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Sustainable Machining of Fe-Al Mechanical Alloy using PCBN Tool Inserts

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Abstract:— **Ferro-Aluminium Mechanical Alloy (Fe-Al MA) is emerging as a popular choice in material selection for critical applications, owing to its favorable versatile attributes. But the metal in bulk form suffers from poor machinability resulting in expensive machining and lesser productivity. In the current work, this drawback is addressed through a sustainable solution obtained from a series of machining experiments to recognize the best suitable cutting parameters using PCBN tool inserts. It recommends that machining of Fe-Al specimen at optimum cutting parameters enhances tool-life significantly and marginally improves productivity and machining economy. Experimental validation of the process outcomes is further carried out to confirm the genuineness of the approach.**

Keywords:----- **Fe-Al Mechanical Alloy, PCBN tool inserts, cutting parameters, tool-life, productivity, machining economy.**

I. INTRODUCTION

Ferro-Aluminium Mechanical Alloy (Fe-Al MA) is an alloy of Aluminium and Steel, which is an emerging metal having potential for various product applications in automotive, aerospace, marine, defence and energy sectors. The alloy offers excellent strength-weight ratio (specific strength), superior resistance to corrosion, wear and thermal distortions [1]. These characteristics make the metal a right choice for making critical components. The conventional alloying process is not suitable in this case due to large variation in melting temperature of the constituents [2]. Hence Fe-Al bulk specimens are prepared in solid state diffusion process (similar to powder metallurgy technique) using ball milling process called mechanical alloying. The structural analysis has been carried out to assess the mechanical, metallurgical and thermal aspects of the alloy [3]. The initial machining test conducted on the metal depicts the poor machinability causing the rapid excessive tool-wear due to porous structure and brittle inter-metallic molecular bonding [4]. Blunting of the tool causes dimensional inaccuracy and surface cracks, which eventually result in excess process rejections [5]. This factor has prompted us to investigate the machining problems associated with the alloy and offer a sustainable solution. Preliminary study ascertains the significant influence of cutting parameters on the tool wear. Experiments are conducted at various input parameters using PCBN tool inserts on CNC Turn Station. After establishing tool wear / tool life pattern, cutting parameters are optimized at which minimum tool wear is observed for the same amount of metal removed. The usage of these optimum values in experiments yields the overall improvement in the machining performance on the subject alloy in terms of tool life, productivity and machining cost. The experiment is repeated with optimum values that validates the genuineness of the approach.

II. METHODOLOGY

Fe-Al specimens are prepared in the sleeve form and are pre-machined. Base line experiment is conducted to establish tool-wear criterion. Machining experiments at multiple levels of speed and feed are conducted on a CNC-Lathe work station using PCBN 450 tool insert under flooded cooling condition. During all the experiments, work quality is verified for compliance with specified tolerances. The flank wear images are captured at regular intervals and analyzed using vision image analyzer software for wear measurement. Using these wear values, experimental outcomes such as Tool-Life, Production Cost and Rate of Production (ROP) are evaluated. The cutting parameters are optimized graphically for maximum tool-life, minimum production cost and maximum ROP. The optimum values are experimentally validated to confirm the reliability of the optimization approach. The methodology is described in Fig.1.

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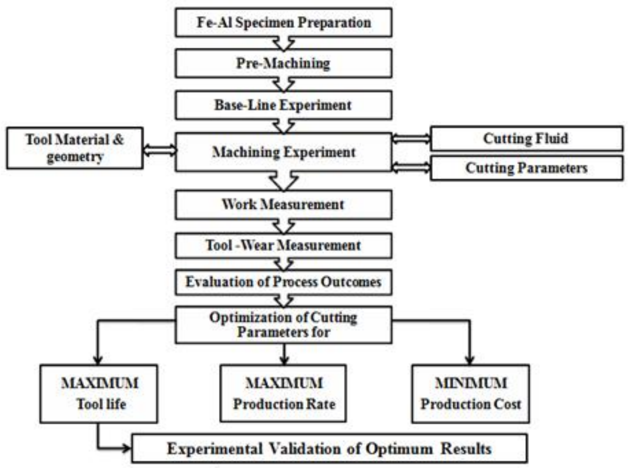

Fig.1. Flow chart of the overall methodology

III. EXPERIMENTATION

Fe-Al Specimen Preparation

Pure elemental Fe and Al powders with a nominal composition of Fe-50 at %-Al are milled in a planetary ball mill under controlled Argon atmosphere. The milling operation is performed at about 300 rpm for time ranging from 15 min to few hours. Hardened steels balls of diameter 20 mm are used (ball-to-powder weight ratio 50:1). The powders are compacted to sleeve form by application of 30 KN load followed by annealing at 1100^0 C for about an hour. The specimens are polished and then etched in Nital solution to remove any surface contamination. The micro structure morphology of a sample is characterized by Scanning Electron Microscope as shown in Fig 2. The structural properties of the work material are enlisted in Table I.

