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Preliminary evaluation of the applicability of F, V and AEsignals in diagnosis of ADI machining process

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Abstract

In this study, a preliminary evaluation was made of the applicability ofthe signalsof the cutting forces, vibration and acoustic emission in diagnosis of the hardness and microstructure of ausferritic ductile iron and tool edge wear rate during its machining. Tests were performed on pearlitic-ferritic ductile iron and on three types of ausferritic ductile iron obtained by austempering at 400, 370 and 320^{0}C for 180 minutes. Signals of the cutting forces (F), vibration (V) and acoustic emission (AE) were registered while milling each type of the cast iron with a milling cutter at different degrees of wear. Based on individual signals from all the sensors, numerous measures were determined such as e.g. the average or maximum signal value. It was found that different measures from all the sensors tested depended on the microstructure and hardness of the examined material, and on the tool condition. Knowing hardness of the material and the cutting tool edge condition, it is possible to determine the structure of the material .Simultaneous diagnosis of microstructure, hardness, and the tool condition is probably feasible, but it would require the application of a diagnostic strategy based on the integration of numerous measures, e.g. using neural networks.

Keywords: Austempered ductile iron, Machining, Machining process diagnosis

1. Introduction

It is the fact well-known that the complexity of the microstructure of ausferritic ductile iron causes problems with its machining [1-4]. In its simplest description, this microstructure consists of graphite nodules and a matrix which is a mixture of the lamellae of ferrite and austenite (ausferrite). However, depending on the heat treatment parameters, i.e. on the austenitising and austempering to which the castings made of ductile iron usually of a pearlitic-ferritic matrix are subjected, the structure of ausferrite may have different features. A classification known from the literature distinguishes between the upper and lower ausferrite [5]. Lower ausferrite, formed in the temperature range of isothermal quenching, i.e. about 270-350^{0}C, is characterised by the morphology of ferrite lamellae similar to martensite and occurs in packets of uniform distribution, surrounded by high-carbon austenite. On the other hand, upper ausferrite formed at about 350-400^{0}C has a feather-like morphology with thick and branched lamellae surrounded by a large amount of high-carbon austenite. So, lower ausferrite is characterised by high hardness, high strength and resistance to abrasion, etc. Upper ausferrite confers to the ductile iron high ductility, fracture toughness, surface hardenability, etc.

The heat treatment “window”, in correlation with complex chemical composition and usually varying robustness of iron castings, makes each production plant painstakingly develop its own production parameters to get the material classified according to a specified standard [6]. Such guidelines are also being developed for the machining process, to which the castings are subjected in subsequent operations. Yet, in many cases even well-defined early in the study, the cast iron exhibits some instability during such treatment. This is mainly caused by the heterogeneity of microstructure and difficult to predict gradient nature of ausferrite due to the massiveness of castings. Therefore special means are needed to support the process of the material identification, especially during the machining process.

There is also another feature of the microstructure of the ausferritic ductile iron, which makes its machining process difficult. This feature is the, difficult to identify and quantitatively estimate, presence of metastable austenite, which during contact of the cast iron with the cutting tool will harden even more and, consequently, will become more difficult in machining. The determination of the presence of this particular type of austenite and of its content in the microstructure is not possible by the conventional testing methods, such as e.g. X-raying, and the more in the production process [7,8]. Therefore effective methods are intensely sought to determine the share of metastable austenite in the microstructure of ausferritic ductile iron and thus enable better control of its impact and of the impact of other phases on the machining process [9].

2. Samples preparation

The study involved seven samples of ductile iron with the chemical composition shown in Table 1.

Table 1.
Chemical composition of materials tested [wt%]

C	Si	Mn	P	S	Mg	Cu	Mo
3,40	2,80	0,28	0,04	0,02	0,06	0,72	0,27

The heat treatment for six samples of cast iron was carried out according to the parameters presented in Table 2, using a Nabertherm chamber furnace and a fluidised bed based on SiC with the grain size of about 100μm, available in the Department of Foundry, Warsaw University of Technology. All seven samples were tested for Brinell hardness; X-ray diffraction was measured on a Rigaku diffractometer to determine the content of austenite in the heat treated cast iron. The results of these measurements are presented in Table 3. All samples were examined on metallographic sections unetched and etched with 3% Nital. The recorded images of the microstructure are shown in Figures 1.

