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EFFECT OF SURFACE FINISHING IN THE CONTACT AREA EVALUATION OF AUSTEMPERED DUCTILE IRON[1]

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Abstract

The effect of surface finishing process in the contact area evaluation of an austempered ductile iron is presented. The graphite nodules can be scratched or even removed during the roughness measurement made by a stylus. Moreover, they are exposed to the surface in different ways, depending on the finishing process. Using a mathematical routine proposed by McCool (1987), the effect of graphite nodules in a contact area is evaluated. Austempered ductile iron (ADI) with 10% volume fraction of graphite nodules was prepared under two finishing process. In the first the surface was sanded up to 1200-grit paper, while in the second set the specimens were metallographic polished. All processes were performed manually. In order to show the effect of the graphite nodules in the roughness parameters (Rq and RDq), a specific software routine (erase defects) was used. The results of ADI "without scratches" were compared to those determined for a quenched and tempered 52100 steel, prepared under similar conditions to those applied for ADI specimens. The surface finishing process almost did not affect the roughness parameters values when the scratches at nodules are not removed from the analysis for ADI. After their artificial removal, the roughness determined for 52100 steel was similar to that obtained for ADI. In this condition, the Rq/RDq ratio of ADI was affected by the finishing process. Finally, the most important implication is the reduction in the contact area values after the artificial removal of scratches caused by stylus probe. For polished specimens, approximately 94% of reduction was observed in the contact area after the scratch removal, while for the sanded ones this reduction was about 80%.

Key words: Austempered ductile iron; Surface roughness; Contact area.

EFEITO DO ACABAMENTO SUPERFICIAL NA DETERMINAÇÃO DA ÁREA DE CONTATO DE FERRO NODULAR AUSTEMPERADO

Resumo

O efeito do processo de acabamento superficial na determinação da área de contato de um ferro nodular é apresentada. Os nódulos de grafita podem ser riscados ou mesmo removidos durante a medida de rugosidade feita por um apalpador. Mais do que isso, eles estão expostos na superfície em diferentes níveis, dependendo do processo de acabamento. Utilizando a rotina matemática proposta por McCool (1987), o efeito dos nódulos de grafita na área de contato é estimada. O ferro nodular austemperado (ADI) com uma fração volumétrica de 10% de nódulos de grafita foi preparado sob dois processos de acabamento. No primeiro a superfície foi lixada até o grão 1200 mesh, enquanto no segundo caso os corpos-de-prova foram polidos metalograficamente. Todos os processos foram conduzidos de forma manual. De modo a demonstrar o efeito dos nódulos de grafita nos parâmetros de rugosidade (Rq e RDq), uma rotina específica do software foi usada. Os resultados encontrados para o ADI "sem nódulos" foram comparados com aqueles determinados para um aço 52100 temperado e revenido, preparado sob as mesmas condições aplicadas aos corpos-de-prova de ADI. O processo de acabamento superficial quase não afetou os valores dos parâmetros de rugosidade quando os riscos nos nódulos não são removidos da análise para o ADI. Após a sua remoção artificial, a rugosidade determinada para o aço 52100 foi semelhante à obtida para o ADI. Nessa condição, a razão Rq/RDq do ADI foi afetada pelo processo de acabamento. Finalmente, a mais importante aplicação é a redução na área de contato após a remoção artificial dos riscos causados pelo apalpador. Para amostras polidas, aproximadamente 94% de redução foi observada na área de contato após a remoção dos riscos, enquanto que para as amostras lixadas essa redução foi em torno de 80%.

Palavras-chave: Ferro nodular austemperado; Rugosidade superficial; Área de contato.

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1 INTRODUCTION

Cast irons containing graphite are in the midst of the most employed materials for automotive industry.(1,2) Their applications include components subject to a severe loadings at surface, resulting in losses by friction and wear.

