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Approach to the prediction of thermal fatigue of aluminium high pressure die casting (AISI H13) using the Basquin equation and finite elements

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Analysis and modelling

ABSTRACT

Purpose: The main aim of the present study was to analyze the influence of the thermal fatigue on the AISI H13 die surface during the aluminium high pressure die casting process.

Design/methodology/approach: Two different gradients of temperature were considered (ΔT = 200 and 250°C). The thermal stresses were obtained through computer numerical analysis - Finite Element Method. Then an analytical study, through the equation of Basquin, was conducted to determine the number of cycles until the die failure.

Findings: Taking in account the divergences found in the solutions for determining the number of life cycles to die failure and guided by technical data and commercial experience of life cycles for the AISI H13 steel it was possible to propose coefficients of correction for the equation of Basquin.

Research limitations/implications: It should be highlighted that the use of the proposed corrected coefficients for the Basquin equation can show a satisfactory results related to the practice - valid only for similar conditions of this work.

Practical implications: The behavior of the steel used for the dies are dependent of the temperature and density, elastic modulus, Poisson's ratio, coefficient of thermal expansion, hardness, thermal conductivity and yield strength and an incorrect steel selection can lead to thermal stresses amplitude favorable for the onset of the cracks.

Originality/value: The dies play an important role in the aluminium high pressure die casting process. During the die manufacturing process the die design and the steels behavior are a major concern on efficient manufacturing, i.e. related to maximize the life cycle. During the injection process the thermal fatigue is one of the responsible factor of onset of cracks - estimated to be approximately 80%.

Keywords: Aluminium high pressure die casting; AISI H13; Basquin; Thermal fatigue

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1. Introduction

High pressure die casting tools are constantly exposed to thermal fatigue which is generated through the thermal stresses, Klobcar et al. [1] and Wang [2]. According to Hu [3], thermal fatigue is responsible for 80% of the failures of the dies during the hot injection process. Ji Lin et al. [4], found that the cracks are generated by stress concentrations, regardless if thermal or mechanical stresses. According Aqida et al. [5], the thermal stresses accelerate the onset of cracks.

Klobcar et al. [1] reported that during the high pressure die casting the temperature is about 700°C when the aluminium is injected, the speeds are between 30 to 100 m/s and the injection pressures are from 50 to 80 MPa. Due to the high speeds involved is extremely important to determine the temperatures and wear stresses during the aluminium high pressure die casting process. These temperatures should be in the range from 250°C to 300°C (Tassin, [6]). An increase of 50°C in the maximum temperature of the process drastically increases the risk of die failure. Also, the number of cycles varies inversely with temperature (Ott et al., [7]). Fissolo et al. [8], reported that in order to increase the number of life cycles of the die the temperature differences during the high pressure die casting process must be kept as low as possible.

According to Persson et al. [9], the traditional choices for the manufacture of dies are the AISI H11, H13, H20, H21 and H22 steels. Wu et al. [10], reported that the AISI H13 steel is the most used - around 90%. Mesquita et al. [11], mentions that in the case of thermal fatigue it is essential to use steels with higher toughness, such as AISI H13 steel. This steel should be used in a hardness range of 44 to 48 HRC (VILLARES, [12]).

Basquin in 1910 through studies of curves of fatigue developed a classical mathematical equation for applications involving thermal fatigue. This studies were extended by Suresh [13] and Magnabosco [14], Equation (1).

$$\sigma_a = \sigma' f (2N_f)^b \tag{1}$$

Where σ'f is the coefficient of resistance to fatigue and can be applied as the ultimate tensile strength UTS obtained in a uniaxial tensile test and b is the coefficient of Basquin (ranging from -0.05 to -0.12). Nf is the number of cycles to fracture and σmax and σmin are the maximum and minimum stresses. σ_a is the stress amplitude, Equation (2).

