Experimental Analysis of the Cutting Forces Obtained in Dry Turning Processes of UNS A97075 Aluminium Alloys

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Abstract

The knowledge of the cutting forces during the machining can be considered as an index to evaluate the machinability of a material due to the fact that the magnitude of cutting forces are strongly related to the amount of heat in the cutting area, tool wear, quality of machined surface and accuracy of the workpiece. In the present work, an experimental analysis was made from the data obtained during dry turning processes of aluminium alloy (UNS A97075); a design of experiments (DOE) 2^4 was used to analyse the influence of the cutting parameters (feed rate, spindle speed and depth of cut) and type of tool (nose radius on the cutting forces. As a conclusion, it can be affirmed the cutting component of the forces ($F_m$) is more sensible to the variations of the cutting conditions than the rest of components analysed in this study. Furthermore, tools with nose radius of 0.4 and of 0.8 mm have similar behaviour from the point of view of the forces generated during the machining at low feed rates.

Keywords: Dry turning processes; cutting forces; aluminium alloys; design of experiments

1. Introduction

The determination of cutting forces during the machining processes can be one of the ways to evaluate the machinability of a material due to the fact that the magnitude of cutting forces have a direct influence on the generation of heat, tool wear, quality of machined surface and accuracy of the workpiece. It can be considered that a material has less machinability when the required power to be mechanized is larger Sánchez Sola et al. (2004). As

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an example of this fact, the aluminium alloys have more machinability than the steels, so the required force to mechanize the aluminium is approximately 30% of the required for machining steels.

A large number of investigations have been focused on the prediction and measurement of cutting forces Sánchez Sola et al. (2004), Rahman et al. (2012), Domingo et al. (2008). Due to the complex tool configurations/cutting conditions of metal cutting operations and some unknown factors and stresses, theoretical cutting force calculations failed to produce accurate results and, therefore, experimental measurement of the cutting forces became unavoidable Korkut (2003). Also it is important to remark that the evaluation of cutting forces plays an important role in the monitoring machining systems. In this context, the signals acquired by dynamometers sensors are employed not only for the monitoring of the cutting forces in machining process to validate the analytical process models, but for the monitoring of other aspects of the machining such as tool wear Chen and Jen (2000), Ertekin et al. (2003), Wang et al. (2013) and surface finish Azouzi and Guillot (1997), Benardos and Vosniakos (2002) Zhang and Chen (2007) Núñez et al. (2006), mainly. This is due to the high sensitivity and rapid response of force signals to changes in cutting states Teti et al. (2010).

In this study, in order to optimize the available means, a design of experiments (DOE) $2^4$ with 2 replications was employed to analyse the influence of the cutting parameters on the cutting forces generated during the dry turning of aluminium alloy (UNS A97075) workpieces. The factors considered for this design were the feed rate, spindle speed, depth of cut and type of tool (nose radius) and the responses variable were the resultant force and the statistical values calculated from the cutting forces (averages and standard deviation): feed, thrust and cutting forces. The obtained data was analysed by means of the analysis of variance (ANOVA) method.

2. Methodology

This investigation is framed within a series of studies in which different materials, types of tools, cutting conditions and duration of tests are involved. The main steps of the methodology carried out in this study are:

- Previous activities to the machining operations. These activities consist on the identification of the used resources: the type of tools, the material workpiece and the tests (type of operation and cutting parameters applied) by alphanumeric codes.
- Design of experiments. In this preliminary stage, full fractional factorial designs of experiments (DOE) are proposed to develop to analyse the influence of cutting conditions on the cutting forces generated during the turning processes. The cutting conditions may include the feed rate, spindle speed and depth of cut, type of tool and material workpiece and the presence of cutting fluids.
- Previous activities of the turning tests. These activities consist on the configuration of the force sensor amplifier and the corresponding software to register the cutting forces. Also it is suggested to carry out one pass of turning with a tool for roughing to prepare the workpiece or workpieces.
- Turning tests. In each test, a workpiece is mechanized during a certain time of machining under certain conditions of feed rate, cutting speed and depth of cut.
- Registration of the measuring forces. The cutting forces are recording and simultaneous graphics are plotting during the tests. From each test, it is calculated the statistical values from the cutting forces ($F_x$, $F_y$ and $F_z$ corresponding to the feed, thrust and cutting forces, respectively), these are their averages ($F_{m_x}$, $F_{m_y}$, $F_{m_z}$) and standards deviations ($F_{d_x}$, $F_{d_y}$, $F_{d_z}$) in time domain. Also the resultant of the averages in the three directions is calculated by the following equation:

$$F_R = \sqrt{F_{m_x}^2 + F_{m_y}^2 + F_{m_z}^2}$$  \hspace{1cm} (1)

- Analysis of the results. For analyzing the results of the experimental designs by statistical tests an analysis of variance (ANOVA) was developed. Besides, Pareto charts and box and whiskers plots are used.
3. Experimental application

For planning the turning tests, the design of experiments selected was a 24 full factorial design with two replications; in total these were 32 experiments. These tests were carried out on cylindrical workpieces with a diameter of 60 mm and a length of 120 mm made of the aluminium alloy (UNS A97075) using 2 types of tools. Concretely, the tools were from SECO manufacturer; DCMT11T304-F2 and DCMT11T308-F2, tools with a radius nose of 0.4 mm (R04) and 0.8 mm (R08).