The control of surface roughness is a very important step of their manufacturing.(3) In addition, the roughness parameters can be used to estimate their real contact area.(4,5) Neverthless, the models for real contact area are based on a 3D description of surface, considering the disctinction between summits (the local maxima on the surface) and peaks (the local maxima on a profile), as pointed out by Greenwood.(6) However, there are few routines proposed in the literature able to employed 2D roughness parameters and convert them into the 3D functional variables, such as proposed by McCool.(5)

Poon and Bushan(7) verified that the accuracy of the roughness measurement depends on the spatial resolution of instrument. Thus, the calculation of real contact area can vary in accord to the instrument used to measure roughness. Although the advance with respect to a 3D surface characterization is well recognized,(8) the stylus method is still the most widely used for measuring the surface roughness, and even if a complete 3D data set is available, roughness characteristics are calculated from a set of 2D line segments.

Surface roughness can affect the wear performance of materials. In a previous study, Brunetti, Leite e Pintaúde(9) showed that the surface preparation affected the contact fatigue life of austempered ductile iron. The main reason for that is the level of exposure of graphite. The effect of graphite in roughness of ductile iron was also investigated by Whitney Jr. and Schwab.(10) These researches verified that the nodules can induce burrs, changing the roughness of this material.

The effect of graphite on the real contact area will be investigated here, considering different levels of preparation for an austempered ductile iron.

2 EXPERIMENTAL

2.1. Specimens Preparation

A ductile iron produced by Tupy Fundições Ltd, using the continuous casting process, was studied. The material was supplied in bars of circular section with a diameter of 95 mm and a length of 45 mm. The chemical composition provided by the manufacturer is presented in Table 1.

Table 1. Chemical composition of ductile iron (mass, %)

C	Si	Mn	P	S	Cr	Cu	Mo	Mg	EC
3.71	2.54	0.18	0.07	0.01	0.03	0.72	0.19	0.04	4.56

EC = equivalent carbon

The bars were austenitized in salt bath at a temperature of 900 °C for 90 minutes and then were austempered also in salt bath at 290 ºC for two hours. The hardness values obtained for ADI were 360±10 $HB_{2.5/187.5}$ (global value) and 510±30 $HV_{0.05}$ for bainitic matrix only. The ductile iron has a volumetric fraction of graphite of 10%.

The ADI bars were machined by turning to obtain specimens in the form of rings with external diameter of 55 mm and thickness of 5.5 mm. Once machined, the two

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sides of specimens were subjected to a grinding using a flat wheel of Al_2O_3 (Class AA 100 G5 VF8) and 0.05 mm was removed from each side. Further, ten specimens were divided into two sets that differ among themselves in their surface characteristics. The first set is the sanded testing specimens, prepared using papers of 220, 320, 400, 600 and 1200 mesh, sequentially. The polished specimens establish the second set and it was obtained subsequently to the sanding with diamond polishing of 3 μm and a final polishing of 1 μm. Both the sanding and polishing processes were performed manually and only one side of each specimen was prepared.

The surface roughness was determined in the equipment Surtronic 25, employing a total measuring length of 4 mm. Fig. 1 shows the directions where the roughness measurements were performed. The profiles of surfaces were exported to the software Talyprofile 3.1.10 where a routine of treatment was used to obtain the roughness parameters (Rq and RDq), included the removal of form error and the application of a cut-off of 0.8 mm. The values of the roughness parameters correspond to an average of 36 profiles for each specimen.

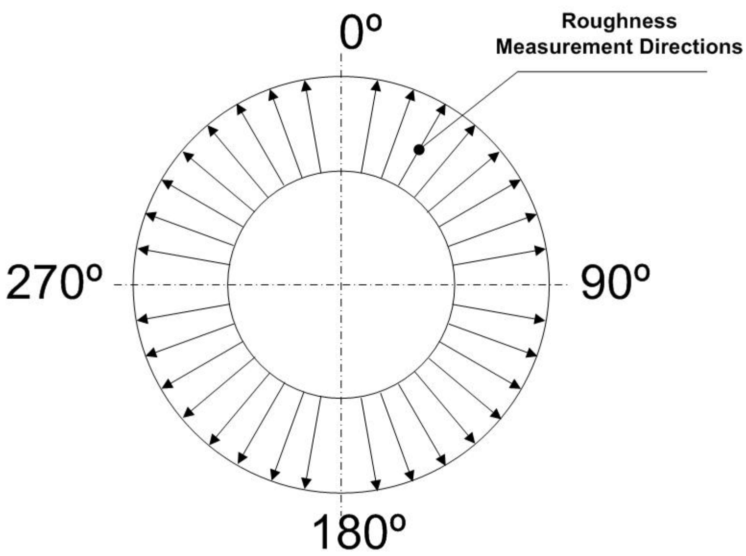

Figure 1. Directions used for the roughness measurements.