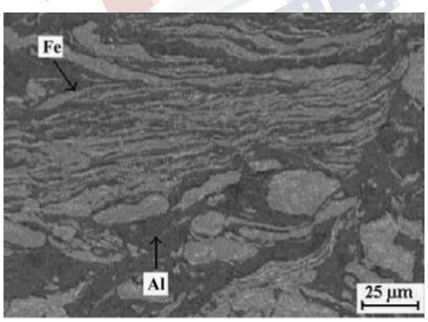

Fig 2 – Microstructure of Fe-Al specimen captured by Scanning Electron Microscope

Table I Mechanical Properties of Fe-50%-Al (Mechanical Alloy)

Relative Density (%)	Flexural Strength (MPa)	Strain at Break (%)	Micro Hardness (HV_{100g})
95.00	831.30	3.20	700

Machining Experiments

The Fe-Al (MA) specimens are pre-machined to required sizes in conventional process. The specimen is clamped to machine spindle using mandrel on PRAGA CNC-Turn Station equipped with SIEMENS control system. Sandvik PCBN 45^0 insert with holder is clamped in tool turret. Turning cycle part program with parametric values (speed, feed, incremental depth, number of passes, tool offsets) is selected for execution. Cutting fluid as per the recommendations is employed during cutting process. Initial progressive experiment (base line experiment) at high speed is conducted to establish the flank wear criterion at which the tool fails to produce the acceptable machining quality. Experiments are conducted at different levels of speed, feed and constant depth, which is described in Table II.

Table II Programmed Values of Cutting Parameters

Level / Parameter	1	2	3	4
Speed (rpm)	1800	1900	2100	2200
Feed (mm/rev)	0.041	0.043	0.047	0.050
Depth of Cut (mm)	0.5	0.5	0.5	0.5

Work Measurement

The work-piece is verified for machining quality in order to know the tool performance. Surface roughness is one of the tool performance indices that reflect the tool failure. Surface finish is compared using Mitutoyo Surface Roughness tester to ensure the process generated results are within the specified tolerances.

Tool Wear Measurement

As the turning process continues, the tool turret is brought to the home position at periodic intervals for tool-wear measurement. The tool is cleaned off and flank wear images of PCBN tool insert are captured using high resolution CCD camera (CANON ZR-320, 4.8 MP). The captured images are analyzed using CLEMEX-Vision Image Analyzer to measure the flank-wear dimensions to ascertain tool-failure as shown in Fig 3. The cutting tool is subjected to severe conditions at the rake and flank surfaces. The wear on the rake surface (Tool-Chip interface) is caused by the chip flow and is termed as Crater wear. It propagates depth wise and bears unreliable behaviour. For this reason, tool-life cannot be predicted precisely based upon crater wear. The flank wear (wear land) is steady, reliable and expands width-wise. Flank wear represents tool performance fairly well. Hence it is considered as Tool-wear Criterion in the current study.

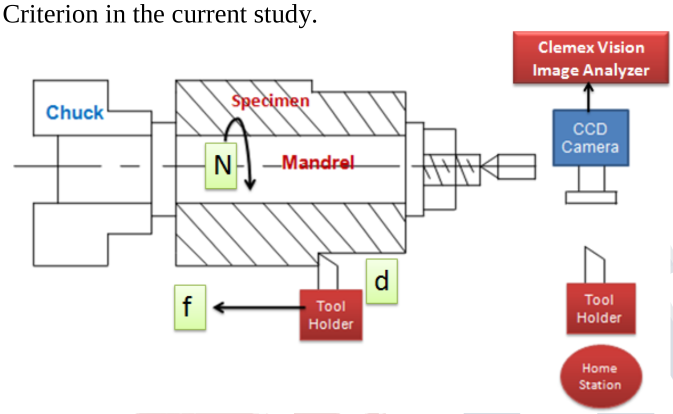

Fig 3 – Experimental Set-up showing Tool Flank Wear Measurement

Empirical Formulae

The following equations, Eq.(1) to Eq.(7) are used to calculate output parameters. T_m is the machining time (min). T_t is the tool time (min). T_{ch} is tool changing time (min). T is tool life (min). w_f is flank wear criterion (mm). k is wear rate coefficient. w_{20} and w_5 are wear sizes (mm) corresponding to 20 passes and 5 passes respectively. R.P is rate of production (pieces/hr.). C_o is cost of production (INR/piece). C_u is unit operating cost (INR/min)) and C_T is tool consumption cost (INR/edge). L is the machining length, f is the current feed rate and N is the current speed.

