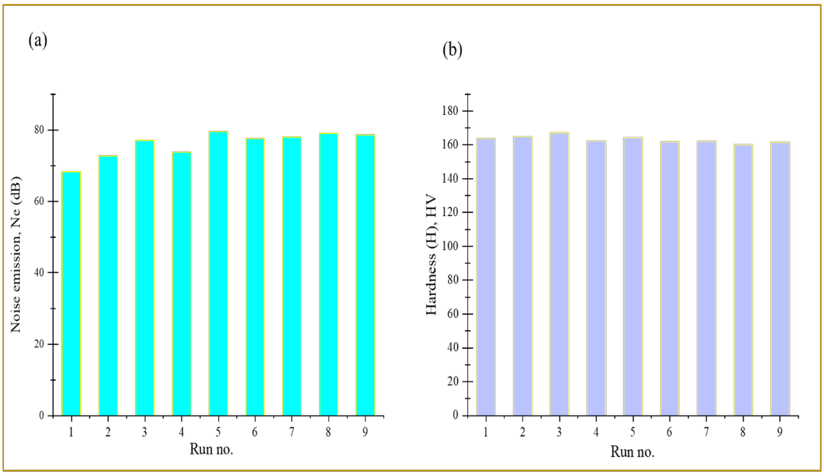


Fig. 2. Experimental outcomes with (a) Noise emission , and (b) Hardness.

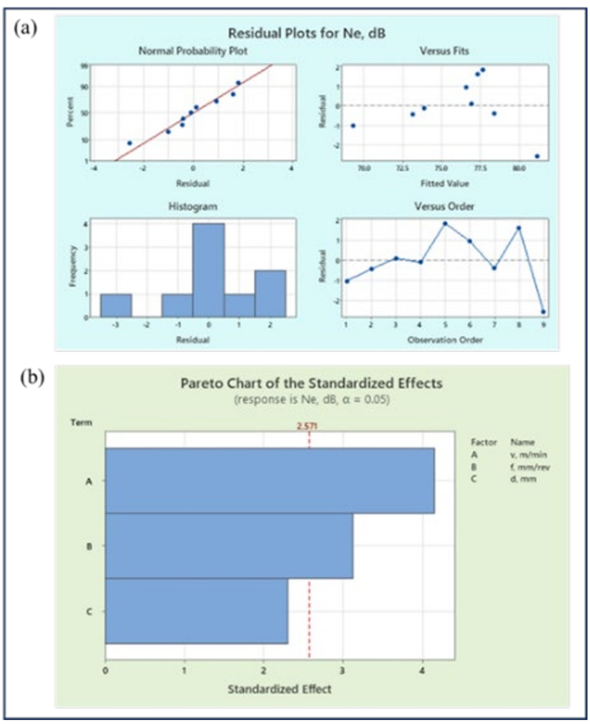
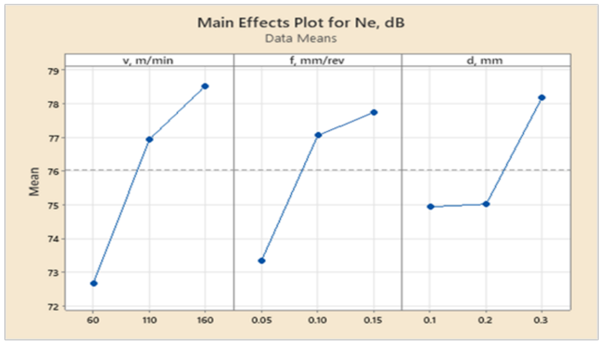


Fig. 3. (a) Main effects plot, and (b) ANOVA for noise emission for Ne.

