EFFECT OF GRAIN SIZE ON MACHINING STRENGTH IN AN AUSTENITIC STAINLESS STEEL[1]

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Abstract

This paper explores the effect of grain size on machining strength in an Fe-Cr-Ni alloy, namely AISI 316L. Ideal grain growth law, proposed by Burke,[1] was used to obtain the activation energy for this steel based on data published by Stanley and Perrota,[2] which was 185 kJ.mol^{-1}. The initial grain size was measured - 12 μm - and by considering these values, both temperature and time values needed to achieve a final grain size ten times larger than the initial one could be calculated, which were 1200°C and 2 hours. Ternary phase diagram analysis showed that austenite was stable at this temperature. Following, samples of 200-mm length were annealed and quenched in water to prevent any formation of sigma (σ) phase. Annealed and as-received bars were then used to compare their machining strength. Results showed that the machining strength is higher in the as received condition than the one after annealing (127 μm). It may be concluded that the bigger the grain size, the lower its machining strength. It is believed that this is caused by the pile-up of dislocations on grain boundaries, since this material exhibits large plastic deformation before fracture.

Key-words: Normal grain growth; Machining strength; Machinability.

EFEITO DO TAMANHO DE GRÃO SOBRE A RESISTÊNCIA À USINAGEM DE UM AÇO INOXIDÁVEL AUSTENÍTICO

Resumo

Este trabalho explora o efeito do tamanho de grão sobre a força de usinagem em uma liga Fe-Cr-Ni, ou seja, do aço inoxidável AISI 316L. A lei crescimento ideal de grãos, proposto por Burke,[1] foi usado para obter a energia de ativação para o aço, com base em dados publicados por Stanley e Perrota,[2] qual seja: de 185 kJ.mol-1. O tamanho de grão inicial medito foi de 12 μm. Os valores de temperatura e de tempo necessários para atingir um tamanho dez vezes maior do que o inicial foi de duas horas e de 1200 °C. A análise do diagrama de fase ternário mostrou que a austenita é estável a essa temperatura. Posteriormente, amostras de 200 mm de comprimento foram recozidas e resfriadas em água para evitar a formação da fase sigma. Amostras nas mesmas condições de recebimento do fornecedor foram usadas para comparação do efeito do tamanho de grão na resistência à usinagem das duas situações. Os resultados mostraram que a Resistência à usinagem é maior nas amostras de grãos finos (da ordem de 10 mícrons) do que nas amostras após recozimento com 127 mícrons. Pode-se concluir que maior o tamanho do grão menor será a resistência à usinagem. Acredita-se que isso seja causado pelo amontoado de deslocamentos em limites de grão, uma vez que este material apresenta grande deformação plástica antes da fratura.

Palavras-chave: Crescimento de grão; Resistência à usinagem; Usinabilidade.

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1 INTRODUCTION

Machining strength is a term that is used in the present paper to investigate one of the main problems in machining, which is machinability. The last term refers to a technological property of materials, not an intrinsic one. A material machinability index is therefore usually measured compared to another one adopted as a standard.[3] It is therefore regarded as a technological one because of its dependence on numerous variables related to machining parameters.[4-8] Moreover, it shows great dependence on the shop floor conditions and its manufacturing scenario.

For this reason, when a long or short machinability test is done, using one specific manufacturing scenario, the results cannot be transferred to another one with a desired reliable condition. If parameters such as feed rate, depth of cut, cutting speed, cutting fluid, to name a few, are changed from test to actual applications, large differences are likely to occur.

A material may be commonly considered to have poor machinability because of its uneasiness to obtain an acceptable surface finish. In these circumstances, comparisons to other materials prove to not exist, but machining practice may be carried out until a satisfactory surface finish is achieved. This type of problem is a typical occasion in which machinability concepts are used, because the tests must be carried out at the shop floor, with the same scenario of the actual material application in manufacturing with high quality and adequate surface finishing.

