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OPTIMIZATION OF MACHINING PARAMETERS IN THE DRY MILLING OF NI-BASED VAT 32® SUPERALLOY WITH TIALN-TIN COATED CARBIDE INSERTS

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Abstract. *The variation of cutting parameters is studied to optimize the milling of the VAT 32® nickel superalloy. The VAT 32® can be applied in the manufacturing of diesel engines valves presenting superior wear resistance associated with lower production costs, however, several problems are faced during the alloy machining process leading to high energy consumption and increase of forces. To optimize the output variables of the process, this work considered the main responses of the process based on the results of power consumption and acoustic emission. To evaluate the main effects during machining it was applied the analysis of variance (ANOVA) and normality tests conducted according the design of experiments of Full-Factorial methodology. Results obtained reveal that it was possible to accomplish the VAT 32® superalloy machining through milling within standard surface quality ranges with reduction of forces to a range of optimized parameters. The coated carbide tools presented a superior performance to machine the VAT 32® by milling, being the best condition that minimizes the power consumption found for the cutting speed of 60m/min and feed of 0.10 mm/t associated with low transient peaks of acoustic emission.*

Keywords: *ANOVA, Power Consumption, Acoustic Emission, Milling, Nickel Superalloy.*

1. INTRODUCTION

Nickel based superalloys present resistance to a wide variety of corrosive environments, typically encountered in various industrial processes, such as in chemical processing, petrochemical processing, aerospace engineering, power generation and energy conversion and thermal processing (Shea, 2005). Superalloys are also designed to provide higher mechanical strength (up to 1200 MPa) and resistance to corrosion and oxidation if compared to steels. As well as combining resistance to fatigue and creep, with ductility and rigidity at high temperatures (above 540°C) (Choudhury; Elbaradie, 1998).

The property requirements will vary and are different for various industries, but the important mechanical properties in the development and characterization of super alloys are: creep resistance, resistance to thermal and mechanical fatigue, structural stability, and resistance to corrosion and hot oxidation (Moura Neto, 2009). However, the superalloy's manufacturing industry is facing serious challenges to incorporate the required modifications caused by the market's environmental standards (Farina *et al.*, 2013) associated with the several difficulties observed during the machining process caused by its chemical composition and microstructure.

In order to attend to a more restrict series of environmental regulations (i.g. EURO V and VI) to materials applied for the manufacture of automotive engine components, Farina *et al.* (2013) developed a new nickel intermediate superalloy for application in automotive high performance valves, designated as VAT 32®. The new developed superalloy was developed as an alternative to the traditionally applied superalloy UNS N07751, showing several advantages combined with similar to better properties than the UNS N07751 alloy, including an important economic-environmental advantage marked by the reduction of nickel content in the total chemical composition. Table 1 presents the nominal chemical composition of the VAT 32® superalloy.

Table 1. Nominal chemical composition of the VAT 32® superalloy (Farina *et al.*, 2013).

Alloy	C	Si	Mn	Ni	Nb	Al	Ti	Cr	Fe
VAT 32®	0.30	0.20	0.30	32	3.90	1.80	2.0	15.50	44
UNS N07751	0.02	0.20	0.30	72.48	1.0	1.20	2.30	15.5	7.0