To show the effect of the graphite nodules in the roughness parameters, a specific task (erase defects) of the software was used. This tool allows removing parts from the whole profile, as the operator indicates them. For comparison of roughness parameters of ADI surfaces without the effect of graphite, surfaces of AISI 52100 steel, sanded or polished, were tested, which were prepared under similar conditions just described for ADI specimens.

2.2 Contact Area Estimation

The routine proposed by McCool[5] was used to estimate the proportion of contact area (A_c/A_0). This proposal is based on only two bidimensional roughness parameters, Rq and RDq. They are equivalent to spectral moments m_0 and m_2, so that $m_0^{1/2} = Rq$ and $m_2^{1/2} = RDq$. *RDq* is the root mean square of the mean slope of the profile.

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A third spectral moment, m_4, is required to complete the contact area estimation. It can be obtained from the ratio between m_4 and m_0, which is related to the spectral exponent, *k*. In this way, McCool's paper provided a plot of *k* against *Rq/RDq*, for especified f_1 and f_2. f_1 is the lower frequency associated with the long wave cutoff of a profile instrument. The upper frequency f_2 is determined by the electronic filter of the stylus instrument or by the finite stylus radius. As the objective of this study is to compare the surface conditions, the values of f_1 and f_2 used were similar than those presented in McCool.(5)

Finally, the proportion of contact area is calculated from

$$A_C / A_0 = 0.064(\alpha - 0.8968)^{1/2} F_1(d/\sigma_S), \qquad (1)$$

where α is the bandwidth parameter defined as $\alpha \equiv (m_0 m_4)/m_2^2$ and $\sigma_s^2 = (1 - 0.8968/\alpha)\, m_0$.

In Eq. (1) *d* is the height that separates the mean planes between two surfaces. For all cases, this value was taken as 0.1 micrometers. This value allowed that all ratios of (d/σ_S) placed into the range of 0 and 4, in which a tabulated values were avaiable in reference (4) for the function F_1. Again, a fixed value of *d* is suitable for the purposes of this investigation.

The consistence of algorithm was tested using the values of the bandwidth parameter, α, obtained by Zavarise, Borri-Brunetto and Paggi(11) for Zr4 ceramic and AISI 304 stainless steel. In this case, the value obtained for these researches for α is about 13.

3 RESULTS

Table 2 presents the Rq roughness parameter values for the studied conditions. In this Table 2 one can observe that the Rq of the sanded ADI is statistically similar than that of the polished ones, an unexpected result.(5) It can be explained by the manner as the nodules are exposed to the surface and by their interaction with the stylus. We observed that during the roughness measurement of the ADI, the stylus produces scratches on the surface and when the probe meets the graphite (Figure 2), it generates in the roughness profile a valley that would not exist (Figure 3 presents an example), affecting the roughness parameters. The graphite is not capable of supporting the pressure generated by the probe (normal force $\approx$ 5 N and contact area $\approx$ 4 μm^2), due to its low mechanical properties, therefore it suffers a deeper deformation than the metallic matrix. A interesting study would be made in grey cast irons, since Pradhan et al.(12) showed that the spherulites had a significantly lower Young's modulus and hardness than the graphite flakes.