1.1 Machining Strength

Destro and Coppini[9] published the first and original results obtained from Destro's Doctoral Thesis[10] in which it was proposed and revealed a new intrinsic material property called machining strength. In honour to his advisor, Destro called CI (Coppini Index), which was a measure of this property, and published a second paper proposing a viable way to measure it.

As seen above, machining strength is an intrinsic property of materials, i.e., it is a characteristic that does not depend on external parameters and machining conditions. It may be understood as the difficulty that a material presents when it is machined and can be expressed by the Coppini Index:

$$CI = \sum_{i=1}^{N} \frac{F_{fi}}{N} \tag{1}$$

where:

F_{fi} is the feed force measured by a dynamometer in each i-esimal scaling (step) [N];
N is the number of steps of the specimen F_{fi}.

As Ashby, Shercliff and Cebon[11] point out, a material property means two things: its value is independent of the way it is measured, i.e., different test geometries, if properly measured, give the same value of this property for any given material; the second is that it can be used for design. In this sense, it is the purpose of this article to pinpoint machining strength as a material property.

Destro[10] initially defined that the CI value is determined by a standardized test in a specimen. This value may be defined as the average of feed forces measured during the test and may be calculated by Equation (1). The measure of feed force was chosen in that paper because of the lesser influence in tool wears when compared to the cutting force or its components.

The idea of machining strength is to use in the development of easy-to-cut materials. Its application seems to be relevant for ferrous materials, more specifically steels, for they are the ones which have high machining strength values.

Different from what was proposed by Destro,[10] Coppini[12] proposed that this index must be the result of the relationship between the global mass of tool material removed under wear action (m_{ferr}) and the mass of material removed from the workpiece (m_{cp}), responsible for the tool material waste, as follows:

$$CI = \frac{m_{ferr}}{m_{cp}} \qquad (2)$$

Where: m_{ferr} and m_{cp} are measured in [g].

Such masses must be measured during the test, which may even be performed by the material producer that intends to develop or characterise its produced materials based on machining strength and specially to produce easy-to-cut materials. Alternatively, these tests can be performed in laboratory facilities from research institutes and universities.

1.2 Grain Growth

Grain growth is a phenomenon in which the average grain size of a metal or alloy increases continuously at high temperatures. Free-deformation grains may grow continuously if this metal or alloy is kept at high temperatures or longer times.[13,14]

This happens because the driving force for grain growth is the decrease in energy caused by the reduction of the number of grain boundaries per unit volume. The total surface area of boundaries is decreased as grain size is increased, causing a reduction in the surface energy, i.e., when grains grow, the number of their boundaries is decreased and their total surface area energy decreases. Grain growth is explained by the migration of grain boundaries, namely the diffusion of atoms through crystal boundaries.

Grain growth may be classified in two types: normal and abnormal grain growth.[15] When grain size of a given structure is continuously increased, it is said to exhibit normal grain growth. Their grain size distribution is usually fit by a log-normal distribution.[16,17] On the contrary, abnormal grain growth takes place when first normal grain growth is inhibited or halted and another factor takes place to make other boundaries able to exhibit a distinct mobility.[18] In this case, grains with these boundaries grow a great deal and their vicinity is commonly found to have very small grains. Statistical grain size distributions and parameters have been put forward to assess this phenomenon, but it has proved to be a very painstaking job.[17]

Beck, Kremer e Demer, in 1947,[19] studied grain growth kinetics and proposed the empirical relationship:

$$D = kt^{n} \qquad (3)$$

where D is the grain size [μm], k and n constants and t is time [min].

By assuming that grain boundaries are similar when the phenomenon takes place, Burke[1] proposed the effective curvature radius of boundary may be related to their grain diameter. In this way, it was possible to put forward the ideal grain growth law:

$$D^2 - D_0^2 = kt \tag{4}$$

where D_0 is the initial grain size and k may be expressed by:

$$k = k_0 \exp\left(\frac{-Q}{RT}\right) \tag{5}$$

where k_0 is a pre-exponential constant, Q [$kJ.mol^{-1}$] is the activation energy for grain growth, R is the general constant of gases (8.314 $J.mol^{-1}.K^{-1}$) and T is the absolute temperature [K].