Table 2.
Ductile iron heat treatment cyclesparameters

Sampledesignation	Heattreatment			
	Austenitising		Austempering	
	Temp. [^{0}C]	Time [min.]	Temp. [^{0}C]	Time [min.]
DI	No heat treatment			
ADI_400_180	900	120	400	180
ADI_370_180			370	
ADI_320_180			320	

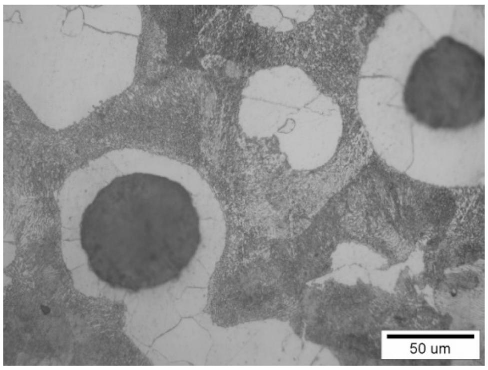
Table 3.
Hardness and austenite content in cast and heat treated ductile iron

Sample designation	Hardness	Austenitecontent
	HB	[%]
DI	239	0
ADI_400_180	270	20,5
ADI_370_180	293	24
ADI_320_180	373	12,1

3. Test stand

Machining tests were carried out on a CNC Cincinnati Milacron 500 ARROW machine tool. This is a 3-axis milling centre with Haidenhain control system. The test track consisted of the three main groups:

1. The first group was responsible for processing of the physical phenomenon into an electrical signal. This group consisted of sensors of the vibration (symbol: V), acoustic emission (symbol: AE) and cutting force (symbol: F).
2. The second group consisted of amplifiers and filters, responsible for the initial processing of signals.
3. The last group was data acquisition and it was composed of:

a)


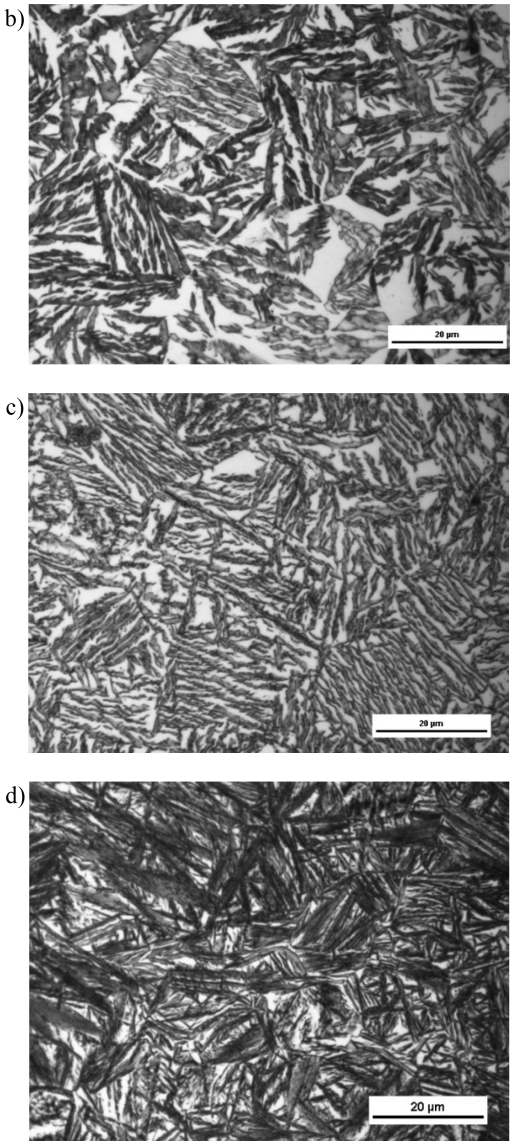


Fig. 1. Microstructure of ductile iron samples;
a) DI, b) ADI 400_180, c) ADI 370_180, d) ADI 320_180

- the terminal connections, whose task was to connect the preamplifier with a data acquisition card
- the DAQ data acquisition card, to process the analogue signal to digital one
- a PC computer equipped with a DAQ card and software for data acquisition.

