Fatigue Behavior of ASTM A36 Steel Considering the Influence of Cutting Parameters

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Abstract

The current study investigates the influence of cutting speed and feed rate of the milling process on the surface finish and the uniaxial fatigue behavior of structural ASTM A36 steel plates. A full factorial design is proposed that considers two levels for experimental factors cutting speed and feed rate. Fatigue tests are performed with a load rate \( R = 0.04 \) and a frequency application of 12 Hz, using a total of 32 dog bone tensile test specimens. The surface quality is characterized by measuring the mean roughness (Ra), the mean roughness depth (Rz) and the maximum roughness depth (Rmax). After several analytic methods are made, it is shown that as the cutting speed increases, surface roughness decreases. In addition, a slower cutting speed during machining increases the probability of fatigue failure survival of the material. Likewise, a greater fatigue life was found as the maximum roughness decreases (Rmax).

Keywords: surface finish, ASTM A36 steel, fatigue, feed speed, cutting speed.

1. Introduction

The incomplete understanding of the fatigue failure in structural and machine elements generated losses of at least 4% of the United States’ GNP [1]. Additionally, the parameter of Surface roughness has become one of the most significant technical requirements improve the tribological properties, corrosion resistance, aesthetic appeal and fatigue strength [2].

One of the most used materials for structures is the ASTM A36 steel. Therefore, studying the ASTM A36 steel is of great importance, as it deals with the fracture to fatigue of manufactured elements with this structural steel, such as tensors hanging or suspension bridges, roads and electrical-welded mesh for reinforced concrete, folded plates for ceilings and floors, slabs, sheets and angular tubular profiles and angular, to mention some types only. Therefore, the issue in fatigue failure of components which generally ensure safety. Therefore, it is vital to analyze the fracture to fatigue so that it can be reduced, predicted, or even eliminated. Accordingly, this document develops a study of the fatigue behavior of ASTM 36-structural steel, versus four different treatments generated by the cutting parameters by milling.

Field and laboratory tests have shown that fatigue failure typically begins on areas of some type of microstructural flaw, such porosity, vacancies, inclusions, second-phase particles, plastic deformations on soft grains, residual stress incompatibility or elastic anisotropy [3]; or in regions of stress concentrations, such as changes of section, wedges, notches, wrong surface finishes, among others. The understanding of these flaws has been the subject of studies on various academic fields. There has been a general agreement that its origin in steels is due to the emergence of microcracks on material caused by variable cyclic loads. The crack is generally split in four main stages, as represented in Figure 1. This graph describes the appearance of the fracture and a stress-life diagram (S-N).

Likewise, the effect of cutting parameters on machining has been studied throughout modern history, mainly for the milling and turning processes in steels. For instance, the research by Hayajneh et al. [5] which studies the influence of cutting parameters: rotation speed of the tool \( (v_t) \), feed speed \( (v) \), cutting depth \( (a_p) \) milling process on the arithmetic average roughness Ra by an analysis of variance (ANOVA), where the given model by the equation is found. (1). It can be concluded the feed speed is the most influential factor on the roughness Ra, as it turns that the lower the feed speed less, the lower value it obtained for Ra. A similar conclusion has been reached by Abdullah et al. [6]. In this latest research, their aim is to determine analytically and experimentally the effect of the machining parameters \( (v_t) \) and cutting speed \( (v) \) of a CNC mill machine in the Ra roughness. Finally, they determine that \( v_t \) is the most important factor on Ra, reaching the regression expression (1).

\[
R_a = 1,178854 - 0,000492v_t + 0,009897v_f - 0,17625a_p - 0,000003v_tv_f + 0,000811v_a_p + 0,003012v_v_a_p
\]