$$\sigma_{a=} \frac{(\sigma_{\max} - \sigma_{\min})}{2} \tag{2}$$

When the minimum value for the stress is very low compared to the maximum value it can be considered zero, Equation (3).

$$\sigma_{m=}\sigma_{a=} \frac{\sigma_{\max}}{2} \tag{3}$$

Suresh [13] and Meyers [15] reported that the coefficient of Basquin can be calculated using Equation (4). To solve the equation, it is necessary to know the strain hardening coefficient - mechanical property obtained by the uniaxial tensile test.

$$b = \frac{n}{1+5n} \tag{4}$$

Where n is the strain hardening coefficient. In fact, the higher the average of stress applied, to the same amplitude of stress, the lower will be the fatigue life. Thus, the Basquin equation needs to be correct considering the calculated average of stress, Equation (5).

$$\sigma_a = (UTS - \sigma_m)(2N_f)^b \tag{5}$$

Where σm is the average of stress, Equation (6).

$$\sigma_{m=} \frac{(\sigma_{\max} + \sigma_{\min})}{2} \tag{6}$$

Despite being so relevant for the manufacturing process the thermal fatigue life is little investigated in the literature - mainly for applications involving AISI H13 steel. In addition, in recent decades, the employment and the development of mathematical modelling, numerical and computational methods are appearing as techniques for a significant reduction of cost and time for tools development [16-19]. In order to advance the subject a little further and as a contribution to the research gap still present in the state-of-the-art, the current work aimed to analyze the behavior of AISI H13 for two different gradients of temperature (ΔT = 200 and 250°C) on the aluminium high pressure die casting process. The next sections will show the experimental procedure to determine the exponent of Basquin and using a commercial Finite Element Method (FEM) code was possible to obtain the thermal stresses. Then, an analytical study, through the equation of Basquin, was conducted to determine the number of cycles until the failure. Based on such results - and guided by technical data and commercial experience of life cycles for the AISI H13 steel - it was possible to develop proposals of coefficients of correction for the equation of Basquin. The objective is that the proposed coefficients of correction can propitiate a more precise determination of the number of life cycles for aluminium high pressure die casting process in applications involving thermal fatigue.

2. Experimental procedure

The material used was AISI H13 steel with 2 mm sheet thickness produced by VILLARES - quenched and tempered for hardness of 44-46 HRC. The uniaxial tensile tests were performed according to ABNT NBR 6673 and NBR 8164 and three specimens were used.The simulations to determine the thermal stresses during the aluminium high pressure die casting process were performed through the commercial FEM code ABAQUS/Explicit [20] using an axisymmetric model. The sheet was meshed with tetrahedral elements with four nodes (type C3D4H), Fig. 1.

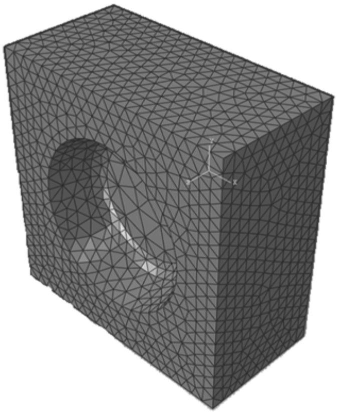

Fig. 1. Die design with tetrahedral elements and four nodes - type C3D4H

For the thermal fatigue analysis two different gradients of temperature were used (ΔT=200°C and ΔT=250°C). The use a constant injection pressure of 70 MPa was a hypothesis, since changes in pressure during the process would present a very wide range of results. Table 1 shows the AISI H13 steel properties used in the simulations.

3. Results and discussions

Table 2 shows the AISI H13 mechanical properties obtained by the uniaxial tensile test. Starting from the AISI H13 mechanical properties data at high temperature (Schmolz-Bickenbach, [21]) and based in the data obtained from the uniaxial tensile test conducted at room temperature was possible to interpolate the AISI H13 mechanical properties for the studied temperatures of 250, 450 and 500°C, Fig. 2.