To record the cutting forces and vibration accompanying this process, it was necessary to install on the machine additional sensors: sensor to measure the pressure in three axes, sensor to measure vibration in three axes, and acoustic sensor. To get fully reliable results, it was necessary to control the tool wear rate in the course of the studies. Machining of ausferritic ductile iron causes high mechanical and thermal load, which leads to wear on the cutting edge and on the rake face. Signals were recorded for the five levels of the cutting tool wear V_{BC}: 0.04 mm, 0.1 mm, 0.25 mm, 0.3 mm, 0.36 mm. The tool used for the study was the end mill type R390-020B20-11L (folded cutter from Sandvik) with a diameter of 20mm and cutting inserts designated as: R390-11 T3 08M-KM.

4. Methodology

The study involved surface machining of all four samples of the ausferritic ductile iron. Before starting the test, the samples required some preparation. Milling of sample grips was necessary to ensure better and repeatable fixing of the workpiece in a chuck. The surface of each sample was subjected to facing to remove the surface layer from the workpiece. The next step consisted in making the ten planes, i.e. "steps", in each of the samples. Figure 2 shows a pictorial drawing of sample ready for testing.

Each step had a length of 13mm and a height of 0.1 mm. Owing to these dimensions, the tool in successive passes did not enter the material with its whole diameter, which would be unfavourable, since milling with the width of about 70% of the tool diameter is recommended. The dimension of 13mm fully satisfied this condition..

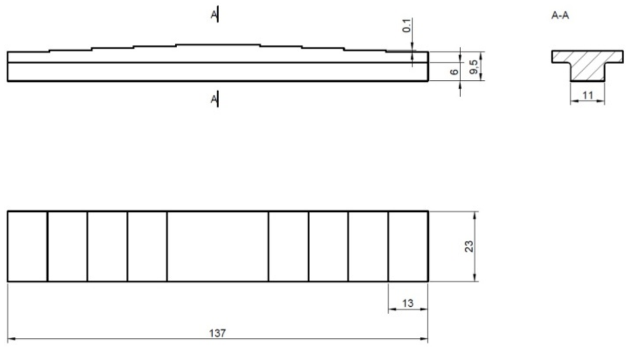


Fig. 2. Pictorial drawing of the sample

After determination of signal components corresponding to the operation of machining, measures of the signals associated with the cutting edge wear rate started to be determined. For signals "S" the following measures were determined:

- the average value of signal Savg for signals: Fx, Fy, Fz, AErms,
- the maximum value of signal Smax for signals: Fx, Fy, Fz, AErms, Vx, Vy, Vz.
- the minimum value of signal Smin for signals Fx, Fy, Fz, AErms, Vx, Vy, Vz.
- the second-order moment value $Smom^2$ for signals: Fx, Fy, Fz, AErms, Vx, Vy, Vz.
- the average of the values of the absolute differences between the successive samples of the signal SSumdY for signals: Fx, Fy, Fz, AErms, Vx, Vy, Vz.

Often, in cases of this type of treatment, the initial and final signal component is disturbed, so all measures were also determined for the 2nd second of machining marking them with an additional symbol 2s.

5. Cutting force measurements

The study assumes that the purpose of the system is to determine the structure of the workpiece from the known current tool wear rate. In this case, in the diagnosis, these measures will be useful that produce a distinctly different level for each type of the cast iron microstructure. With data available for one cutting tool only, it is necessary to determine whether differences in the measures for individual structures are not random. For this purpose it was decided to compare the waveforms of measures depending on the structure of material for different levels of the wear. If we can find a sequence of structures for which all waveforms will be monotonic, then this measure can be considered a useful tool in diagnostics of the structure of the workpiece.

