ANALYZING THE REAL AREA OF CONTACT WEAR USING ANOVA

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Abstract. Austempering is a relatively new treatment in the field of ductile iron casting. This heat treatment was found to improve the ductile irons at high levels of strength, rendering ductile iron castings superior to steel forgings Austempered ductile irons usually contain a large quantity of retained austenite that can help to optimize their mechanical properties. Many of the properties of austempered ductile iron depend on the austenite which is retained following the bainite reaction. The studied cast iron had the following composition: 3.70 %C; 2.46 %Si; 0.56 %Mn; 0.038 %P; 0.009 %S; 0.25 %Mo; 0.23 %Cu; 0.065 %Mg. This cast iron was elaborated in an induction furnace. Nodular changes were obtained with the "In mold" method, with the help of prealloy FeSiCuMg with 10-16% Mg, added into the reaction chamber in a proportion of 1.1% of the treated cast iron. The structure in raw state is perlito-feritic typical for a cast iron with geometrically regular nodular form. The casted raw iron had the following mechanical properties: Rm = 650 N/mm^2, HB = 180; KC = 10 J/cm^2; A = 12 %. The paper presents an example of calculation for the one-way repeated measures applied for the results of an austempered ductile iron. This research has a number of objectives which can be started as follows:

1. To calculate the real area variation (A_r) at the end of a bainitic S.G. cast iron wear process;
2. Study of the real wear contact values (A_r) variation, depending on the isothermal heat treatment parameters (T_{iz} and τ_{iz}) and the micro hardness $HV_{0.01}$ for F_N = 4 kgf;
3. The calculation for the one-way repeated measures applied for the results of the real area variation (A_r).

Keywords: cast iron, heat treatment, wear, analysis of variance

1. Introduction

Austempered ductile iron (ADI) with a bainitic matrix, obtained by heat treatment and isothermal hardening is the material which combines a lot of superior attributes of the classical ductile iron or forged iron [1].

A wide range of properties can be obtained in these material components owing to changes in proportions of the major phases present in the microstructure: bainitic ferrite, high carbon austenite and graphite nodules. Martensite, ferrite, iron carbides and other alloy carbides may also be present.

At present, very limited information on the abrasive wear properties of austempered ductile iron is available. Wear is one of the major ways by which materials cease to be useful [2].

Wear, in effect, is the progressive detachment of material from the surface layers of a component during its operation, to change the initial status of contact surfaces. Placental material may be caused by mechanical action, chemical attack corrosion), thermal requests, a.o.

In general, it supports the proposed classification by F.T Barwell [3, 4] relating to the four fundamental types of wear (dry and in the presence of lubricants):

- Wear adhesive or adhesion, which seems to be the result of joining surfaces when the actual contact surfaces reach distances at which manifests molecular forces of attraction;
- Abrasion and abrasive wear, is due to the effect of cutting and scratching, exercised hard particles which, coming from different sources, came from friction surfaces;
- Wear corrosion or corrosion, which is due to chemical reaction between agencies aggressive environment existing in the lubricant or friction and rolling bodies in the joint friction torque;
- Tiredness or fatigue wear, wear is a complex and the underlying phenomena of plastic deformation, compression, hardening, residual stresses production, etc.

Process plant and subsidiary processes contend with a much bigger wear problem than in the case of machine parts, although their life is often much shorter. Therefore, it is important to enhance the wear resistance of cast irons.

Austempered ductile iron is a relatively-recently-developed material which combines high strength and good wear resistance [1].

The nature of abrasive wear is dependent on several factors such us microstructure of the abraded surface, type of abrasive, relative movement and loading, chemical action and temperature. There have been a number of papers published which refer to the wear resistance of ADI. Some contradictory opinions have been expressed in these works, such as those concerning the effect of hardness on wear.

This research has a number of objectives which can be started as follows:

1. To calculate the real area variation (A_r) at the end of a bainitic S.G. cast iron wear process;

2. Study of the real wear contact values (A_r) variation, depending on the isothermal heat treatment parameters (T_{iz} and τ_{iz}) and the micro hardness $HV_{0.01}$ for F_N = 4 kgf.

3. The calculation for the one-way repeated measures applied for the results of the real area variation (A_r).

2. Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is the method used to compare continuous measurements to determine if the measurements are sampled from the same or different distributions [5]. It is an analytical tool used to determine the significance of factors on measurements by looking at the relationship between a quantitative "response variable" and a proposed explanatory "factor". This method is similar to the process of comparing the statistical difference between two samples, in that it invokes the concept of hypothesis testing. Instead of comparing two samples, however, a variable is correlated with one or more explanatory factors, typically using the *F*-statistic. From this *F*-statistic, the *P-value* can be calculated to see if the difference is significant [6].