On the other hand, several researches have focused to find correlations between the surface roughness and the phenomenon of fatigue. Some of them have been reported by Siebel [7] where it was found that the decrease the boundary of fatigue resistance \( (Se) \) on steels is proportional to \( \log(Rt) \) when the maximum depth of the surface profile is greater than a certain critical depth of the furrow. This Rt is very close to 2 \( \mu m \) for tempered steels and 5 \( \mu m \) for annealed steels. Furthermore, it is important to mention that research in structural steels made by Koster [8] where it is concluded that,
in absence of residual stress influences the resistance to fatigue through the surface finish. In their presence and with a roughness within the range 2.5 – 5.0 μm, the surface finish does not significantly affect the fatigue lives. Later, Maiya & Busch [9] studied the effects of average quadratic roughness (Rq) on the fatigue of stainless steel AISI 304. The study was conducted for Low Cycle Fatigue (LCF), focusing on fatigue life (Nf). Their results fit according to equation (2), where the fatigue life depends on the roughness Rq.

\[ N(R_q) = 1,012R_q^{-0.21} \]  

(2)

On the other hand, Deng et al. [10] evaluated the effect that surface roughness effect on fatigue life. To reach this, they made a three-point flexural fatigue test in notch specimen on S50C steel JIS. These were subjected to a Ra surface roughness sample and during the fatigue test, the cycle in which the crack started was found. It was done by means ohmic-sensor resistance based on coated-power cathode. Results confirm the boot cycle of crack decreases as the roughness increases. Research by Yao et al. [11] aims to optimize the milling machining of the titanium alloy Ti-10V-2Fe-3Al. It sought to reach better resistance to fatigue. To do this, they designed an three-cutting speed level experiment (vc), tooth feed speed (fz) and milling width (ac). As a response, Ra and the Rz partial roughness Rz were measured by 3D-topography with a Veeco NT1100 equipment. The dog bone-test pieces were subjected to uniaxial fatigue testing, with a load ratio equal to R=0.1 and an application frequency of cyclical load of 85-87 Hz. It can be concluded that, in terms of decreasing sensitivity: a lower fz, and ac coupled with increased vc yield a better finish and a better fatigue life in a titanium alloy.

Vulliez et al. [12] correlate the roughness of the machined surface with fatigue life. To reach this, they made specimens with a ball-nose mill with angles of 45° and \( \beta = \beta = -3^\circ \), as for two machining paths (transverse and parallel to the load), with and without annealing. By using a confocal microscope, they took the 3D-topography from the critical area and used a recent geometrical method to measure the roughness profile based on Heron's formula with 1120 curvatures (multi-scale curvature analysis). They conclude there is a strong correlation \( (R^2 > 0.96) \) between the obtained data by the multiple-curvature analysis and fatigue life, which translates into a new prediction method for fatigue life on machined surfaces by milling. As it relates to Huffman [13], he carried out a mathematical model by establishing a relationship between elastic energy density by external loads, energy density of dislocations and resistance to fatigue (S-N, ε - N and da/dN - AK). This model becomes valid with the results of different SAE FD&E steels. The quality is worth being highlighted, as results agree with the information organized in the diagrams S-N, ε-N and da/dN-AK for different values of R. It is concluded that this achieved model properly emulates the experimental data for several types of steels, aluminum, titanium, nickel alloys, copper and iron foundries. Likewise, it shows the influence of both the temperature and the hardness of the material in the fatigue life. Thus, the effects of residual stress and the machining technique become intrinsic. However, the model does not work well for low cycle fatigue.

In general, the surface roughness is not enough to estimate the fatigue life in machined metals. Even in some studies focused only on the surface roughness, as those by Moussaoui et al. [14] and Koster [8], it is shown there is not any influence over fatigue resistance and high-quality surface finishes. However, as opposed to this, Vulliez et al. [12] reach a strong model to estimate the resistance to fatigue from the surface finish generated by milling. The latter requires a censured hardware of higher quality to perform a correct statistical analysis of the superficial information that defines the finish. In addition, Zuluaga [15] shows that an inspection method through the surface finish in the CFRP composite material does not evidence a true estimate of fatigue life. It can be noted that the hardness and grain size of the material influences the fatigue life, and these vary as the manufacturing process used.