The study of machinability and cutting forces during the milling of this material will directly contribute to the current industrial scenario, where there is a scarcity of works on machining of nickel-based super alloys, as pointed out by Davoodi and Eskandari (2015). Moreover, the study of forces by analysis of the power consumption and acoustic emission can contribute to describe the machinability of the new nickel alloy, allowing the in-deep knowledge of its behavior during the cutting process. The power consumption analysis during machining processes allow the evaluation of cutting conditions that represent less energy demand, allowing the possibility of cost and energy reduction (Gonçalves *et al*., 2010). Reducing energy usage is an essential consideration in sustainable manufacturing. In the past, metal cutting operations have been mainly optimized based on economic and technological considerations without the environmental dimension. It is essential to improve production rate and cutting quality while simultaneously mitigating the effect of manufacture on the environment (Yan; Li, 2013). In addition, the study of forces during machining is essential to provide the better understanding of the material machinability. The evaluation of forces according to the cutting direction, that is, the cutting force allows a direct correlation to the power, since it is the main responsible aspect for the power consumption. It is know that higher machining forces are observed when machining superalloys than commercially pure iron. According to Marques (2015), the cutting forces tends to decrease as the cutting speed increases, as the chip-tool contact area becomes smaller and the chip thinner. However, for all cutting speeds, forces are relatively high for machining nickel superalloys, promoting high tool wear rates and increasing the difficulties to understand the process. The monitoring of power consumption and analysis is a very efficient alternative that not only complement and describe the study the forces during the cut, but also allows the comparison of different materials, tools and cutting fluids in the various machining operations.

As considering the analysis of acoustic emission during machining can help to detect and correlate wear, damages and other phenomena that can occur during machining processes, helping to identify the material's machinability response.

In this work, the study of power and acoustic emission allowed a better understanding of the machining process, providing the resulting tendencies of the output variables of the process allowing to evaluate the machinability of the VAT 32® superalloy.

2. MATERIALS AND METHODOLOGY

The machining experiments were performed on a 5 Axis CNC Machining Center (model DMU50ECO, DMG Ecoline, Germany) with spindle power of 9 kW and maximum spindle speed of 8000 rpm. The experiments were performed through a series of consecutive tests. Beginning by a preliminary test phase where the best cutting parameters were selected considering the supplier recommendation and previews studies of the coated carbide tools application. Then, the definitive testing phase was executed with selected parameters.

The milling tests were conducted without any application of cutting fluids. The VAT 32® specimen (workpiece) dimension was 59x85x30 mm. The workpiece was submitted to machining tests as provided, without any application of further heat treatments that were not included in the alloy's fabrication process. The VAT 32® billet was provided by the Villares Metals.

The cutting tools applied were TiAlN-TiN coated carbide inserts (Figure 1) from Seco Tools Company with code-key RNMG120400-MR4, according the ISO 1832:2012 standard. Both coating layers were deposed by the physical vapor deposition process and are ideal for roughing and semi-finishing applications in superalloys, according to the supplier. The inserts specifications were 12 mm diameter, 4,76 mm thickness, 0° side clearance angle and since this work considers the application of round inserts to machine by frontal milling and the position angle changes during the cut, the maximum major cutting edge angle was consider at 23°. To the inserts fixation it was used a modular milling cutter system, with a holder code SECO-EPB-E3476 5820 1260, according the DIN 69871 standard; and a milling cutter code R220.26-0050-RN1204.6A with a 50 mm diameter. Three inserts were placed in the milling cutter (number of teeth) to the machining tests.

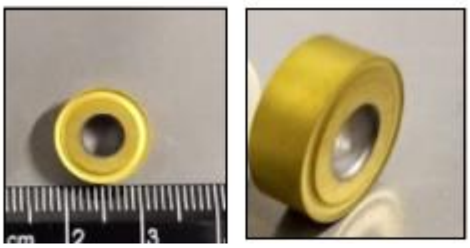

Figure 1. TiAlN-TiN coated carbide inserts.

To the power consumption and acoustic emission acquisition during machining, it was applied an acquisition system assembled to the machining center. The data acquisition system allowed the real-time capture of data of cutting power, acoustic emission and vibration signals during the tests. The system was composed of a shielded connector block (National Instruments, model BNC-2120, USA) cable coupled to the PCI (National Instruments, model NI 6220, USA) connected to a computer machine.

All variations in the studied physical variables were captured in an acquisition rate of 4000 Hz, where any variation was converted into proportional electrical signals by the sensors and transducers. To the power consumption, it was used an AC Current Transducer AT-B10 (brand LEM, model AT100B10, China) connected to the machining center engine. To the acoustic emission, it was used a narrow band resonant sensor (Physical Acoustic Corporation, model R15α, USA) coupled to a pre-amplifier (Physical Acoustic Corporation, model 1272-1000, USA) with a RMS output to the connector block.