Analysis of variance (ANOVA) is the most efficient method available for the analysis of experimental data. Analysis of variance is a method of considerable complexity and subtlety, with many different variations, each of which applies in a particular experimental context.

A One-Way Analysis of Variance is a way to test the equality of three or more means at one time by using variances [6].

Take into account the following assumptions:

- The populations from which the samples were obtained must be normally or approximately normally distributed.
- The samples must be independent.
- The variances of the populations must be equal.

3. Materials

The studied cast iron had the following composition: 3.70 %C; 2.46 %Si; 0.56 %Mn; 0.038 %P; 0.009 %S; 0.25 %Mo; 0.23 %Cu; 0.065 %Mg.

This cast iron was elaborated in an induction furnace. Nodular changes were obtained with the "In mold" method, with the help of prealloy FeSiCuMg with 10-16% Mg, added into the reaction chamber in a proportion of 1.1% of the treated cast iron.

The structure in raw state is perlito-feritic typical for a cast iron with geometrically regular nodular form. The casted raw iron had the following mechanical properties: Rm = 650 N/mm^2, HB = 180, KC = 10 J/cm^2, A = 12 %.

4. Heat treatment

The parameters of the heat treatment done were the following: the austenizing temperature, t_A = 900 °C, the maintained time at austenizing temperature was, τ_A = 30 min; the temperature at isothermal level, t_{iz} = 300 and 400 °C; the maintained time at the isothermal level, specific the first step of bainitic transformation are τ_{iz} = 5, 30, and 60 minutes.

5. Experimental procedure and results

The experiment groups performed at isothermal maintenance in salt-bath (55% KNO_3 + 45% $NaNO_3$), being the cooling after the isothermal maintenance was done in air. From this material, six typical wear-test specimens (ϕ 20×3 mm) was done. Abrasive wearing was done on a laboratory plant type fixed cylindrical pin/disk involved typical car plate with fixed specimens, with a torque level IV. Each sample (ϕ 20×3 mm) was tested for wear with the same pressing force, F_N = 40 N (4.078864852 kgf) for one hour at room temperature. It was also determinate the microhardness ($HV_{0.01}$) with an "Akashi MVK - E3" machine. If research on tubes of S.G. cast iron wastage, nominal surface is 314 mm^2, for all samples used. In the calculation of actual contact area (A_r), totaling micro surfaces roughness contact (surfaces contact spots), it was used for determination of a specific formula for calculation, presented by M.A. Martinez [4]:

$$A_r = F_N / HV , \quad \text{in [mm}^2\text{]} \qquad (1)$$

where F_N is normal tightness force, in kgf, and HV is Vickers micro hardness, in kgf/mm^2.

The indicative values of the actual contact area (A_r) are presented in Table 1.

Studying the real surface value (A_r) set the Table 1, are mentioned the following:

- for the al isothermal maintained temperatures (t_{iz} = 300 and 400 °C), the A_r value increase with increasing of the isothermal maintaining time (τ_{iz}) from 5 to 60 minutes, this being due to micro hardness values $HV_{0.01}$, dependent values obtained after treatment of the structure;
- values of A_r increased for each isothermal maintaining time (τ_{iz} = 5, 30 and 60 minutes) with increasing of the isothermal maintained temperatures from t_{iz} = 300 to 400 °C and that due to the structure components and the micro

hardness evidence;
- the maximum microhardness's value was obtained for the specimen who are maintained at the isothermal level for five minutes. Less maintaining provides higher values for microhardness and this can be explained by the increasing of the proportion of the martensite, when the specimen are cooling in air after the isothermal maintaining.

Table 1. The variation of the real wear contact values (A_r) depending on the isothermal heat treatment parameters (T_{iz} and τ_{iz}) and the micro hardness $HV_{0.01}$ for F_N = 4 kgf

T_{iz} [°C]	τ_{iz} [min]	$HV_{0.01}$ [kgf/mm^2] parallel observations			A_r [mm^2] parallel observations		
		Obs. 1	Obs. 2	Obs. 3	Obs. 1	Obs. 2	Obs. 3
300	5	520	528	515	0.0769	0.0757	0.0776
	30	475	471	476	0.0842	0.0849	0.0849
	60	458	448	446	0.0873	0.0892	0.0896
400	5	390	391	393	0.1026	0.1023	0.1018
	30	352	354	354	0.1136	0.1130	0.1130
	60	343	345	343	0.1166	0.1159	0.1166

6. Calculation of ONE-WAY ANOVA

A one way repeated measures ANOVA is used when you have a single group on which you have measured something a few times [7, 8, 9]. The values of the real surface value (A_r) "Data Analysis" for calculation are presented in Table 2.