In the present study, grain growth was promoted to investigate the effect of its size, and their grain boundaries, on the machining strength of a stainless steel that contains only one phase, which is austenite.

Stanley and Perrota[2] investigated grain growth in several stainless steels. Their data for the AISI 316 were used in the present investigation to determine the activation energy for grain growth by using Equation (5). In this case, the purpose was to make grain growth take place to a certain degree in which the effect of grain size could be investigated in the machining strength of this alloy.

2 MATERIALS AND METHODS

2.1 Grain Growth Experiment

Samples from a bar made of AISI 316L stainless steel of a 51 mm diameter were cut to a 200 mm length for the machining strength tests. A small sample was also cut to be examined by metallography. This sample was mechanically polished and finally etched by nitric acid (60%) in water under a current density of 50 $mA.cm^{-2}$ and 1 V, for 35 seconds. This technique reveals grain boundaries except twins; the later ones may mislead grain size measurements.

Grain size was determined by ASTM-E-112.[20] At least 50 fields were counted by a circle test method. The average number of intercepts was 38, which is in accordance to the standard. This grain size was used in Equation (4). This result may be used in Equations (4) and (5), so it becomes:

$$D^2 = 12^2 + [5.173.10^6 \exp(\frac{-184.9.10^3}{8.314T})]120 \rightarrow D^2 \cong 120 \tag{6}$$

For a 2-hour period, to achieve a grain size ten times larger than the initial one may be calculated by Equation (4), resulting in 1200°C. After annealing, they were all quenched in water to avoid precipitation of sigma phase.

In this way, four samples were annealed at 1200°C for 2 hours. In the end, 8 samples were submitted to the machining strength tests, 4 of which in the initial condition (12 μm grain size) and 4 in the annealed condition.

2.2 Machining Strength Tests

The specimens mentioned above were prepared in order to obtain a 50 mm diameter and 150 mm in length; 50 mm in length was used to hold the specimen on a lathe. The tests were performed on an Okuma© lathe with 15 kW of power.

A carbide tool class M, from Sandvik© Coromant TNMMG 16 04 04 MF was selected as a preliminary test. This selection was based on the fact that its wear resistance and toughness is on average. So, this kind of tool is interesting to be used as a standard for IC determination. The following machining conditions were set:

Cutting Speed = 300 $m.min^{-1}$
Feed Rate = 0.15 $mm.rot^{-1}$
Depth of Cut = 1.0 mm

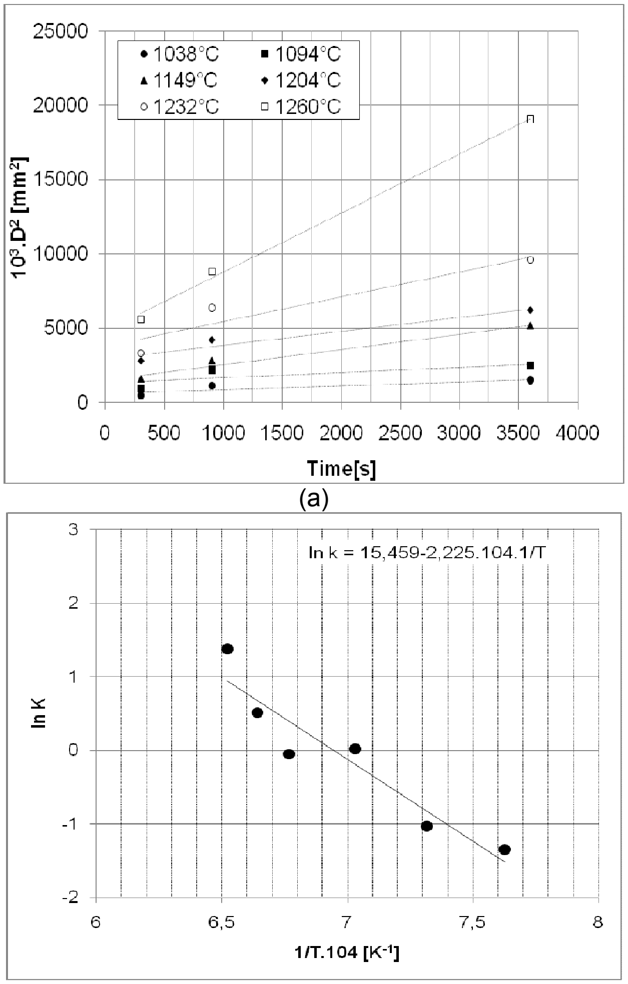
The criterion used to change both the tool and specimen was to run the process until it was possible to identify the tool being prone to fail. Because of this criterion, the number of steps was not constant, as will be seen further in Table 2.