When the cutting force is measured, the most common waveform that can be plotted for a tool edge wear - sample type relationship is the signal recorded for the force Fz in the 2nd second of cutting taken as an average of the values of the sum of absolute differences between the consecutive samples (Fig. 3). The diagram mainly shows us the difference in signal levels for the initial state of the tool edge wear (0-0.1) and for the more advanced state of wear (0.2-0.5); it also shows a significantly lower level of signals for the base sample as compared to the sample after heat treatment - red line in the graph. Yet, this waveform will be more useful when determining the degree of the tool edge wear in contact with a specific material.

In distinguishing the type of cast iron microstructure, more useful seem to be the graphs plotted for a sample/ structure type – tool edge wear system. From the signal recorded for the force Fz in the 2nd second of cutting as an average of the values of the sum of absolute differences between consecutive samples in the above system, one can derive a relationship where for the wear values > 0.1, signals for the ausferritic ductile iron are at a completely different level than the signals for the base cast iron - red line in the graph (Fig. 4). Isolating in this chart the cast iron subjected to isothermal quenching at different temperatures poses no real problem. The waveforms in Figure 4 show signal at an obviously different level for the base cast iron sample DI, although general trend is similar for all states of the cutting tool wear.

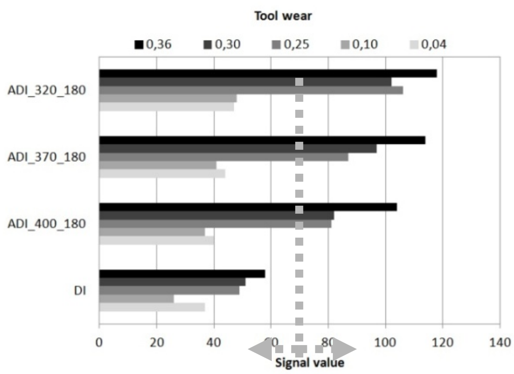


Fig. 3. Signal of cutting force -Fz in the 2nd second of cutting for different DI samples

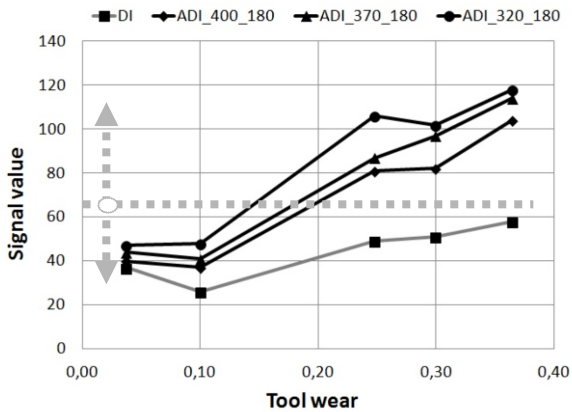


Fig. 4. Signal of cutting force -Fz in the 2nd second of cutting for different DI samples

6. Acoustic Emission measurements

Similar trends as for the cutting force measurements can be found in the acoustic emission (AE) waveforms. It was observed that the recorded signals of the maximum or minimum effective value give the most interesting sequences in terms of the material analysis. For further studies, the analysis of AE signals which in a rearranged system are presented in Figure 5 was selected. A comparison of the signals shows a tendency prevailing among these trends to correspond to different temperatures of the isothermal quenching. This suggests their applicability in differentiating between the individual types of ausferritic ductile iron and the base ductile iron DI. For all signals, the values are arranged in ascending order with the increasing temperature of isothermal transformation for the tool edge wear > 0.1.

In all graphs of the AE measurements, one can easily distinguish between the values obtained for a base sample and the, collected in groups, values for the samples of cast iron after heat treatment. However, it would be difficult to definitively separate them using a simple criterion, especially when looking for a specific microstructure. Recording the signal of a value of the second-order moment offers a useful solution here. In Figure 6, showing values of the above-mentioned signals, these signals are clearly grouped and set at certain levels for the base sample and for the samples of cast iron after heat treatment – the signals are separated by a red line. Therefore, to these AE signals can be given the attribute of a measure that enables us to distinguish between the microstructure of base material and the microstructure of ausferritic ductile iron matrix. The only thing to do is to point out that this distinction applies to the tool wear ≥ 0.1