Table 2. Average parameter Rq and RDq values for ADI

Surface Condition	R_q (μm)	*RDq, rad*
Sanded	0.25 $\pm$ 0.08	0.042 $\pm$ 0.008
Polished	0.20 $\pm$ 0.06	0.033 $\pm$ 0.007

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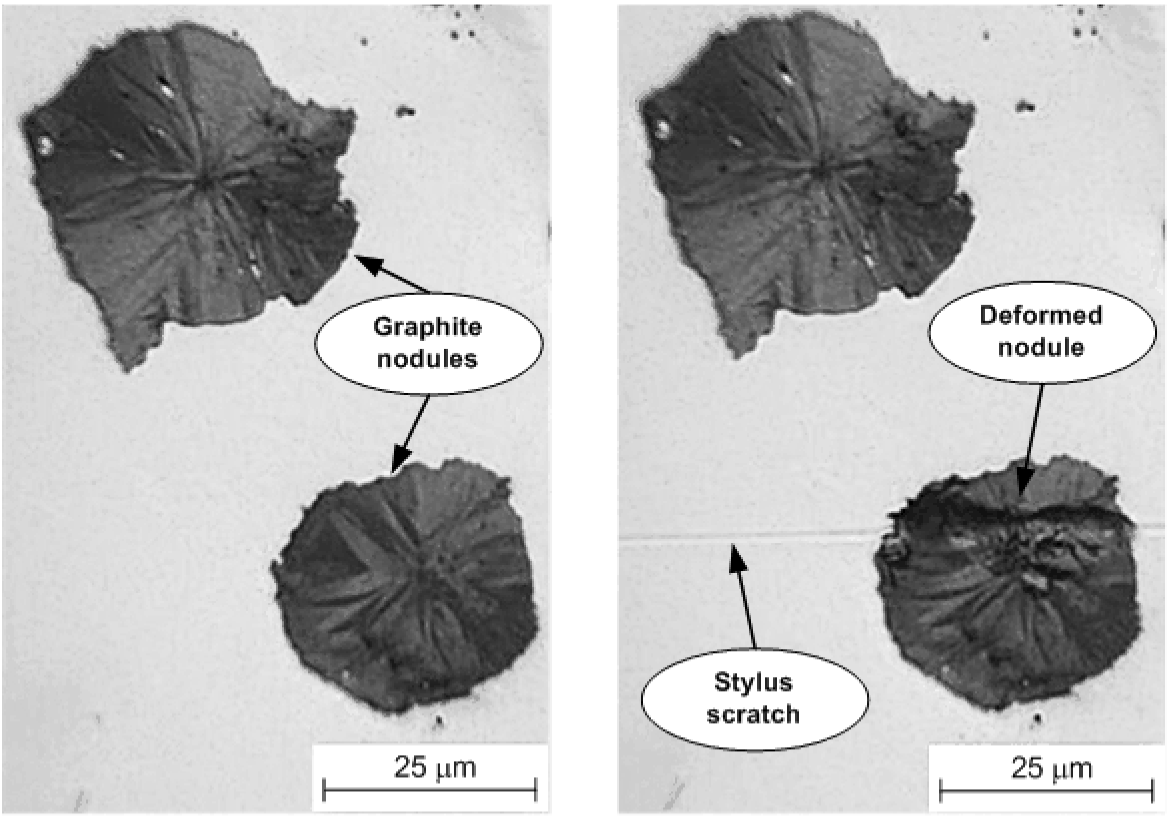

Figure 2. Image of deformed nodule of graphite during the roughness measurement.

