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# Development of Mathematical Model for Chip Serration Frequency in Turning of Stainless Steel 304 using RSM

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**Abstract.** Chatter is defined as the self-excited violent relative dynamic motion between the cutting tool and work piece. Chatter is detrimental to all machining operations. In metal turning operations it leads to inferior surface topography, reduced productivity, and shortened tool life. Avoidance of chatter has mostly been through reliance on heuristics such as: limiting material removal rates (to stay within the dynamic stability boundary) or selecting low spindle speeds and shallow depth of cuts. However, the correct understanding of the mechanism of chatter formation in metal cutting reveals that chip morphology and segmentation play a predominant role in chatter formation during machining. Chatter is found to appear as a resonance phenomenon when the frequency of chip serration is equal to or integer multiple of the prominent natural frequency/frequencies of the system component(s). Hence, it is important to study the chip serration frequency. At lower cutting speeds the chip is often discontinuous, while it becomes serrated as the cutting speed is increased. It has been identified that the chip formation process at higher speeds also has a discrete nature, associated with the periodic shearing process of the chip. In this paper a statistical technique is proposed to predict the frequency of chip serration as a function of cutting parameters for two different tool overhang values in turning of stainless steel AISI 304 using Response Surface Methodology (RSM).

## Introduction

In manufacturing industries, chatter formation during the machining operations plays a predominant role in determining machinability, since the metal removal rate and hence, productivity is influenced by chatter. Earlier studies indicate that chip formation instability is mainly responsible for chatter formation. Due to its importance, the chip segmentation phenomenon has been extensively investigated worldwide. Attempts to describe the chip morphology in cutting titanium and other difficult to cut materials date back to the work performed by Cook in 1953 [1]. He investigated the chip morphology of titanium at different cutting speeds and proposed a thermodynamic theory for chip formation. Nakayama et al. [2] and Shaw et al. [3] proposed the periodic crack formation theory in machining hard steel. Other early investigations into chip segmentation in the cutting of titanium alloys were performed by Lee [4] and Gente et al. [5] proposed the well-known ‘catastrophic shear band’ theory. Amin [6] determined the frequency of the primary and secondary serrated teeth formation and found that chip serration frequency was responsible for the chatter formation in machining. In this paper a mathematical model was developed to predict the chip serration frequency in terms of the cutting parameters (cutting speed, feed, and axial depth of cut) using RSM for two different tool overhang values for turning of stainless steel AISI 304.

## Experimental Procedure

The main thrust of the experiments was on determining the chip serration frequency and morphology during turning operations for 70 and 120 mm tool overhangs. Scanning Electron Microscope (SEM) was used in studying chip morphology and serration frequency. Turning operation was carried out on a conventional lathe machine (Harrison M390, England) with rated power of 5.5 kW and maximum spindle speed of 2000 rpm. M type TiN-coated cemented tungsten carbide inserts were used to machine a stainless steel (304) cylinder. Levels of independent and coding identification are presented in Table 1.

Table 1: Coding identification for turning operation using TiN-coated cemented carbide inserts

| Levels<br>Coding | Lowest<br>- 1.4142 | Low<br>-1 | Centre<br>0 | High<br>+1 | Highest<br>+1.4142 |
|---|---|---|---|---|---|
| Cutting Speed (m/min) | 18.93 | 50 | 125 | 200 | 231 |
| Feed (mm/rot) | 0.08 | 0.1 | 0.16 | 0.22 | 0.24 |
| Depth of cut (mm) | 0.8 | 1 | 1.5 | 2 | 2.21 |

The frequency of the serrated teeth, *fc* was calculated from the length of the chip fragment in the SEM pictures, *L*; the coefficient of chip shrinkage, *K* (determined by dividing the uncut chip length by the actual chip length); cutting speed, *V* m/min; and the number of secondary serrated teeth, *n*, observed on the SEM picture.

**Result and Discussion**

In this work, a small central composite design with (α = 1.4142) was employed to develop the chip serration frequency models. The analyses of the mathematical models were carried out using Design-expert 6.0.8 package. Cutting conditions in coded factors and the chip serration values obtained using two different overhangs are presented in Table 2.

Table 2: Chip serration frequencies and cutting parameters in coded forms

| Run No | Cutting Speed (m/min) | Feed (mm/rot) | Depth of Cut (mm) | Chip Frequency (70mm ) | Chip Frequency (120mm) |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 12626.66 | 11215.67 |
| 2 | 0 | 0 | 0 | 12144.07 | 11459.44 |
| 3 | 0 | 0 | 0 | 10773.3 | 10253.12 |
| 4 | 0 | 0 | 0 | 11614.62 | 11207 |
| 5 | 0 | 0 | 0 | 11904.76 | 10969.65 |
| 6 | 1.41421 | 0 | 0 | 29116.03 | 28564.83 |
| 7 | -1.41421 | 0 | 0 | 10537.26 | 2082.96 |
| 8 | 0 | 1.41421 | 0 | 9531.17 | 5163.52 |
| 9 | 0 | -1.41421 | 0 | 16811.35 | 16218.84 |
| 10 | 0 | 0 | 1.41421 | 12835 | 9935.3 |
| 11 | 0 | 0 | -1.41421 | 18371.54 | 16016.46 |
| 12 | 1 | 1 | -1 | 23667.87 | 23313.18 |
| 13 | -1 | 1 | 1 | 2143.15 | 2047.71 |
| 14 | -1 | -1 | -1 | 19794.69 | 9845.44 |
| 15 | 1 | -1 | 1 | 28601.64 | 27512.48 |