3.1. Thermal stresses in gradients of temperature of 200 and 250°C

The simulations of the thermal stress amplitudes for gradients of temperatures (ΔT=200ºC and ΔT=250°C) were performed through the commercial FEM code ABAQUS/Explicit applying the criterion of von Mises.

Fig. 3(a) and 3(b) - ΔT 200°C - shows the thermal stresses of 600.96 MPa which is the maximum amplitude of the thermal stress and 377.43 MPa which is the minimum stress. Fig. 3(c) and 3(d) - ΔT 250°C - illustrates that the thermal stresses are ranging from 683.95 MPa to 457.40 MPa. For both ΔT = 200 and 250°C, the time interval of 20 seconds represents the total time of the high pressure die casting process, represented mathematically as the total time of the increment.

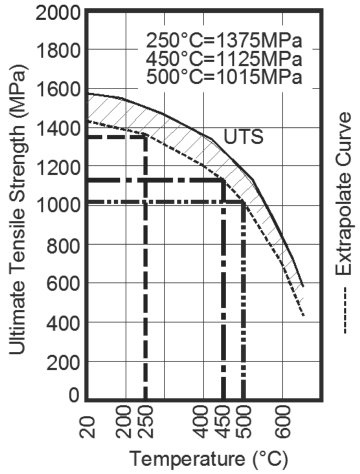

Fig. 2. AISI H13 ultimate tensile strength as a function of temperature.

Table 3 shows the distribution of thermal stresses as a function of time for their respective gradients of temperature (ΔT = 200 and 250°C). It is worth noted that, the stress amplitude decrease with the increase of the time increment - both cases.

Fig. 4 shows the variation of the thermal stresses and the temperature as a function of time - total time of increments of 20 seconds. For both temperature gradients studied (ΔT = 200 and 250°C), the amplitudes of the thermal stresses were below the ultimate tensile strength of AISI H13. It can be seen that the amplitudes of thermal stresses σt are critical only in the first few seconds, Fig. 4. After that both stresses decreases gradually with the stabilization of the temperature.

Table 1.
AISI H13 thermal and mechanical properties in the temperatures of 250, 450 and 500°C

T (°C)	ρ (Kg/m³)	E (GPa)	ν	α (1/°C)	K (W/mK)	UTS (MPa)
250°C	7,950	200.46	0.34	1.22e-5	27.6	1,375
450°C	7,723	131.32	0.37	1.28e-5	30.3	1,125
500°C	7,700	100.00	0.38	1.29e-5	30.3	1,015

Source:.Bin Wang (2000)

Table 2.
AISI H13 mechanical properties

El (%)	e (%)	ε	YS (MPa)	RTS (MPa)	UTS (MPa)	n
2.50	10.02	0.095	1,220	1,231	1,425	0.042