The machine tool employed was the Pinacho Modelo L-1/200 lathe on which the Kistler 9257B force dynamometer together with the Kistler multichannel charge amplifier type 5070A, were mounted to record, simultaneously during the tests, the cutting forces in three mutually perpendicular directions corresponding to the $x$ direction (feed force $F_x$), $y$ direction (thrust force $F_y$), and $z$ direction (cutting force $F_z$). The measured numerical values and graphics were stored in a computer by a data acquisition system (DASYLab®). The cutting conditions for each turning test are collected in the following Table 1.

The measurements of the surface roughness, in terms of $R_a$, were taken with a Mitutoyo SJ-401 tester and its software Surftest SJ-401.

| Tool | Feed rate (mm/rev) | Spindle speed (rpm) | Depth of cut (mm) |
|------|--------------------|---------------------|------------------|
| R04  | 0.15               | 800                 | 0.25             |
| R08  | 0.2                | 1470                | 0.50             |

4. Results

The range of the values of the three cutting components forces, $F_m$, $F_m$, and $F_m$, are illustrated by a box and whiskers plot shown in the next Figure 1. As was expected the larger magnitudes were obtained in the cutting direction, $F_m$, reaching a maximum value of, approximately, 95 N.

![Fig. 1. Box and whiskers plot with the ranges of values of the cutting forces: $F_m$, $F_m$, and $F_m$.](image)

Taking into account that the larger magnitudes of forces were obtained in the cutting direction, $z$, only the influence of the cutting conditions on the $(F_m)$ are presented (Figure 2). From this figure, it can be observed that the cutting influential conditions were, in order of importance, the feed rate, $f$, depth of cut, $p$, the type of tool, $T$, the interaction of feed rate and spindle speed $f^*N$, spindle speed, $N$, and the interaction of the type of tool and feed rate, $T*f$. With the use of greater values of depth of cut (0.5 mm) and feed rates (0.20 mm/rev) larger magnitudes of forces were obtained due to the fact that the increase of such parameters provokes also a larger contact area between the tool and the chip. In table 2, the ANOVA analysis of $F_m$ is shown, in which, uniquely, the influential factors are included. The last column collects the contribution on the response variable ($F_m$) in percentage of each factor.
Regarding the type of tool, $T$, larger values of cutting forces, $F_{mz}$, were obtained with the R04 tools than with the R08 tools (Figure 3). Nevertheless, it can be seen, in Figure 4, in which the cutting forces have been plotted versus the interaction $T*f$, that this tendency strongly reduces at low feed rates (0.15 mm/rev).
With respect to the standards deviations, $F_{d_x}$, $F_{d_y}$, and $F_{d_z}$ forces, the effect of the different factors considered was similar on the three directions of the cutting forces (feed, thrust and cutting forces) presented in Figures 5, 6 and 7, respectively. The influential factor were the spindle speed, $N$, the feed rate, $f$ and the interaction of the feed rate and spindle speed, $f*N$.

![Fig. 5. Standardized Pareto chart for $F_{d_x}$](image1.png)

![Fig. 6. Standardized Pareto chart for $F_{d_y}$](image2.png)

![Fig. 7. Standardized Pareto chart for $F_{d_z}$](image3.png)
5. Conclusions

The following conclusions drawn from the results obtained in this study are:

- During the dry turning processes of an aluminium alloy UNS A97075, the cutting component of the forces is more sensible to the variations of the cutting conditions than the rest of components analysed in this study. The influential factors on the cutting forces are, in order of importance, the feed rate, the depth of cut, the type of tool, the interaction of feed rate and spindle speed, the spindle speed and the interaction of type of tool and feed rate.
- Tools with nose radius of 0.8 mm have, in general, better behaviour than ones with radius of 0.4 mm from the point of view of the forces generated during the machining, being similar at the lower feed rates employed in this study.
- The most influential factor on the dispersion of forces generated during the turning is the spindle speed; the greater the spindle speed is the more dispersion of the forces is obtained; this fact could indicate an increment of vibrations performing on the tool. Nevertheless, at low feed rates, this tendency reduces significantly so it is possible to apply higher values of spindle speed with no detriment on the aspect mentioned above.

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