The design of the machining experiments was a 3-levels full factorial design, with 2 factors. The first factor, was the applied cutting speed (v_c) with three levels (60; 80 and 100 m/min. The second factor was the feed (*fz*) with three levels (0.1; 0.15 and 0.20 mm/t). In this work, it was considered the variation of feed per tooth, designated as “feed”, given in mm per tooth (mm/t). The axial depth of (a_p) cut was maintained constant at 0.5 mm. The radial depth of cut was 29.9 mm. The full factorial allowed the investigation of all possible effects of all the factors and their interactions on each response variable, fact that would not be possible in other designs. In total, 9 experiments were conducted with one repetition, summarizing 18 experiments.

Table 2. Machining Parameters.

Factors	**Level 1**	**Level 2**	**Level 3**
Cutting Speed v_c [m/min]	60	80	100
Feed *fz* [mm/t]	0.10	0.15	0.20

3. RESULTS AND DISCUSSION

This section covers the analysis of power consumption and acoustic emission results acquired during the milling machining tests. The main findings and the ANOVA statistical analysis were discussed.

3.1 Power Consumption

At first, the Anderson-Darling normality test was applied to the power consumption data obtained during the machining experiments. The obtained P-value of 0.896 was greater than the level of significance of 5% (0.05), what indicates that to a 95% confidence interval, the data obtained can be considered as part of a normal population.

To ensure the normality tendency it was applied the Ryan-Joiner normality test that revealed a correlation coefficient of 0.990, supporting high normal distribution tendency of results. The Ryan-Joiner test assesses the strength of the correlation between the power data and the normal scores of the obtained data, as the coefficient is close to 1, strong normality tendency is verified. Figure 2 shows the normality results to both tests applied.

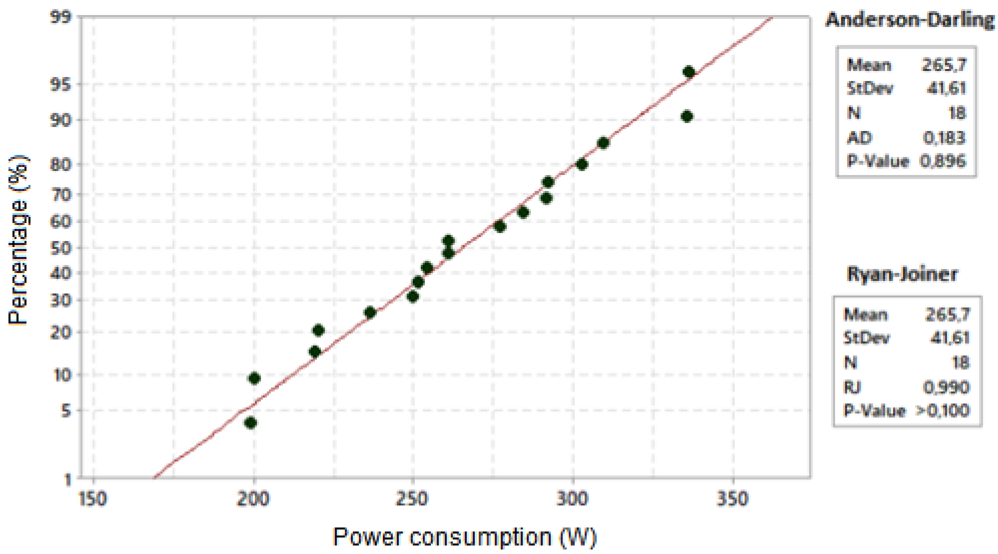

Figure 2. Normality test to power consumption.

Since the normality of results was proven, the analysis of variance was applied to the Power consumption data. ANOVA results are displayed in Table 3.

Table 3. ANOVA to power consumption results using the TiAlN-TiN carbide tools.