Yao et al.‘s study. [16] shows that a quality-manufacturing process, such as milling, polishing, sand-blasting and re-polishing the experimental unit generates a better fatigue life, as residual compressive stresses are generated; the hardness increases, and the roughness is reduced. In addition, Novovic et al. [17] conclude that polishing after surface reciprocating grinding generates the most resistance to fatigue of their analyzed processes, including milling. Likewise, a rise on fatigue life can be observed within the samples with greater compressive residual stress, because of the machining, more than in the annealed specimen with worse surface roughness. On the other hand, Kikuchi [18] shows that using titanium can reduce the size of grain through a longer machining and to do this increases the resistance to fatigue. Parallel to a conclusion...
[19] arrives Erviti, concluding that, if you give very good machining conditions followed by a correct standardization and a surface hardness enough, then Boothroyd's roughness model can be used [20]. But, as opposed to most works, this last one falls under the most influential parameter on Ra is vc and not vr. To conclude that, as the cutting speed increases, the exposure time to a plastic behavior gets reduced. Therefore, it has greater impact in the roughness.

The behavior of milled ATSM A36 steel to fatigue to different cutting parameters has not been studied sufficiently. Due to that fact and the importance this material poses, this work aims to study its fatigue behavior under different machining conditions, which include combinations between the parameters of feed speed (vf) and the cutting speed (vc). To reach this goal, a characterization about the study material through a methodology of tests based on the acquiring of composition and microstructure according to current laws. After choosing the experimental design to develop the study, the experimental ASTM A36 units are manufactured. They should have a geometry that can lead to study the phenomenon in high cycling fatigue (HCF). Finally, the characterization of the Rs, Rz, and Rmax roughness is performed on the machined sides of the specimens and the uniaxial fatigue tests are to determine uniaxial fatigue life. This procedure allowed to reach interesting conclusions about how machining parameters influence the fatigue behavior on this structural steel low-carbon content.

2. Materials and Methods

A progressive methodology was used for the ASTM A36 steel fatigue study, as shown in Figure 2. First a characterization of the base material was made. To carry it out, a metallurgical and composition analysis was made to analyze the material. The mechanical properties of the material were taken from the quality certificate. Later, to study the machining process, the cutting parameters to be used for the manufacture of the specimens were defined. The cutting experimental factors were defined for two levels of study, thus a full factorial design 22 could be established. This is illustrated in Figure 3 and recorded in Table 1. However, the existence of other factors that may influence the experiments are well-known: laboratory-environment, pads and cutting tools, the cutting pattern direction, the residual stress and the initial hardness. These factors were kept constant, according to ASTM E 466. By performing this manner, a greater complexity was avoided, so it could make testing costs go higher.

![Methodology used in the current study.](image)

As it relates to the manufacture of each experimental unit, as dimensions are shown in Figure 3, a Leadwell CNC V-20 machining center was used to get better precision and control of the machining process. This machining center can define and monitor each of the relevant process variables related to the manufacturing. The setting up of the test specimens on the machining center can be seen in Figure 4. This illustrates a first process that reduces the size of the base material. Next, the material is machined and drilled through holes for the testing machine to be gripped. Thereunder, the machining parameters are the object of study. Therefore, they are the independent variable that will be used in the cutting tool R217.69-3240.0-18-4W (a=40.0 mm, 4 teeth and dry cutting).

The rest of the cutting parameters remained fixed, i.e. a width cut ap of 0.02 mm per pass for the final finish of the unit, an edge radius r of 0.8 mm and a cutting direction parallel to the load. The ah parameter is omitted, as the pill measures 8 mm. The latter is greater than the thickness of the plate from which the specimens are obtained.

$$r \geq 2 \left[ \frac{z_{0.95}}{z} + z_{0.5} \right] \left[ \frac{\% CV}{\delta} \right] = 2 \left[ 1.96 + 1.65 \right] \left( \frac{0.02}{0.06} \right)^2 = 6.52$$

(3)

<table>
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<th>Proof</th>
<th>vc [rpm]</th>
<th>vf [mm/min]</th>
<th>Combination of treatment</th>
<th>No. replicas</th>
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<td>159</td>
<td>Vc, low, vf, low</td>
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<tr>
<td>BC</td>
<td>1870</td>
<td>159</td>
<td>Vc, high, vf, low</td>
<td>8</td>
</tr>
<tr>
<td>AD</td>
<td>1560</td>
<td>450</td>
<td>Vc, low, vf, high</td>
<td>8</td>
</tr>
<tr>
<td>BD</td>
<td>1870</td>
<td>450</td>
<td>Vc, high, vf, high</td>
<td>8</td>
</tr>
</tbody>
</table>