$$T_m = \frac{L}{fN} \quad (1)$$

$$k = \frac{w_{40} - w_{20}}{40 - 20} \quad (2)$$

$$T = w_f \times \frac{T_m}{k} \quad (3)$$

$$T_t = T_{ch} \times \frac{T_m}{T} \quad (4)$$

$$T_O = T_m + T_t \quad (5)$$

$$R.P = \frac{1}{T_O} \quad (6)$$

$$C_O = T_O \times C_U + C_T \times \frac{T_m}{T} \quad (7)$$

F. Optimization

Tool-wear rate drastically varies with respect to speed and feed employed in the cutting process. Lowest wear rate offers maximum tool-life, minimum tool consumption cost and minimum number of tool changes. Machining time is a function of speed and feed. Machining and tooling are the two important components in overall production cost and rate of production. Hence, optimization of cutting parameters becomes very important in the improvement of machining performance. There are several optimization techniques available and in the current study, graphical method using contour plots is employed to recognize the optimum values at which higher tool-life, lower cost and higher productivity would be achieved. This method also shows the reliability of the experimental results in the form of probability distribution charts.

IV. RESULTS AND DISCUSSION

The experimental findings are analyzed for optimum values of speed and feed using contour plots developed for tool-life, production cost and rate of production. The genuineness of these findings is verified by probability charts in terms of standard deviation with respect to mean values.

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As shown in Fig 4, the performance of the PCBN tool is better at peak values of speed and feed that indicates that the tool is considerably suitable in high speed and finish machining of the Fe-Al alloy. This phenomenon of PCBN tool proves that they are favorable in mass production of the subject metal components. Excessive tool-wear at lower values of speed-feed combination indicates the lesser suitability of tool in slow machining. Tool-life contour plot as shown in Fig 5(a) depicts the optimum speed range of 1883-1926 rpm and corresponding feed range of 0.04-0.05 mm/rev for a maximum tool life greater than 305 min. The results fall within the standard deviation of 49.68 in probability chart that confirms the reliability of findings, which is explained in Fig 5(b). Production cost contour plot as shown in Fig 6(a) predicts the optimum speed range of 2088-2200 rpm and feed range of 0.049-0.05 mm/rev for the minimum cost of less than Rs. 59.50/-. Corresponding probability plot (Fig 6(b)) certifies the correctness of findings as they fall within the standard deviation of 8.176. Rate of Production contour plot reveals the optimum speed range of 2184-2200 rpm and feed range of 0.048-0.05 mm/rev for maximum productivity greater than 54 pieces per hour as described in Fig 7(a). Standard deviation of 4.964 in the probability chart as shown in Fig 7(b) verifies the accuracy of the results.

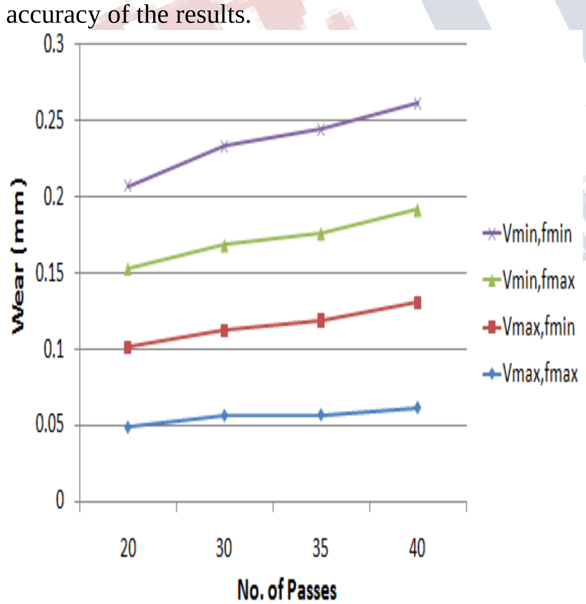
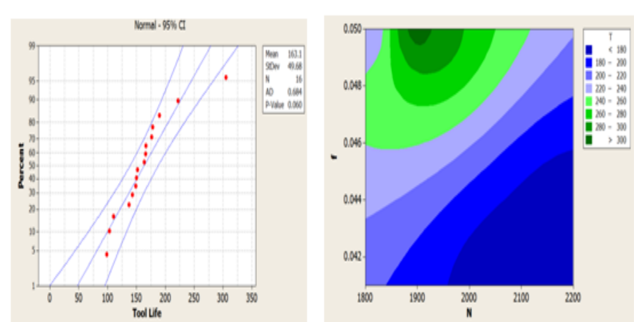