It was selected the level of significance (the default is 5% or 0.05). The Summary Table of the ANOVA-Single Factor is presented in Tables 3 and 4.

The Source of Variation of the ANOVA-Single Factor is presented in Tables 5 and 6.

Table 2. Data Analysis

Parallel observations	Samples, k = 3					
n = 3	t_{iz} = 300 °C			t_{iz} = 400 °C		
	τ_{iz} = 5 min	τ_{iz} = 30 min	τ_{iz} = 60 min	τ_{iz} = 5 min	τ_{iz} = 30 min	τ_{iz} = 60 min
Obs 1	0.0769	0.0842	0.0873	0.1026	0.1136	0.1166
Obs 2	0.0757	0.0849	0.0849	0.1023	0.1130	0.1159
Obs 3	0.0776	0.0840	0.0896	0.1018	0.1130	0.1166

Table 3. Summary Table of the ANOVA-Single Factor, t_{iz} = 300 °C

ANOVA: Single Factor SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.2302	0.076733	9.23E-07
Column 2	3	0.2531	0.084367	2.23E-07
Column 3	3	0.2618	0.087267	5.52E-06

Table 4. Summary table of the ANOVA-Single Factor, t_{iz} = 400 °C

ANOVA: Single Factor SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.3067	0.102233	1.63E-07
Column 2	3	0.3396	0.1132	1.2E-07
Column 3	3	0.3491	0.116367	1.63E-07

Table 5. Source of variation of the ANOVA-Single Factor, t_{iz} = 300 °C

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F*-crit
Between Groups	0.000178	2	8.88E-05	39.94653	0.000341	5.143243
Within Groups	0.0000133	6	2.22E-06			
Total	0.000191	8				

Table 6. Source of variation of the ANOVA-Single Factor, t_{iz} = 400 °C

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F-crit*
Between Groups	0.00033	2	0.000165	1108.366	1.97E-08	5.143243
Within Groups	8.93E-07	6	1.49E-07			
Total	0.000331	8				

Dependencies between factors are shown in relationships (2), (3), (4) and (5):

$$SS\ \text{Total} = \text{SS Within} + SS\ \text{Between}; \quad (2)$$

$$MS\ \text{Within} = \frac{SS\ \text{Within}}{df\ \text{Within}} = \frac{SS\ \text{Within}}{N-k}; \quad (3)$$

$$MS\ \text{Between} = \frac{SS\ \text{Between}}{df\ \text{Between}} = \frac{SS\ \text{Between}}{k-1}; \quad (4)$$

$$MS\ \text{Total} = \frac{SS\ \text{Within} + SS\ \text{Between}}{N-1} = \frac{SS\ \text{Total}}{N-1}, \quad (5)$$

where

SS = Sum of squares (i.e. sum of the squared deviations from the mean);

MS = Mean square;

MS Total = Mean square total;

k is the number of experimental points;

N is the total number of determinations, $N = k \cdot n$;

n is the number of parallel determinations performed each experimental points *k*;

df – the degrees of freedom is equal to the sum of the individual degrees of freedom for each sample. Since each sample has degrees of freedom equal to one less than their sample sizes, and there are *k* samples, the total degrees of freedom is *k* less than the total sample size: *df* = N – *k*;

F is the calculated value of the Fischer criteria;

$$F = MS\ \text{Between} / MS\ \text{Within}; \quad (6)$$

F-crit is the critical value of the Fischer criteria: for the level of significance, α = 0.05 (the default is 5% or 0.05.), the critical value for *F*, *F*-crit with *df*(2, 6) is 5.143243;

P value is determined from the *F* ratio and the two values for degrees of freedom;

SS Within captures variability within each group;

SS Between captures variability between each group.