![Table 1. Nomenclature for the chosen experimental design.](image)
must be measured with an instrument of at least 0.001 in (0.03 mm) resolution for dimensions equal to or greater than 0.200 in (5.08 mm). The latter was accomplished using a Vernier Caliper with a resolution of 0.02 mm to measure units of the neck region. As this region was found, the stress to support the neck could be projected. Therefore, the stress cycling was established with a maximum stress $\sigma_{\text{max}} = 280 \pm 2$ MPa and minimum stress $\sigma_{\text{min}} = 11 \pm 2$ MPa ($R = 0.04$). After the test, the obtained data were reported according to ASTM E466 and a statistical analysis of the S-N linearization curve was made according to ASTM E739.

3. Results

Material Characterizations

Three tests were carried out by UV-VIS spark spectrometry, each in different locations of the material, thus obtaining the chemical composition of steel plate. The average results of this test are shown in Table 2. Then, a metallographic analysis was carried out, supported with an optical microscope, as shown in Figure 5. The samples were polished to get the required surface finish. Later, it was treated with Nital 3% to observe the different phases and distributions of grain in the steel. There is a 55% microstructure composed of ferrite and 45% of perlite. The latter is typical for this type of steel.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value (%)</th>
<th>Item</th>
<th>Value (%)</th>
</tr>
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<td>Fe</td>
<td>98.998</td>
<td>Co</td>
<td>Less than 0.001</td>
</tr>
<tr>
<td>If</td>
<td>0.2</td>
<td>B</td>
<td>0.0014</td>
</tr>
<tr>
<td>Mo</td>
<td>0.005</td>
<td>P</td>
<td>Less than 0.001</td>
</tr>
<tr>
<td>Al</td>
<td>0.053</td>
<td>Cr</td>
<td>0.03</td>
</tr>
<tr>
<td>C</td>
<td>0.175</td>
<td>Ti</td>
<td>0.002</td>
</tr>
<tr>
<td>Cu</td>
<td>0.011</td>
<td>Pb</td>
<td>Less than 0.002</td>
</tr>
<tr>
<td>W</td>
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<td>S</td>
<td>0.018</td>
</tr>
<tr>
<td>Nb</td>
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<td>V</td>
<td>0.001</td>
</tr>
<tr>
<td>Mn</td>
<td>0.484</td>
<td>Sn</td>
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</tr>
<tr>
<td>Ni</td>
<td>0.018</td>
<td>Mg</td>
<td>Less than 0.000</td>
</tr>
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Results for the surface finish

From the results, three surfaces are obtained $\mathbb{R}^3$ dependent on experimental factors in their four combinations. As to represent it, there will be a parallel cut to the plane for the cutting speed factor vs. the roughness parameter to be analyzed. This mode is carried out to observe the influence of...
the cutting speed, according to the two defined levels 1560 rpm and 1870 rpm, respectively. The behavior of the arithmetic average roughness, partial z and maximum roughness with the rotation tool speed are shown in Figures 6, 7 and 8, respectively. From curves Ra, it is observed that a greater vc and vf it produces a lower roughness, which equates to a reduction close to 0.3 μm, which is equals a percentage difference of 30%. The same trend is observed in the curve for Rmax where the difference between the average value of the treatment with increased surface roughness compared to one with less roughness is 20%.

![Fig. 6](image_url)

**Fig. 6.** Behavior of the arithmetic average roughness (Ra) with milling parameters.

![Fig. 7](image_url)

**Fig. 7.** Behavior of the average roughness (Rz) with milling parameters.

![Fig. 8](image_url)

**Fig. 8.** Behavior of maximum roughness (Rmax) with milling parameters.

### Results for the testing of uniaxial fatigue

A compilation of the data obtained in each test to fatigue carried out to the A36 steel test specimens is presented. In Figure 9 results are shown in a S-N diagram as for the experimental results of uniaxial fatigue, along with the theoretical curve calculated with the Marin's coefficients and the confidence band considering a dispersion of ±30%.