Fig.4. Progressive flank-wear for various speed-feed combinations

Table III Summary Of Results And Interpretations

Parameters	Experimental Outcomes		
	Tool Life (min)	**Production Cost (INR)**	**Production Rate (pieces/hr)**
Optimum Speed Range (rpm)	1883 - 1926	2088 - 2200	2184 – 2200
Optimum Feed Range (mm/rev)	0.04 – 0.05	0.048 – 0.05	0.048 – 0.05
Current Speed (rpm)	2000	2000	2000
Current Feed (mm/rev)	0.045	0.045	0.045
Predicted outcomes at optimum conditions	305	59.50	54
Outcomes at Current Values	230	64.5	48
Gain/Loss due to optimization	+75.00	+5.00	+6
% Gain/Loss	+32.6 %	+7.75 %	+12.34 %
% Influence of Speed	28 %	12 %	16 %
% Influence of Feed	72 %	88 %	84 %



(a) (b)

Fig.5. (a) Tool life Vs. Speed and Feed (b) Probability plot for Tool life

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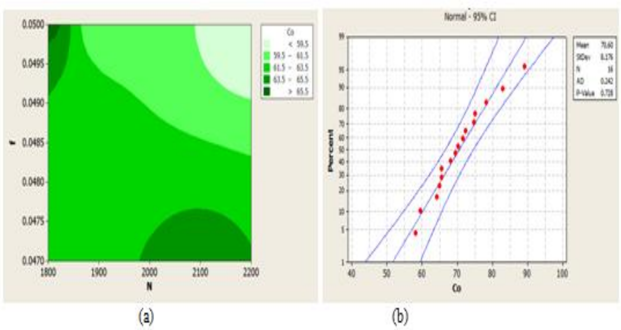

Fig.6. (a) Production Cost Vs. Speed and Feed (b) Probability plot for Production Cost

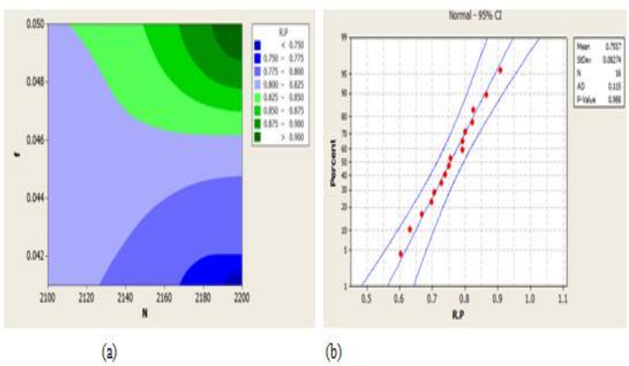

Fig.7. (a) Production Rate Vs. Speed and Feed (b) Probability plot for Production Rate

The above mentioned findings and interpretations are summarized in the Table III for the purpose of comparison of optimum values with that of the current values. The usage of optimum values offers an improvement in tool-life by 32.60%, reduction in production cost by 7.75% and increase in the rate of production by 12.34% when compared to results of the base line experiment.

V. EXPERIMENTAL VALIDATION

In order to confirm the reliability of the optimization approach, the experiment is re-conducted at optimum speed and feed. Tool wear is checked at time period of maximum predicted tool-life and verified with tool-wear criterion and found to be in line with the anticipations.

VI. CONCLUSION

The research work focuses on the cutting parameters to improve the machining of Fe-Al Mechanical Alloy using PCBN 450 without foregoing the quality of machining. Factor of Safety of 15% is taken on the tool wear criterion to prevent the process rejections. In mass production, it is demand/supply ratio that influences the decision making whether to opt for economical plan or productivity plan. In lean situation, economical plan is preferred by adopting minimum cost strategy. In peak demand situation, productivity plan is recommended and maximum rate of production is implemented to attain a balance between demand and supply. Associate benefits of the research work are summarized as follows.

- Sustainable solution to address the process related issues.
- Declined process rejections.
- Improved utilization of manufacturing facilities.
- Minimum effort with no additional cost is demonstrated in this approach.
- The current methodology acts as a model in similar functional domain of research.
- Optimization of other parameters such as tool grades, geometry and coatings can be attempted in the similar lines.
- Optimization of "Machine-Tool-Work-Operation" in the combined state can be innovated for the given situation using various techniques like Artificial Neural Networks, Genetic Algorithm and Swarm Optimization.

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