(a)

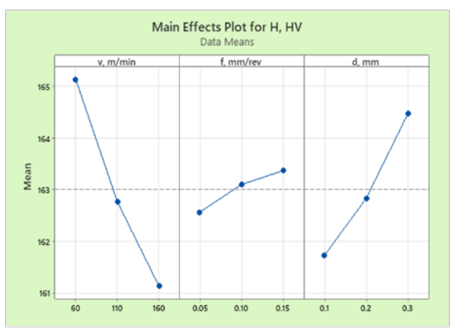


(b)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%age contribution
V (m/min)	2	54.664	27.3322	28.94	0.033	49.45
f (mm/rev)	2	33.424	16.7122	17.70	0.053	30.23
d (mm)	2	20.553	10.2764	10.88	0.084	18.57
Error	2	1.889	0.9444			
Total	8	110.531				

Fig. 4. (a) Residual tables and (b) Pareto chat of the standardised effects for Ne.

(a)



(b)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%age of Contribution
v, m/min	2	24.2689	12.1344	253.98	0.004	66.11
f, mm/rev	2	0.9956	0.4978	10.42	0.088	2.71
d, mm	2	11.3489	5.6744	118.77	0.008	30.91
Error	2	0.0956	0.0478			
Total	8	36.7089				

Fig. 5. (a) Main effects plot, and (b) ANOVA for noise emission for H.

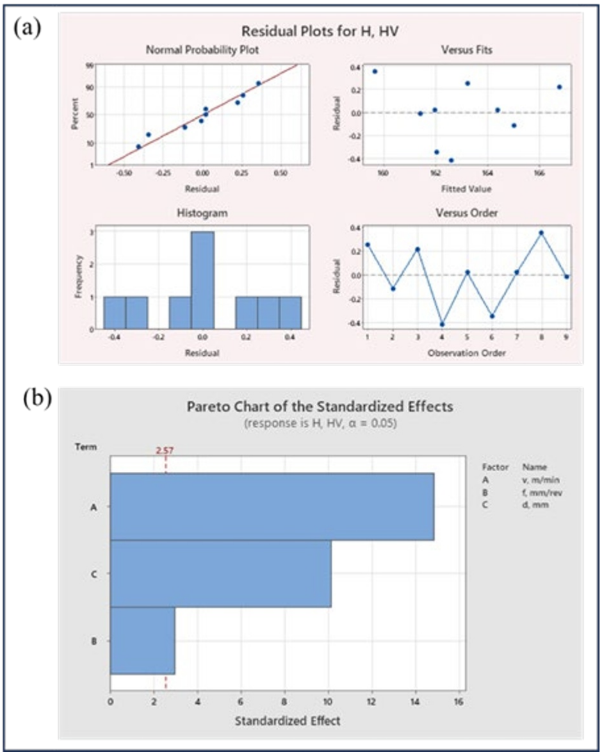


Fig. 6. (a) Residual tables and (b) Pareto chat of the standardised effects for H.

Table 2. Experimental vs predicted values and prediction error (%).

Run	**Responses (Experimental)**		**Responses (Predicted)**		**Prediction error (%)**	
	Ne, dB	H, HV	Ne, dB	H, HV	Ne, dB	H, HV
1	68.3	163.5	69.31	163.24	1.47	0.16
2	72.7	164.9	73.12	165.01	0.57	0.06
3	77.05	167.0	76.94	166.77	0.14	0.13
4	73.75	162.2	73.85	162.61	0.13	0.25
5	79.5	164.4	77.66	164.37	2.31	0.01
6	77.56	161.7	76.61	162.04	1.22	0.21
7	78	162.0	78.39	161.97	0.5	0.01
8	78.96	160.0	77.34	159.64	1.59	0.22
9	78.6	161.4	81.15	161.41	3.24	0.00
					Mean % of error = 1.24	Mean % of error = 0.11