![Fig. 9](image_url)

**Fig. 9.** Points cloud of the experimental results along with the S-N theoretical curve.

### 4. Discussion

#### Behavior of the surface finish along with the machining parameters

As with the data obtained from maximum roughness, the response surface is obtained, according to the cutting and feed speed, as the experimental arrangement was defined. It is found that the function defining the behavior of the roughness Rmax is described, according to expression (4) with a correlation coefficient R²=84.6%. As for this behavior model of the maximum roughness, there is a contour graph shown in Figure 10. Based on this, it can be seen that the cutting speed has a greater influence than the feed speed over the maximum roughness. On the other hand, after making a visual examination of the maximum roughness dispersion, through the box-and-whisker diagram in Figure 11, it is seen their averages are not far from each other.

\[
R_{\text{max}} = -5.90 + 0.074 v_f + 0.079 v_c
\]  

(4)

![Fig. 10](image_url)

**Fig. 10.** Contour graph for the maximum roughness Rmax.

![Fig. 11](image_url)

**Fig. 11.** Box-and-whisker diagram for the maximum roughness Rmax for the four treatments studied.

#### Influence of surface finish in the fatigue life

A method used to analyze the fatigue life that do not come from a single population is recommended by Hobbacher [21]. To reach this, a load capacity is estimated (C) next to a probability of survival for all the data provided by the fatigue
The load capacity is calculated according to expression (5), where $m$ is a distribution coefficient that takes the value of 3 for steels. Later, a normal distribution of $\log C$ is generated from its average and standard deviation and is represented in a diagram of cumulative normal distribution, as shown in Figure 12. When the location on the curve of each experimental unit is observed, it is found that those with higher probability of survival were treated with a slower feed speed. Two of their two combinations and at least half of these specimens got a survival chance greater than 60%. This allows us to partially conclude that those milled specimens with a feed speed of 159 mm/min have a higher survival probability to fatigue failure. The latter is consistent with the results from other authors [22,23,13], who have found that longer machined periods generate a better machined surface integrity and a longer fatigue life. 

$$\log N = \log C - m \times \log \sigma_a$$  \hspace{1cm} (5)

![Cumulative normal distribution of fatigue test results.](image)

On the other hand, as the experimental units were taken in an arbitrary manner from those which had a greater survival probability of 23%, it can be found that treatments show a trend related to fatigue life. Figures 13, 14 and 15 illustrate that, in general, a longer fatigue life is obtained when the roughness parameters are low. In addition, there is a perceived trend of a longer fatigue life for treatments that have less feed speed ($v_f=150$ mm/min), which is consistent with the previous analysis. Likewise, there was a more consistent behavior defined by one same trend on the graphs between roughness $R_{\text{m}}$ with fatigue life, with respect to the other measures of roughness. There was the same trend as reported by Novovic et al. [17]. This may be since $R_{\text{m}}$ denotes the deepest discontinuity on the surface of the test specimen, which is related to the local increase of the stress and the most likely place for the emergence of a fatigue crack.

**Influence of the feed speed ratio on fatigue life**

The relationship between the cutting parameters is used to better identify the effect of treatment on the fatigue life. To this end, the rate between the feed speed and the rotation speed of the tool is determined, thus resulting into a feed speed rate in function of the revolutions. Figure 16 displays results, where the average value of roughness $R_z$ for each treatment is shown.

The diagram shows that the specimens that reached a longer life to fatigue were those that experienced a higher value of the cutting rate when they were milled. The treatments which generated the greatest fatigue life in the experiment were obtained by those with a higher level of feed speed. When examining the average roughness for each treatment, it was found that those units with greater roughness got a greater fatigue life, as opposed to the common thought.
Effect of milling on the roughness measurements

For a comparative analysis has to Whitehouse [24] suggests a model of ideal roughness ($R_a$) around the cutting diameter of the tool and the cutting parameters $v_c$ and $v_f$. After applying this information to the geometry of the cutting tool in the milling process, there is a family of curves given by equation (6). In addition, Knight & Boothroyd [25] published experimental results from the influence of the cutting speed on a turning process on a tempered steel. Thus, in Figure 17 the experimental results are represented, along with the curves defined by the latter model.