Source	***DF***	***Seq SS***	***Contribution***	***Adj SS***	***Adj MS***	***F-value***	***P-value***
Cutting Speed "v_c" (m/min)	2	22386.3	76.06%	22386.3	11193.1	52.22	0.000
Feed "f_z" (mm/t)	2	4258.6	14.47%	4258.6	2129.3	9.93	0.002
Error	13	2786.7	9.47%	2786.7	214.4		
Lack-of-fit	4	835.6	2.84%	835.6	208.9	0.96	0.472
Pure Error	9	1951.1	6.63%	1951.1	216.8		
Total	17	29431.5	100.00%				
			R-Sq = 90.53%		R-Sq (adj) =87.62%		

The analysis of variance indicated that the cutting speed and the feed factors were significant to a 95% confidence level (α=5%). That means, that the cutting speed and feed had significant influence the power consumption during the machining. Both P-values of 0.000 and 0.002 are below the set significance level of 5%.

Moreover, it is possible to affirm that between the two parameters, the speed factor had greater influence in the power results, if compared to the feed factor. The F-value of 52.22 denotes a strong relevance of v_c in the power, since the F-value estimate the correlation of the variation between the power means to the variation within all power data. Therefore, the cutting speed also exerts greater contribution, of almost 77% to all power data, while the feed have a contribution of approximately 15%, close to the error contribution of 9.47%.

To evaluate the variation within the factors, the main effects plot exhibit the tendency of influence of the levels into the power results (Figure 3), this analysis is also known as ANOM (Analysis of means). The center line in the main effects plot represents the obtained average power value of 227.56 W. As was stated in the ANOVA table, there is a strong dependence of cutting speeds levels. It is observed a constant increase in the power with the increase of applied cutting speed. The application of higher cutting speeds (100m/min) lead to an increase of 100 W in power.

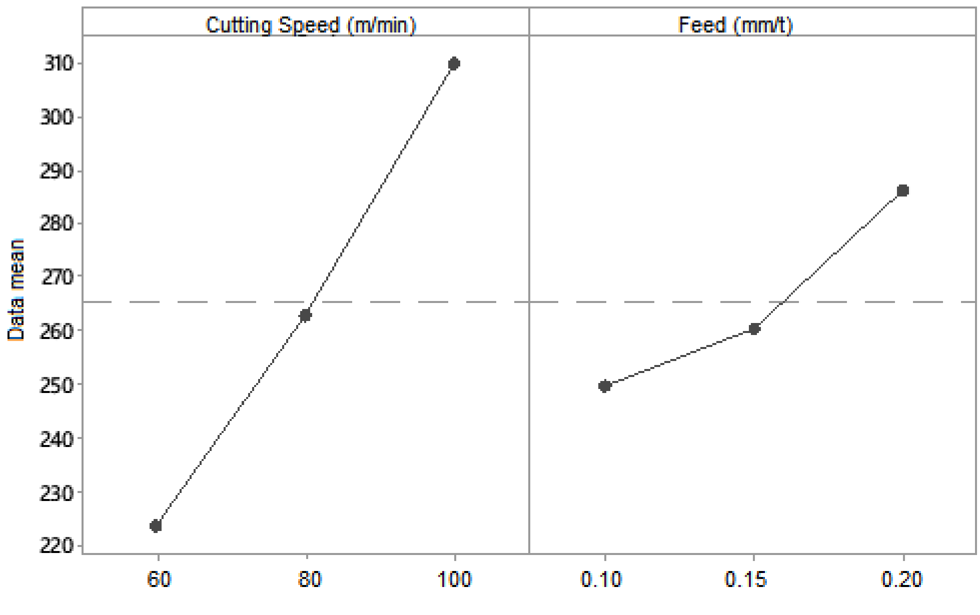

Figure 3. Main Effects Plot of power consumption using the TiAlN-TiN coated carbide tools.