7. Discussion

The following observations can be made after analyzing the results:

- examining the data revealed that at shorter austempering time for all maintaining temperature, the bainitic transformation is not enough and austenite converts to martensite with the increasing the values of hardness (HB).
- for the isothermal maintained temperatures (t_{iz} = 300 °C), the specific structures expended is made by inferior bainitic ferrite with martensite and an amount of retained austenite, due to the micro hardness evidence (Table 1);
- for the isothermal maintained temperatures (t_{iz} = 400 °C), the specific structures expended is made by superior bainitic ferrite with martensite and with the a higher amount of retained austenite, due to the micro hardness evidence (Table 1);
- for the al isothermal maintained temperatures (t_{iz} = 300 and 400 °C), the A_r value increase with increasing of the isothermal maintaining time (τ_{iz}) from 5 to 120 minutes, this being due to micro hardness values $HV_{0.01}$, dependent values obtained after treatment of the structure;
- values of A_r increased for each isothermal maintaining time (τ_{iz} = 5, 30 and 60 minutes) with increasing of the isothermal maintained temperatures from t_{iz} = 300 to 400 °C and that due to the structure and the micro hardness evidence;
- the evolution of the hardness properties is determined by the structural changes reported to the parameters of the heat treating. Together with increasing the level of the isothermal maintenance temperature inside the structure will appear the superior bainite and the martensite will disappear [6].

8. Conclusion

By studying all the data presented in this paper following remarkable conclusions:

(a) The wear process was influenced by the structural changes of the specimen's surface;

(b) To establish accurate values real contact area (*Ar*), a particularly important assessment of the worn surfaces micro hardness;

(c) Real contact surface is directly influenced by heat treatment of quenching isotherm parameters (T_{iz} and τ_{iz}) who have undergone tests and wear process parameters (F_N and press of its time);

(d) While the isothermal maintained temperatures increases from t_{iz} = 300 to 400 °C, the micro hardness values $HV_{0.01}$, decreases, influenced by structural changes;

(e) Analysis of variance (ANOVA) is the most efficient method available for the analysis of experimental data. This method is used to compare continuous measurements to determine if the measurements are sampled from the same or different distributions. It is an analytical tool used to determine the significance of factors on measurements by looking at the relationship between a quantitative "response variable" and a proposed explanatory "factor". This method is similar to the process of comparing the statistical difference between two samples, in that it invokes the concept of hypothesis testing. Instead of comparing two samples, however, a variable is correlated with one or more explanatory factors, typically using the F-statistic. From this F-statistic, the *P-value* can be calculated to see if the difference is significant;

(f) From Table 5 and 6 it was compares the two values of the *F* test statistic: calculate value (*F*) and critical value (*F*-crit). Note that in this case the calculated value (*F*) is greater than the critical value (*F*-crit), i.e. 39.94653 > > 5.143243 and 1108.366 > 5.143243. In both cases, it can be concluded that the analysis performed during stepwise isothermal maintenance is an important parameter for the studied variation of the real wear contact values (A_r) process.

References

1. Bahmani, M., Elliott, R., Varahram, N. (1997): *Austempered ductile iron: a competitive alternative for forged induction-hardened steel crankshafts*. International Journal of Cast Metals Research, ISSN 1364-0461, vol. 9, no. 4, p. 249-257
2. Francucci, G., Sikora, J., Dommarco, R. (2008): *Abrasion resistance of ductile iron austempered by the two-step process*. Materials Science and Engineering: A, ISSN 0921-5093, vol. 485, no. 1-2, p. 46-54
3. Yazdani, S., Rahimi, M.A. (2005): *Wear Behavior of an Austempered Ductile Iron Containing Mo-Ni-Cu*. Materials Science Forum, ISSN 1662-9752, vols. 475-479, p. 199-202
4. Martinez, M.A., Martin, A. (1993): *Tribologia en aceros - Una vision actualizada de la friccion y el desgaste*. Ingineria Chimica, ISSN 0210-2064, vol. 9, p. 81-87
5. Armstrong, R.A., Eperjesi, F., Gilmartin, B. (2002): *The application of analysis of variance (ANOVA) to different experimental designs in optometry*. Ophthalmic and Physiological Optics, ISSN 1475-1313, vol. 22, no. 3, p. 248-256
6. Taloi, D. (1983): *Optimizarea proceselor metalurgice - Aplicații în metalurgie* (The optimization of the metallurgical processes. Aplications in metallurgy) E.D.P. Publishing, Bucharest, (in Romanian)
7. Budde, J. (2009): *Variance analysis and linear contracts in agencies with distorted performance measures*. Management Accounting Research, ISSN 1044-5005, vol. 20, no. 3 (September), p. 166-176
8. Wing, K.T. (2005): *Using enhanced cost models in variance analysis for better control and decision making*. Management Accounting Quarterly, ISSN 1528-5359, vol. 4, no. 2, p. 27-35
9. Yahya-Zadeh, M. (2011): *A new framework for capacity costing and inventory variance analysis*. Journal of Applied Management Accounting Research, ISSN 1044-5005, vol. 9, no. 2 (Summer), p. 61-81

Received in October 2015