$$R_a(v_c, v_f) = \frac{0.0642}{40} \left( \frac{v_c}{v_f} \right)^2 = \frac{0.0642 + 40(v_c/v_f)^2}{(4000v_f)^2}$$ (6)

![Fig. 17. Experimental results of surface roughness by turning, as stated by Knight & Boothroyd [25], along with the theoretical curve of the Whitehouse model [24] and the results of the current research.](image)

When observing the curve for tempered steel machined by turning, it can be understood that high cutting speeds generate the roughness to remain stable. As a partial conclusion, this can be interpreted as a decrease in the natural roughness. It leaves only the ideal roughness given by the geometry of the insert, the geometry of the specimen and the machining process. In addition, it can be highlighted from the model it has a quadratic sensitivity to feed speed $v_f$, or, in other words, the tooth feed speed $f$. The latter is not observed graphically from the results of the experiment, but it can be noted in the family of curves from the model and the general literature. Finally, when analyzing the results obtained for the roughness, it was found that the specimen with lowest cutting speeds had a percentage difference of 7% against the ideal roughness, while the specimens with greatest cutting speeds had a percentage difference of 30% against the ideal roughness.

Effect of the roughness on the resistance to fatigue

The parameter $R_t$ is defined as the sum of the greatest peak and the largest valley, from the roughness $y(x)$ function. However, $R_t$ is the average of the greatest peak and valley from the division of length measurement in five stretches. So that Rodriguez [26] suggests the use approximation $R_t \approx R_a$. If this approach is adopted, it can be interpreted that the roughness generated by the experiment is close to the ideal, which would make it possible to use such an approach with a greater criterion on the results given. In such a way, by considering this approach, Siebel’s model results can be overlapped with [7] the experimental data that reached infinite fatigue life with its corresponding $S_s$, as can be seen in Figure 9. However, it should be carefully analyzed that the current research did not conduct a study on the resistance limit to fatigue of the ASTM A36 steel specimens [27].

The diagram in Figure 9 you can see that the data obtained are contained in a range of ±20% of the theoretical equal to 158 MPa for the ASTM A36 steel; The latter shows a trend and allows the study to continue with historical data from Siebel. Figure 18 allows to conclude that the present study is being analyzed on the critical points of roughness, where the fatigue strength ceases to be constant and begins to be governed by the function $S_s = \log(R_t)$. Therefore, it is being studied on a range of roughness where a transition occurs in the behavior of the resistance to fatigue for steels. As a result, the behavior observed for resistance to fatigue must be analyzed by considering this transitive effect.

5. Conclusions

The executed milling process with the highest levels of cutting speed and feed speed generated a lower roughness. In terms of absolute comparison with other treatments from specimens, there is decrease in the value of roughness $R_t$ close to 0.3 μm which is the same as the percentage difference of 30%. Likewise, between roughness $R_{max}$, there is a difference close to 2 μm (20%).

The cutting speed had greater influence than the feed speed on the surface roughness for the levels applied in the treatment. In addition, when comparing results with literature and historical data, it was found that the experimental conditions are in the transition region, where the roughness $R_t$ has little variability, as an output of certain machining conditions that favor an ideal roughness. The latter is given by the geometry of the cutting tool and material properties.

The range established for the cutting parameters does not cause a large variation of the surface roughness for the material under study. After applying Siebel’s model, it is concluded that the experimental results from this study are arranged near the transition glass, where fatigue strength turns from being constant to being dependent on the value for $R_t$.

When performing a load/fatigue capacity analysis, it can be perceived there is a trend where, as roughness $R_{max}$ is decreased, fatigue life increases. The latter primarily occurs for the treatments with a low feed speed. However, by observing the behavior of the cutting rate ($v_f/v_c$), it is found that those specimens subjected to treatments with higher cutting rate showed the longest fatigue life results, even though they were not precisely the experimental units with the best surface finish.

Acknowledgment

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References

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<th>Symbol</th>
<th>Term</th>
<th>Unit</th>
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<td>𝑎_𝑐</td>
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<td>𝛿</td>
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<td>Cutting speed per tooth</td>
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<td>l</td>
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