To the feed factor, there is the same increase tendency in power results, but with a lower variation of 40W between the lowest and highest feed. The increase in the power results can be explained due to the increase in the feed generates an increase the cutting area of the primary and secondary shear planes, increasing the cutting force and consequently the power.

The interaction between the factors can be evaluated by the interaction plot (Figure 4). As the lines with the different machining conditions are almost parallels, it can be affirmed that the interaction between the two factors is weak. However, to the 60 and 80 m/min speeds is possible to notice a tendency of interaction between the cutting speed and feed by extrapolation.

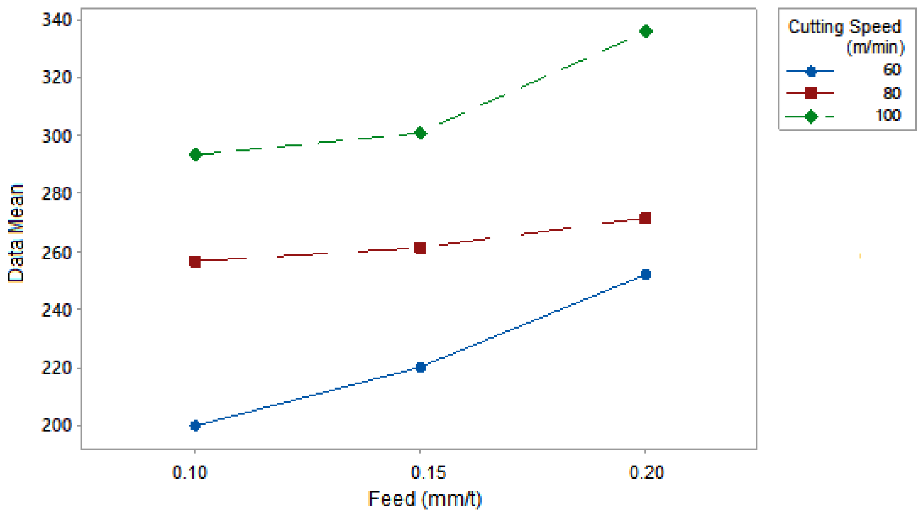

Figure 4. Interaction Plot of Power Consumption using the TiAlN-TiN coated carbide tools.

Therefore, according to the statistical analyzes carried out, the best machining condition that allow obtaining lower values of power consumption is v_c of 60 m/min and f_z of 0.10 mm/t. This condition, consequently allows a lower energy consumption for the machining using the TiAlN-TiN coated carbide tools.

3.2 Acoustic Emission

To the AE results, the Anderson-Darling normality test assured normal data distribution with a P-value of 0.425. After the ANOVA, it was possible to observe that the parameters presented no statistical influence to the Acoustic Emission output, considering 95% of reliability.

However, the obtained F-value of the feed factor presented a contribution close to 21% to the acoustic emission data that can be stated as relevant, and therefore must be consider to evaluate the factors contribution and impact to the AE results. Even though the contribution of the total error was higher than the factors contribution, the feed relevance (F-value of 1.80) was stronger than the lack-of-fit (F-value of 1.37) allowing to support the relevance of this factor analysis.

Table 4. ANOVA to acoustic emission results using the TiAlN-TiN carbide tools.

Source	***DF***	***Seq SS***	***Contribution***	***Adj SS***	***Adj MS***	***F-value***	***P-value***
Cutting Speed "v_c" (m/min)	2	0.000021	3.70%	0.000021	0.000010	0.32	0.732
Feed "f_z" (mm/t)	2	0.000116	20.92%	0.000116	0.000058	1.80	0.203
Error	13	0.000418	75.38%	0.000418	0.000032		
Lack-of-fit	4	0.000158	28.50%	0.000158	0.000039	1.37	0.319
Pure Error	9	0.000260	46.87%	0.000260	0.000029		
Total	17	0.000554	100.00%				
			R-Sq = 24.62%		R-sq (adj) = 1.43%		

In the main effects plot to the acoustic emission is possible to qualitative analyze the results through AE continuous and transient signals and tendencies observed to the variation of machining parameters. In Figure 5 a tendency of higher AE results can be seen to the 80 m/min speed with feed of 0.15 mm/t.