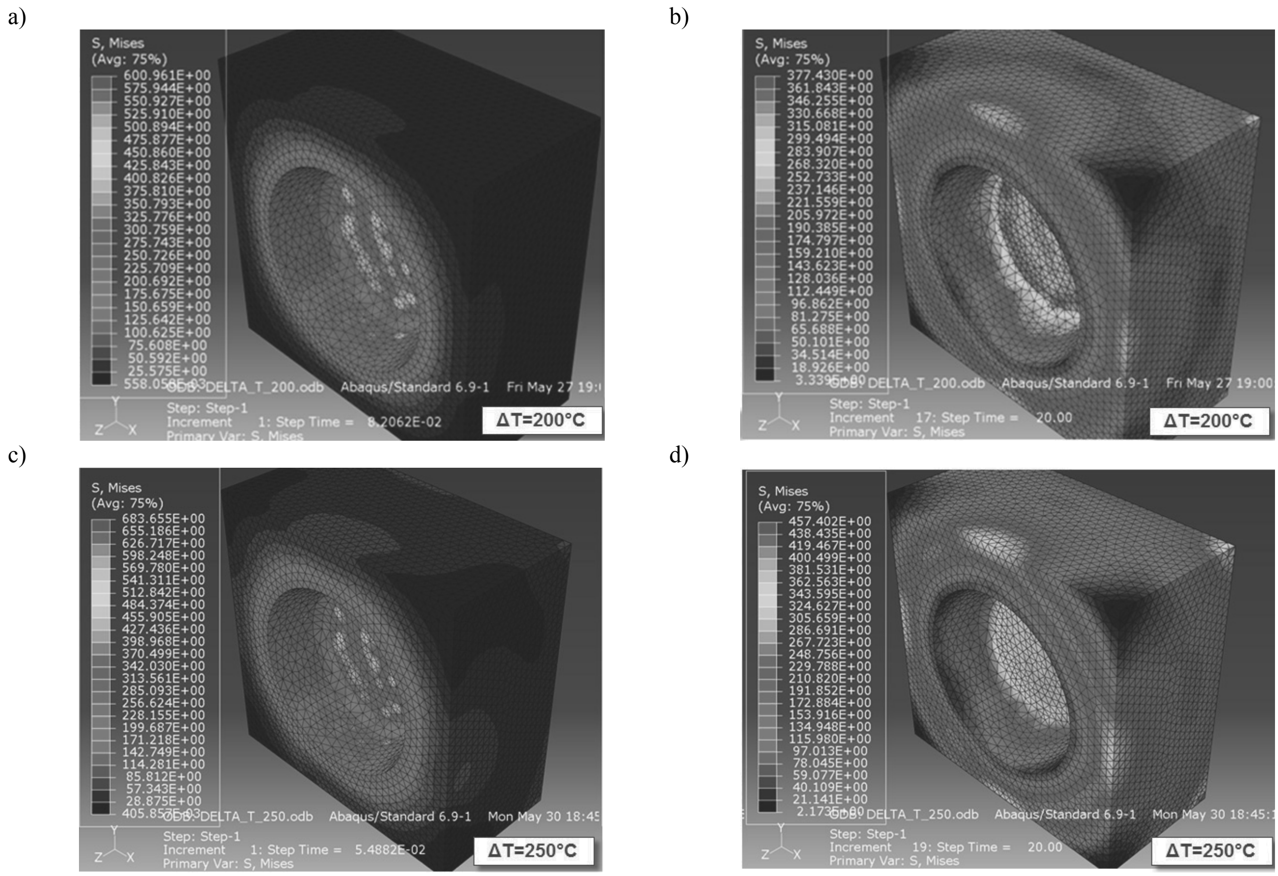

Fig. 3. Thermal stress distribution: (a) maximum Mises stress - ΔT 200°C, (b) minimum Mises stress - ΔT 200°C, (c) maximum Mises stress - ΔT 250°C and (d) minimum Mises stress - ΔT 250°C

Table 3.
Distribution of thermal stress as a function of time

ΔT=200°C				ΔT=250°C			
t (s)	σt (MPa)	t (s)	σt (MPa)	t (s)	σt (MPa)	t (s)	σt (MPa)
0.08	600.96	2.57	467.90	0.05	683.65	2.11	511.07
0.16	578.81	3.50	460.99	0.10	661.89	2.74	510.08
0.24	562.01	4.91	451.29	0.16	648.70	3.67	509.30
0.32	550.78	7.01	438.02	0.21	637.62	5.08	501.42
0.45	543.29	10.17	420.45	0.42	602.87	9.30	473.50
0.63	543.23	14.90	398.06	0.61	578.87	12.47	400.29
0.91	542.13	19.90	377.82	0.79	559.28	17.22	431.14
1.32	539.34	20.00	377.43	1.49	531.47	20.00	457.40

Table 4.
First condition for the calculation of the number of life cycles

ΔT (°C)	σas (MPa)	σms (MPa)	UTS (MPa)	Nfs (cycles)
200	600.96	489.19	1,125	2.50
250	683.65	578.69	1,015	1.2e-6