For both cases, Fit and Summary tests suggested that the second order model was the most significant model for predicting the chip serration frequencies in turning of stainless steel. The analysis of variance (ANOVA) was used to check the adequacy of the developed model. From the ANOVA analysis for 70 mm overhang (Table 3, below) the "Model F-Value" of 219.56 implied that the model was significant. The Lack of Fit value of 0.0774 implied that the LOF was not significant relative to pure error. ANOVA analysis for 120 mm tool overhang is shown in Table 4. The "Model F-Value" of 533.44 implied that the model is significant. The Lack of Fit value of 0.728 implied that the LOF was not significant relative to pure error.

Table 3: ANOVA analysis for chip serration frequency (a) 70 mm and (b) 120 mm overhang

| Source | Sum of Squares | DF | Mean Square | Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 7.66E+08 | 9 | 85067485 | 219.5638 | < 0.0001 | Significant |
| A | 1.73E+08 | 1 | 1.73E+08 | 445.4522 | < 0.0001 | |
| B | 2.65E+07 | 1 | 2.65E+07 | 68.39927 | 0.0004 | |
| C | 1.53E+07 | 1 | 1.53E+07 | 39.55889 | 0.0015 | |
| A2 | 1.26E+08 | 1 | 1.26E+08 | 326.2416 | < 0.0001 | |
| B2 | 4.00E+06 | 1 | 4.00E+06 | 10.32604 | 0.0236 | |
| C2 | 2.89E+07 | 1 | 2.89E+07 | 74.63995 | 0.0003 | |
| AB | 2.98E+06 | 1 | 2.98E+06 | 7.708243 | 0.0391 | |
| AC | 1.88E+07 | 1 | 1.88E+07 | 48.72831 | 0.0009 | |
| BC | 2.05E+06 | 1 | 2.05E+06 | 5.31112 | 0.0694 | |
| Residual | 1.93E+07 | 5 | 387438.5 | | | |
| Lack of Fit | 36792.48 | 1 | 36792.48 | 0.077442 | 0.7946 | Not Significant |
| Pure Error | 1.90E+07 | 4 | 475100 | | | |
| Cor Total | 7.68E+08 | 14 | | | | |

| Source | Sum of Squares | DF | Mean Square | Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 8.31E+08 | 8 | 1.04E+08 | 533.4433 | < 0.0001 | Significant |
| A | 2.31E+08 | 1 | 2.31E+08 | 1184.3 | < 0.0001 | |
| B | 6.11E+07 | 1 | 6.11E+07 | 313.6608 | < 0.0001 | |
| C | 1.84E+07 | 1 | 1.84E+07 | 94.90532 | < 0.0001 | |
| A2 | 9.56E+07 | 1 | 9.56E+07 | 490.8168 | < 0.0001 | |
| C2 | 9.25E+06 | 1 | 9.25E+06 | 47.49465 | 0.0005 | |
| AB | 3.12E+06 | 1 | 3.12E+06 | 16.05021 | 0.0071 | |
| AC | 1.65E+06 | 1 | 1.65E+06 | 8.48939 | 0.0269 | |
| BC | 9.14E+06 | 1 | 9.14E+06 | 46.92991 | 0.0005 | |
| Residual | 1.16E+06 | 6 | 194828.4 | | | |
| Lack of Fit | 311972 | 2 | 155986 | 0.728057 | 0.5375 | Not Significant |
| Pure Error | 856998.6 | 4 | 214249.6 | | | |
| Cor Total | 8.33E+08 | 14 | | | | |

Therefore, the second order of chip serration frequency for both cases:

$$f_{c(70mm)} = 11789 + 6568x_1 - 2573x_2 - 1957x_3 + 4047x_1^2 + 720x_2^2 + 1936x_3^2 + 1221x_1x_2 + 3072x_1x_3 - 1014x_2x_3 \quad (1)$$

$$f_{c(120mm)} = 10926 + 7594x_1 - 3908x_2 - 2150x_3 + 3518x_1^2 + 1094x_3^2 - 1250x_1x_2 - 909x_1x_3 - 2138x_2x_3 \quad (2)$$

Equations 1 and 2 above are in the coded form where $x_1$ is cutting speed, $x_2$ is feed, and $x_3$ is depth of cut. Both of the quadratic models showed that cutting speed had most significant effects on chip frequency. The interaction for both cutting parameter are shown in perturbation plot in Figure 1.