3 RESULTS

Statistical data taken from Stanley and Perrota[2] were used to calculate the activation energy for grain growth in AISI 316 steels. This value was used in the present work, although the studied one has lower content of carbon than the one investigated by them. Nevertheless, the activation energy was found to be 184.9 $kJ.mol^{-1}$. Figure 1 presents the results of this analysis.

This calculus led to the conclusion that the chosen annealing was capable of increasing the grain size in ten times, which was really what took place. A new preparation was also made in a sample from the annealed specimens. The average grain size was 127 μm. Figure 2 present examples of microstructures from these two samples.

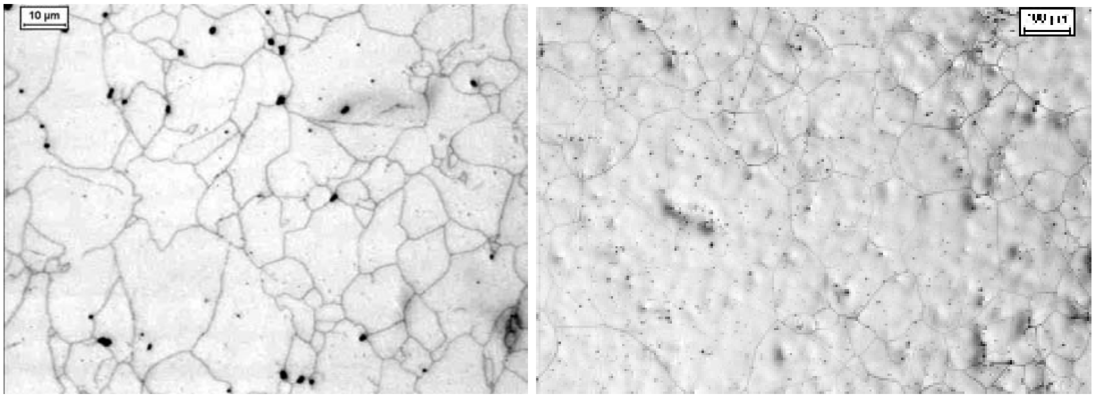
Ternary phase diagrams – Fe-Cr-Mo and Fe-Cr-Ni – may conclude that the more stable phase at 1200°C was only austenite. The subsequent quenching in water had the purpose to prevent sigma (σ) phase from precipitating in grain boundaries. This can be observed in Figure 2.



(a)

(b)

Figure 1. Experimental results from Stanley and Perrota[16] for AISI 316 steel. (a) Ideal grain growth kinetics, (b) activation energy and diffusion constants calculated for grain growth phenomenon.



(a) (b)

Figure 2. Micrographies by light microscopy from AISI 316L steel showing grain boundaries in austenite. (a) As-received condition and (b) after annealing at 1200°C for 2 hours. Etchant: nitric acid 60% in water, current density: 50 mA.cm^{-2}, tension 1V, time 35 s.

A series of Rockwell G hardness tests were performed in the samples to be machined. The results can be seen in Table 1. On average hardness values of samples with larger grain sizes are lower than the ones from samples with small grain sizes.