Table 5.
Second condition for the calculation of the number of life cycles

ΔT (°C)	σa (MPa)	σm (MPa)	UTS (MPa)	Nf (cycles)
200	111.76	489.19	1,125	1.94e21
250	113.12	570.52	1,015	4.77e16

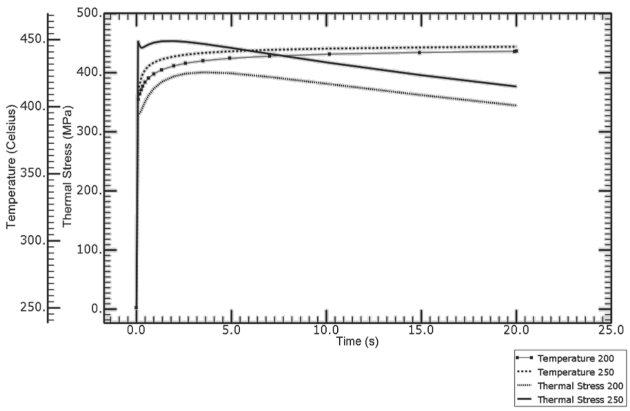

Fig. 4. Variation of the thermal stresses and the temperature as a function of time

3.2. Determination of number of cycles to crack

In order to determine the number of cycles of fatigue (Nf) the Equation (5) was utilized. The data considered to define the number of cycles to crack can be obtained as follows. In order to solve the equation of thermal fatigue life it was necessary to determine the exponent of Basquin for AISI H13 steel. In order to do so, is necessary to use the strain hardening coefficient obtained in the uniaxial tensile test n=0.042. From the Equation (4) b=-0.035 is calculated.

The σa and σm are obtained replacing the values of thermal stresses obtained in Equation (2) and (6), Table 6. Due to the divergence of the results, the obtained stresses were divided into σa - which is the theoretical amplitude of the thermal stress - and σas - amplitude of the thermal stress obtained in the simulation. So it was determined σm - which is the theoretical average of the thermal stress and σa - which is the average of the thermal stress obtained in the simulation (ΔT = 200 and 250°C). For σms it was assumed the hypothesis that the resulting average of stresses should be determined from the Equation (7).

$$\sigma_{ms} = \frac{\sigma_{\max\_time1} + \sigma_{\max\_time2} + \sigma_{\max\_time3} + \sigma_{\max\_time4}}{4} \quad (7)$$

Where σ_{max}_time is the average of the thermal stress amplitudes divided into increments of time interval. Each partial increment was divided into four intervals of 5 sec. - hypothesis defined starting from the simulated increments (ΔT=200 and 250°C).

Table 4 resumes the first boundary conditions to determine the number of cycles for thermal fatigue life. It was considered the critical element of die the element that showed the highest concentration of thermal stress (for both cases ΔT = 200 and 250°C). σas and σms were obtained from the simulations.

The average of the numbers of cycles obtained by simulation (Nfs) for each temperature gradient was defined as the average of number of simulated cycles. Considering the values of 2.5 and 1.2e-6 the average value of 1.25 cycles is obtained. The number of cycle to fatigue of 1.25 does not meet the practical experience. Moreover, Table 5 shows that there is a wide variation between the number of life cycles for the two gradients of temperature studied. It is worth to be noted that the exponent of Basquin (b) of - 0.035 was obtained for n of 0.042. As the number of cycles obtained does not meet the expected a new condition to determine Nf was proposed. It was utilized σa and σm obtained through theoretical calculations for the two gradients of temperatures (ΔT = 200 and 250°C).