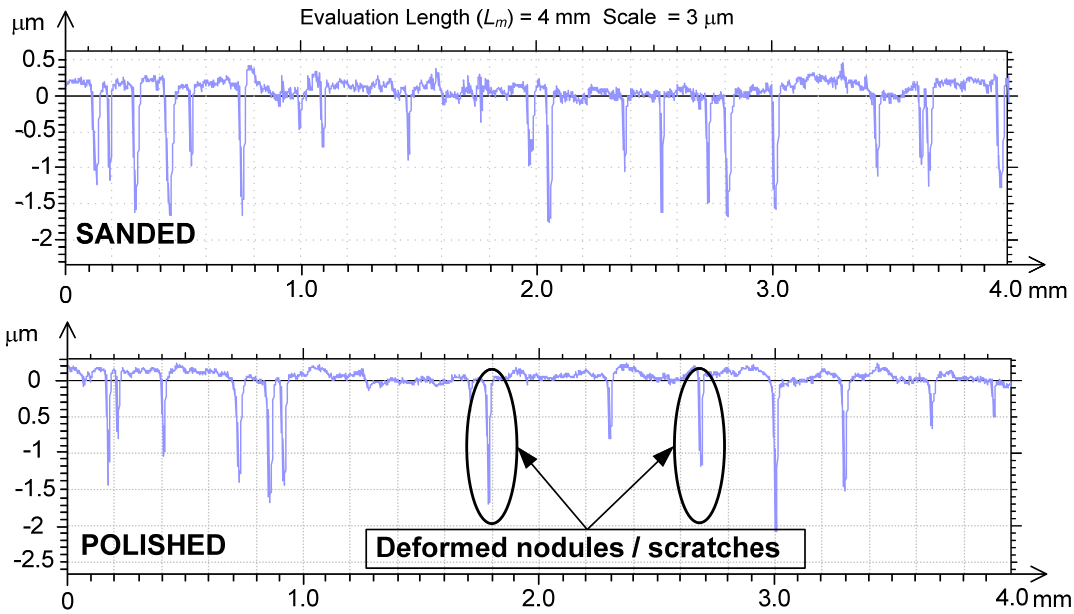

Figure 3. Profiles of the ADI surfaces

Using the routine “erase defects” of the software, all scratches was removed. The result of this operation is shown in Figure 4, showing the filtered roughness profiles of ADI surfaces.

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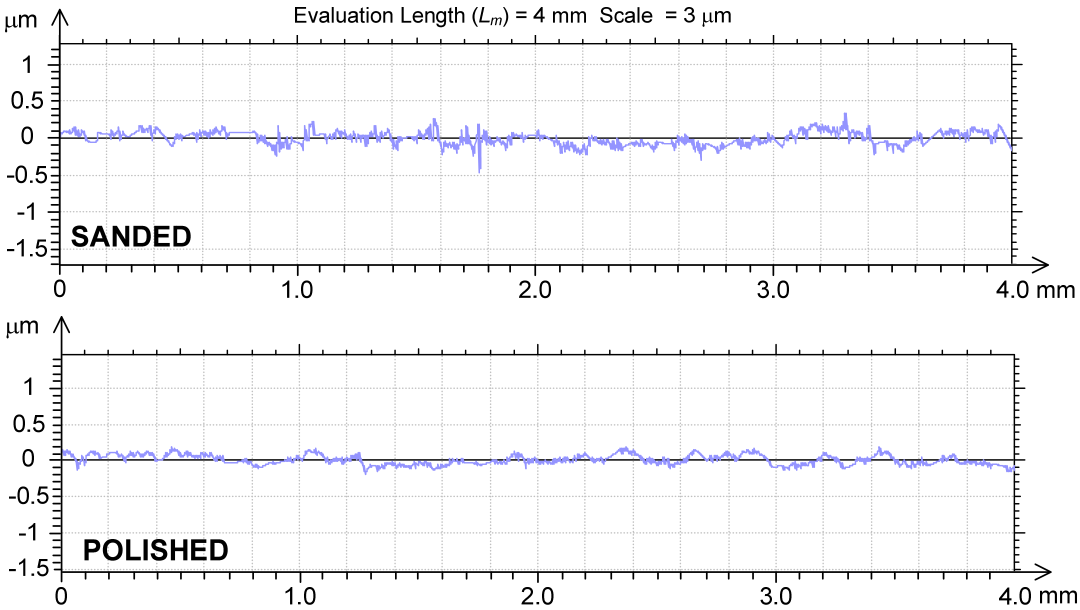

Figure 4. Profile of the ADI surfaces after the removal of scratches using the software.

The removal of the scratches implies in a series of lowermost discontinuities along the profiles. Thus, to keep their continuity very small segments were added to them. After the removal operation, it was verified that the values of the parameter Rq decreased significantly (A → B and C → D), as shown in Figure 5. There was also a considerable alteration in the value of the parameter RDq.