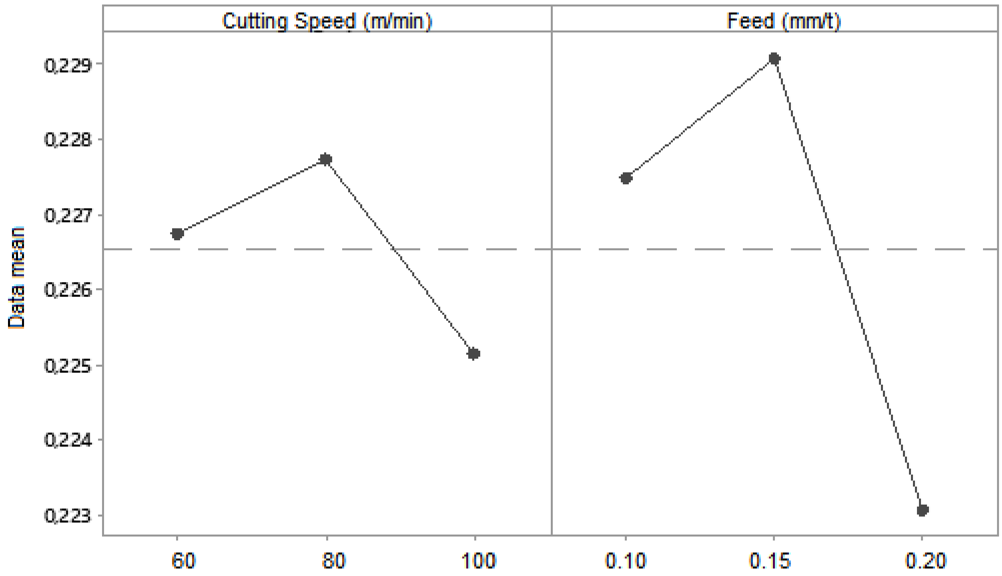

Figure 5. Main Effects Plot of AE using the TiAlN-TiN coated carbide tools.

From the main effects plot, the best condition to achieve low AE signals is to apply v_c=100 m/min and f_z=0.20 mm/t. It is observed an increase of the acoustic emission to the application of the 0.15 mm/t indicating that this condition favors the transient signals occurrence and therefore must be avoided. The AE data was lower to the application of 0.10 mm/t and 0.20 mm/t feeds, indicating that its application represents the condition with adequate amount of material being removed, avoiding the tool damage. It is important to note that the difference in results to the application of the two better conditions to AE of 60 or 100 m/min cutting speeds is close to 0.001, favoring the final selection according the power consumption preferences since the cutting speed of 60 m/min and 0.10 mm/t feed presented the decrease tendency of AE results, consisting of a more stable condition during machining.

4. CONCLUSION

To the TiAlN-TiN coated carbide inserts application, the condition of cutting speed of 60 m/min and feed of 0.10 mm/t presented the best results regarding the reduction of machining forces validated by the low power consumption and consistent acoustic emission results, presenting not only the reduction of transient signals but lower energy usage. Considering that the acoustic emission can be caused by any plastic and elastic deformations, for both of the workpiece and of the cutting tool, as well as friction or fracture during wear, is recommend the cutting condition of cutting speed of 60 m/min, this condition reduces the occurrence of damage phenomena, being responsible to more stable machining assuring best energy consumption. The tendencies observed with the statistical analysis application of main effect plots also allowed to estimate the best feed per tooth of 0.10 mm/t, where the forces during machining have a tendency to cancel or demote the self-inducted chatter characteristic presented by the superalloy leading to lower power consumption and providing the reduction of acoustic emission transient signals.

Finally, the feasibility to machine the VAT 32® superalloy with TiAlN-TiN coated carbide inserts was proven due to the association of lower power consumption and acoustic emission.

5. ACKNOWLEDGEMENTS

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