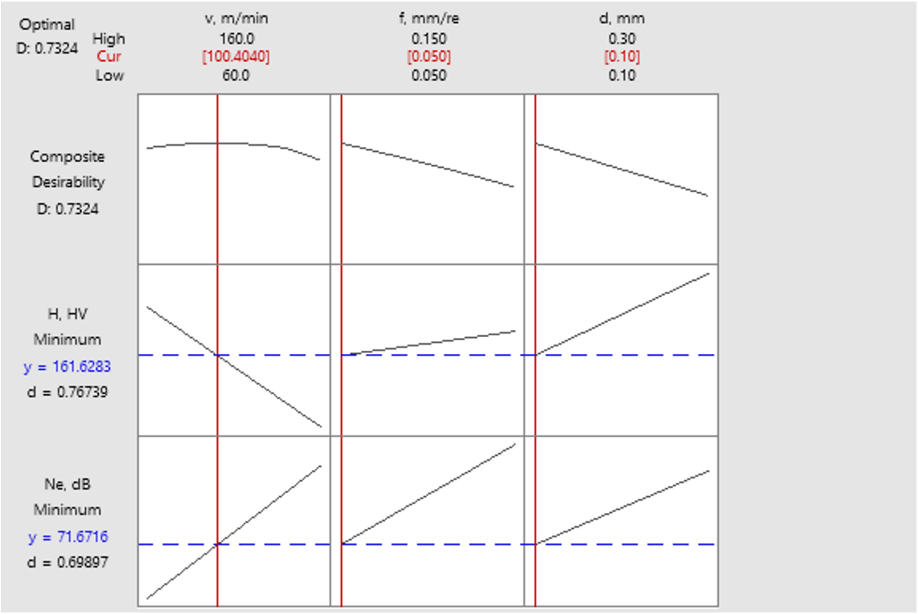


Fig. 7. Multi-response optimization through desirability approach.

4 Conclusions

From machinability assessment of Al7075/Ferrochrome metal matrix nanocomposite using uncoated carbide insert, following conclusions are made:

- From experimental investigation, noise emissions are in the range of 68.3dB-79.5dB which are within the acceptable limit of human hearing i.e. 85dB as per the National Institute for Occupational Safety and Health (NIOSH) and thus found to be environmentally sustainable as higher noise level can cause health issues in humans. It also induced lower micro-hardness values of 160-167HV respectively. Reduction of micro-hardness is noticed at higher cutting speed for ease of machining and may be attributed due to the formation of thinner chips and less chip reduction coefficients.
- Most significant parameter for noise emission during turning have been found to be the cutting speed with 49.45% contribution at 95% confidence level. Multiple linear regression model of Ne has been found to be significant because of higher R^2 value (86.62%) and p-value < 0.05. Also, pareto chart of the standardized effects reveals that cutting speed and feed have the highest statistically significant as it crosses the reference line of 2.571.
- Cutting speed and depth of cut influence on micro-hardness is higher with 66.11 % and 30.91% respectively. Multiple linear regression model of H has been found to be significant because of higher R^2 value (98.52%) and p-value < 0.05.
- The prediction errors for both Ne and H are found to be in the range of 0.13-3.24 and 0.00-0.25 respectively with mean % of error are 1.24 and 0.11 respectively which are below 5% for reliability of the prediction model developed.
- Mult-response optimization of process parameters has been carried out through desirability approach and found to be v: 100.404 m/min, f: 0.05 mm/rev, d: 0.1 mm with composite desirability (D) of 0.72324. The readings of Ne and H at optimal conditions are found to be 71.67 dB (desirability, d=0.69897) and 161.628 HV (desirability, d=0.76739) respectively. The percentage of error between experimental

and optimal values are 1.34% and 0.26% respectively for both Ne and H which are less than 5% and thus found to be effective and reliable in the multi-response optimization process.

- The research has shown the improvements in machinability characteristics in terms of noise emission and micro-hardness evolution and found its effectiveness with utilization of low-cost uncoated carbide insert during machining of nanocomposite and may be adopted towards sustainable manufacturing and consideration in industries.
- The temperature rise and hardness variation should be correlated to visualize the relationship and effect of cutting and environmental parameters to other machining responses such as tool wear, force and power, surface roughness and chip characteristics are also to be investigated in future for Al7075/Ferrochrome nanocomposite.

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