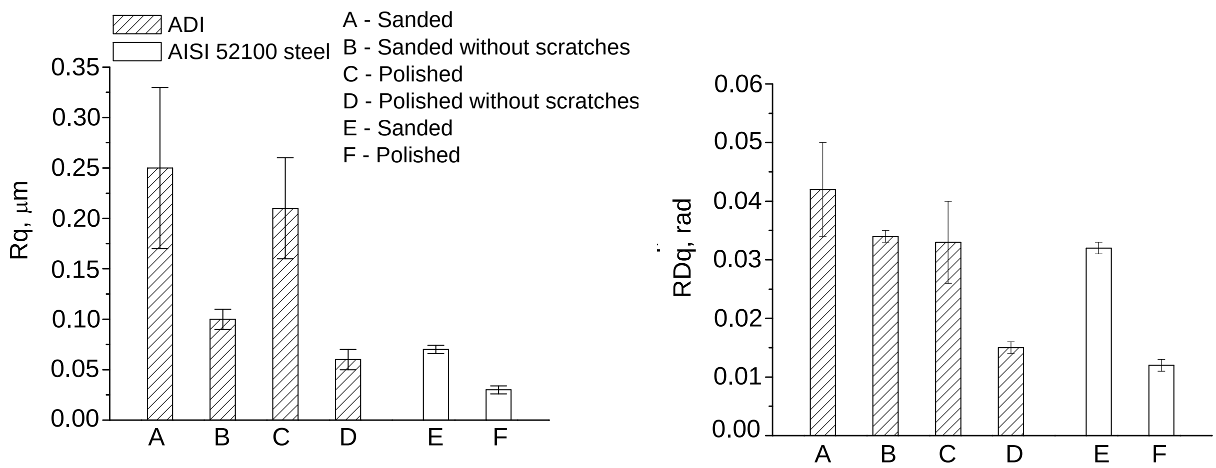

Figure 5. Effect of the scratches removal of the ADI profile regarding values of roughness parameters *Rq and RDq* .

More than that, Figure 5 shows that in the condition “without scratches” the roughness parameters of ADI are comparable to the specimens of 52100 steel (B → E and D → F).

Table 3 shows the proportion of the real contact area to the nominal area for each combination of material (ADI or 52100 steel) and kind of preparation.

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Table 3. Proportion of contact area for each material (ADI or 52100 steel) and surface condition combination

Surface condition/Material	Ac/Ao, %
Sanded ADI	12.0
Polished ADI	10.8
Sanded 52100 steel	0.692
Polished 52100 steel	0.00223
Sanded ADI after removal of scratches	2.45
Polished ADI after removal of scratches	0.69

The routine applied here can be tested using the values obtained for the sanded 52100 steel, which the (d/σ_S) ratio was 1.5, the same value used by McCool[5] for his calculations. When a material with similar Rq used by this research was taken into account (0.069 micrometers), the proportion of contact area (in %) provided by him is 0.507, which is in the same order of magnitude calculated for the sanded 52100 steel. In addition, the bandwidth parameter for this condition is 14.5, very close to that found in reference 10.

As the values of Table 3 are validated, one can observe that the proportion of contact area of ADI is practically unaffected by the preparation process (sanding or polishing). On the other hand, polished 52100 steel presented much smaller proportion of contact area compared to that observed for the sanded specimens (two orders of magnitude). The different behaviors can be attributed to the presence of graphite nodules, as previously discussed.

When the scratches were removed from the roughness profiles of ADI, the Ac/Ao values (%) were reduced. These reductions were 80% (12 to 2.45) and 94% (10.8 to 0.69), for sanded and polished specimens, respectively. Then, the proportion of contact area is now affected by the surface condition: the proportion of contact area of polished specimens is one order of magnitude smaller than the values for sanded ones.

4 CONCLUSIONS

From the measurements of surface roughness, performed using contact sylus in austempered ductile iron (ADI), we concluded that:

1. The graphite nodules of ADI are scractched by stylus during a two-dimensional measurement of roughness.
2. The proportion of contact area of ADI is similar for polished and sanded specimens, an artefact created by the presence of graphite nodules.
3. The artificial removal of scratches made by stylus on graphite nodules reduced the proportion of contact area in ADI specimens, resulting in a smaller proportion for the polishing condition than that observed for the sanded specimens.

Finally, we wish to run on this investigation performing roughness measurements making use of some interferometric technique, in order to evaluate the dependence on the graphite nodules without mechanical contact.

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