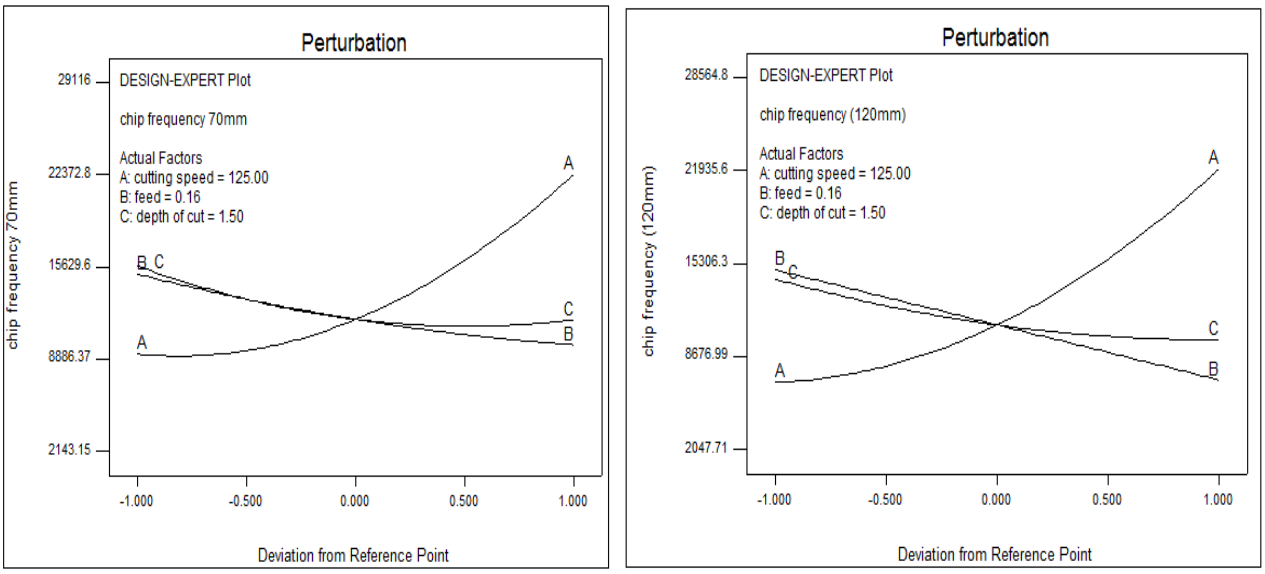


Fig. 1: Perturbation plots for vibration amplitudes for 70 mm (left) and 120 mm (right) overhang

Figure 1 shows the perturbation plots for three cutting parameter for 70 mm and 120 mm overhang. For both the cases it was clear that cutting speed (A) had the most significant effect on chip serration frequency. With the increase of cutting speed (A), chip serration frequency increases. However, it is observed that the effects for feed (B) and depth of cut (C) are less significant on the same frequency. With decrease in feed and depth of cut, chip frequency tends to decrease.

## Conclusion

The general conclusions are summarized below:

1) Central Composite Design (CCD) of experiments was used for generating the chip serration frequency in turning stainless steel AISI 304. Based on the experimental values of chip serration frequency quadratic models of the frequency were developed in terms of the machining parameters for two different tool overhang values using RSM. The equations were checked for adequacy with a confidence level of 95% and found to be significant with non significant lack of fit, which suggested that the models can be used for predicting the value of chip serration frequency for the given tool-work material pair within the selected ranges of the machining parameters.
2) From the developed models, it is observed that cutting speed has the most significant effects on chip frequency followed by feed and depth of cut. The frequency of chip serration is found to increase with the increase in cutting speed but decrease with the increase in feed and depth of cut.

## References

[1] N.H. Cook: *Chip Formation in Machining Titanium*, Proceedings of the Symposium on Machine Grind. Titanium, Watertown Arsenal, MA, pp. 1–7 (1953).

[2] K. Nakayama, M. Arai, T. Kanda: *Machining Characteristics of Hard Materials*, CIRP 37 (1) 89–92 (1988).

[3] M.C. Shaw, A. Vyas: *Chip Formation in the Machining of Hardened Steel*, CIRP 42 (1), 29–33 (1993).

[4] D. Lee: *The Effect of Cutting Speed on Chip Formation under Orthogonal Machining*, J. Eng. Ind., Trans. ASME 107 (1) 55–63 (1985).

[5] A. Gente, H.W. Hoffmeister: *Chip Formation in Machining Ti–6Al–4V at Extremely High Cutting Speeds*, CIRP 50 (1) 49–52 (2001).

[6] A.K.M.N. Amin: *Investigation of the Mechanism of Chatter Formation during the Metal Cutting Process*, Mech. Eng. Res. Bulletin, 6, 1, pp. 11-18 (1983).