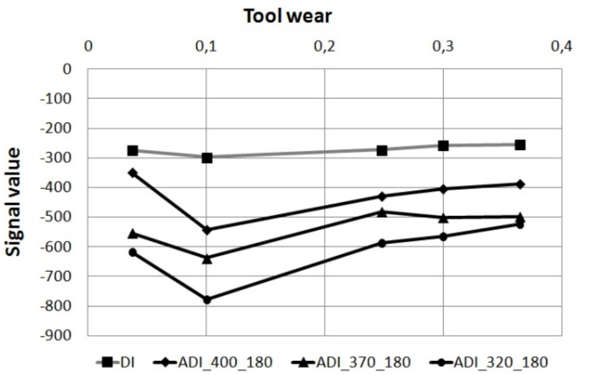


Fig. 5. Signal of acoustic emission –Ae min. for different DI samples

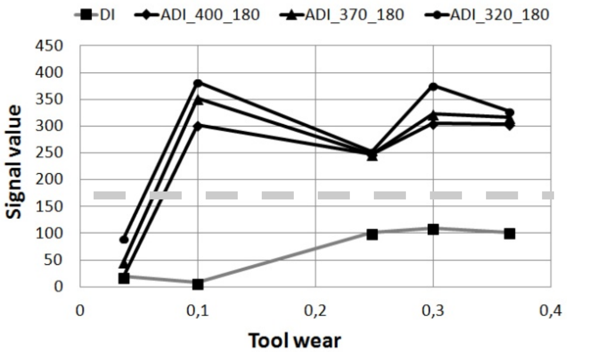


Fig. 6. Signal of acoustic emission –Ae mod. in the 2^{nd} second of cutting for different DI samples

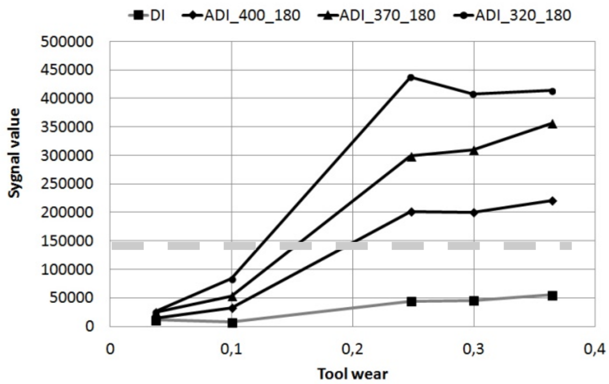


Fig. 7. Signal of vibration –Vz mom2 for different DI samples

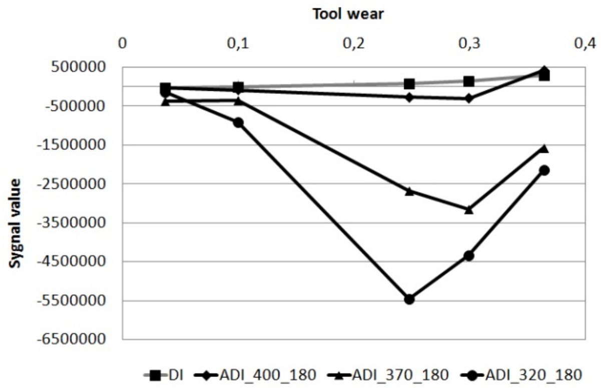


Fig. 8. Signal of vibration –Vz mom3 for different DI samples

7. Vibration measurement

Vibration measurements show similar trends to the measurements of force and acoustic emission, especially as regards the waveform of the signal of a value of the second-order moment. They indicate that it is easy to separate signals originating from the base ductile iron and from the cast iron after heat treatment (Fig. 7). This is particularly true for signals emitted when the tool edge wear is larger than 0.1 - red line in Figure 7.

The most interesting from the viewpoint of a difference in the microstructure of the examined material and also diagnosis of the tool edge wear is the relationship of signals for a value of the third-order moment (Fig. 8). The waveform shows that it is possible to simultaneously make a diagnosis of the tool wear and detect the type of cast iron. In both graphs (Figs 7 and 8) one can easily extract the specific trends accompanying both time and temperature of the isothermal transformation. Also, for the tool wear >0.1, the extremes can be set, which may serve as a simple criterion of wear. Both graphs show that, by establishing certain threshold value, the difference between the base ductile iron and cast iron after heat treatment can also be traced.