Table 1. Rockwell G* (Load 150 kgf and indenter 1/16") hardness values from as-received and after annealing samples. Values on the right side indicate conversion to Brinell hardness. *SI values: load 1475 N and indenter diameter of 1.5875 mm

Sample	Condition	HRG	HB30
1	As received	73±11	206±2
2	As received	74±11	208±9
3	As received	72±10	201±9
4	As received	71±11	200±9
5	Annealed	64±2	182±2
6	Annealed	61±2	173±2
7	Annealed	51±3	154±2
8	Annealed	51±4	154±2

The results from the machining strength tests may be seen in Table 2. Coppini Indexes are at the last right side of this table. Again, on average, specimens with larger grain sizes showed a lower machining strength, varying from 0.45 to 1.76. On the other hand, specimens with smaller grain sizes showed a higher machining strength, varying from 0.34 to 4.38. Although some results showed some discrepancies, it is believed that they are due to the number of steps taken in the test, which was unusually high. This will be explored further.

Table 2. Machining strength values for the specimens as-received and annealed. Where: m_{ferr-i} is the tool mass before turning; m_{ferr-f} is the tool mass after turning; n is the number of turning steps achieved in each sample; m_{cp} is the removed mass from the sample, after n steps

Sample	Tool	Condition	m_{ferr-i},[g]	m_{ferr-f}, [g]	n	m_{cp}, [g]	10^7.CI
1	3	As received	7.1104	7.1044	9	1369.19	4.38
2	2	As received	7.1044	7.1038	13	1784.77	0.34
3	1	As received	7.1128	7.1121	10	1484.21	0.47
4	3	As received	7.1038	7.0986	9	1369.19	3,80
5	4	Annealed	7.1215	7.1187	11	1591.82	1.76
6	4	Annealed	7.1187	7.1179	13	1784.77	0.45
7	2	Annealed	7.1096	7.1075	13	1784.77	1.18
8	4	Annealed	7.1179	7.1159	13	1784.77	1.76

4 DISCUSSION

The present paper has the purpose of showing the effect of grain size in machining strength in austenitic stainless steel. The chosen material was due to its ductility, which is usually pronounced when compared to other metals or alloys. It was also chosen for it is a stable solid solution, particularly with minor amounts of carbon. The purpose, in this case, was to not have dislocations halted or their movement impeded by interstitial solute atoms. In other words, the purpose was to have a pronounced effect of grain boundaries in the motion of dislocations.

The results in Table 2 show, on average, that machining strength, measured by the Coppini Index, are 2.25 and 1.13 for small and large grain sizes, respectively. This means that it was more difficult to machine specimens with small grain sizes than specimens with large grain sizes. This is due to the number of grain boundaries.

In the first case, because of the fact that small grain sizes mean that the specimens have more grain boundaries per unit volume and therefore impede the movement of dislocation, leading them to be piled up at them. On the other hand, large grain sizes have fewer grain boundaries per unit volume so there will be fewer event of pile-up of dislocations.

Assuming that there is a substantial plastic deformation before the cut of scrap during the machining test, the movement of dislocations may explain the machining easiness found in these specimens, particularly because the chosen material was a very ductile one. It is clear then that the number of grain boundaries was probably the main cause for the difference found between the machining strengths in these two groups of specimens.

However, the number of steps seems to be important in the test and consequently, its results. This may be seen by analyzing samples 2, 3 and 6. Although their results are unusually low, the number of steps may have caused the tool to be not worn. A further step in this paper will be to fix the number of steps to be used in the machining strength tests, allowing the comparison of the results more accurately. In this sense, the test, when performed in a company, will have to first do a preliminary test to discover the minimum number to compare the results and only then may a more accurate comparison be done.

5 CONCLUSIONS

The present paper leads to the following conclusions:

a. The test presented in this work, despite being a preliminary one, showed to be successfully adequate to measure the Coppini index;

b. Machining strength is higher when there are more grain boundaries in stainless steels;

c. Coppini Index values are sensitive enough to characterize distinct values of machining strength in solid solutions with different number of grain boundaries;

d. Machining strength test may be performed preliminarily to discover the minimum number of steps in order to get more accurate results.

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