8. Analysis of material

The results presented so far in the article clearly indicate the possibility of diagnosing the structure of the workpiece, assuming that the cutting edge wear is known. For the diagnosis of material structure, the measures taken from all sensors are useful. To sum up this analysis, it is worth comparing additionally the waveforms with the properties of the examined cast iron types, i.e. hardness and austenite content (Figs. 9 and 10). The charts can be compared with the waveform of the maximum tool edge wear presented earlier in Figure 11 for the registered cutting force signal Fz_{max}. Analysing particular values, relatively large convergences can be observed, especially between the values of force and hardness – the waveforms of hardness and force Fz grow in both groups with increasing temperature of the transformation. However, it is easiest to compare trends for the whole group of ausferritic ductile irons. They allow concluding that the higher is the hardness of this cast iron, the larger are the forces Fzmax, but this is not consistent with the austenite content in the microstructure of the cast iron matrix. Perhaps it is related with the heterogeneity of austenite and its hardening as a result of the stress and strain effect [9,10].

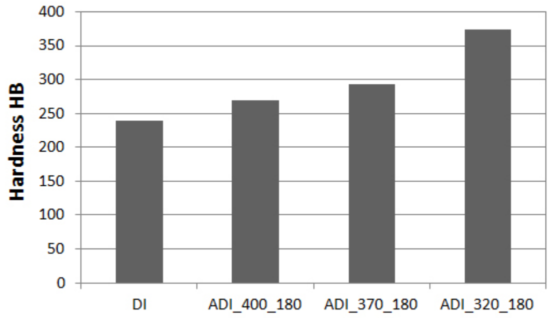


Fig. 9. Hardness of the tested DI and ADI samples

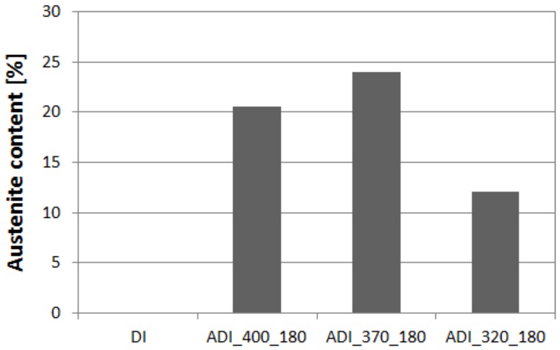


Fig. 10. Austenite content in samples of the tested DI and ADI

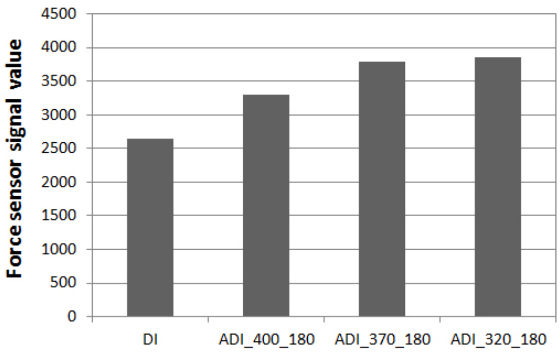


Fig. 11. Changes in values of the signal of the cutting force Fz_{max} recorded for the maximum tool edge wear of 0,36

9. Summary

A relationship was detected between signals of the cutting forces, vibration and acoustic emission, and the tool wear rate, hardness of material and its structure. Unfortunately, none of the measures tested was sensitive to a change in one of the parameters only (wear, hardness, structure), thus making the diagnosis based on a single-signal measure and the simple boundary strategy impossible. The use of such strategy is possible in respect of one of the parameters, provided other parameters are known (their values are measured by another method). The influence of different parameters on different measures is not the same, which gives the opportunity to use a diagnostic strategy based on the integration of numerous measures of the signals, such as strategies using methods of artificial intelligence, neural networks and fuzzy logic. The differences in the parameters impact on the measures are best seen on the waveforms of the measures from various sensors, thus providing an effective system for monitoring of the ausferritic ductile iron machining process.

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