With the results obtained for each gradient of temperature it was determined the new number of cycles for the studied temperature gradients. Considering the values of 1.94e21 and 4.77e16 the average value of 9.7e20 cycles is obtained. The number of cycles obtained using the data from the simulations (Nfs) when compared with the value obtained through theoretical calculations (Nf) generate a large margin of error. Through practical industrial reports it is expected that, for similar conditions of this work, an aluminium high pressure die casting can reach an average of 130,000 cycles (Nf). It is worth noted, that Nfs as much as Nf did not show satisfactory results when compared to the expected fatigue life cycles, i.e. the number of cycles expected in practice.

As the procedure adopted in the present work does not show as an acceptable method to predict the thermal fatigue life a better evaluation of the Basquin coefficient influence was proposed. In order to do so, and as a third attempt, a mathematical simulation to determine the number of cycles of a high pressure die casting as a function of the Basquin coefficient variation - showed in the literature - was presented. Intervals for the Basquin coefficient of -0.01 were adopted - the literature shows the Basquin coefficient varying from -0.05 to -0.12, Table 6. The number of cycles obtained with the Basquin exponent variation shows an unreliability of results, i.e. it shows a very sensitive response for small coefficient variations.

3.3. Proposed coefficients of correction for the Basquin equation

After several computational and mathematical simulations, it was found that the equation of Basquin cannot describe the thermal stress influence on the high pressure die casting process, i.e. when compared with the expected practical behavior of the process.

Table 6.
Third condition for the calculation of the number of life cycles

Basquin b	ΔT=200°C Nf	ΔT=250°C Nf	Nfm
-0.05	108,356	506	3,6511
-0.06	13,981	159	4,780
-0.07	3,238	70	1,131
-0.08	1,081	37	387
-0.09	460	23	170
-0.10	232	15	88
-0.11	133	11	52
-0.12	83	8	33

Table 7.
Coefficients of correction for the equation of Basquin

ΔT (°C)	σas (MPa)	σms (MPa)	UTS (MPa)	Nf (cycles)	Y	b
200	600.96	489.19	1125	130,000	0,010	0.045
250	683.65	578.69	1015	130,000	0,001	0.036

As a final approach for the prediction of thermal fatigue of aluminium high pressure die casting using the Basquin equation it was carried out mathematical calculations in order to determine the coefficients of Basquin as a function of the number of cycles provided in practice, i.e. 130,000 cycles (Nf). The new coefficients of Basquin proposed consider the strain hardening coefficient obtained in the uniaxial tensile test. As a result it was proposed a coefficient of correction (Y) for the Basquin formulation, Equation (8).

$$b = -\frac{n}{1+5n} + Y \tag{8}$$

Through the Equation. (8) the coefficients of 0.045 and 0.036 was calculated for the temperature gradients of ΔT 200 and 250°C, Table 7.

It should be highlighted that the use of the proposed corrected coefficients for the Basquin equation can show a satisfactory results related to the practice - valid only for similar conditions of this work.

4. Conclusions

The thermal stress has a direct influence on the number of cycles of aluminium high pressure die casting (AISI H13). For the prediction of the number of life cycles - using the presented methodology - became necessary experimentally obtain the coefficient of Basquin. The thermal stresses were obtained by numerical simulations taking into account two temperature gradients (ΔT 200 and 250°C). It was found that the equation of Basquin cannot describe the thermal stresses influence in the aluminium high pressure die casting process. Taking in account the divergences found in the solutions for determining the number of life cycles to crack an approach attempt for the prediction using coefficients of correction (Y) for the Basquin formulation was proposed.

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References

[1] D. Klobcar, B. Tusek, B. Taljat, Thermal fatigue of materials for die-casting tooling, Materials Science and Engineering A 472/1-2 (2008) 198-207.
[2] Y. Wang, A study of PVD coatings and die materials for extended die casting die life, Surfaces and Coatings Technology 94-95 (1997) 60-63.
[3] X. Hu, Thermal fatigue behaviour of niobium microalloyed H13 steel, Journal of Shanghai University (English Edition) 10/4 (2006) 375-376.
[4] J. Lin, A.O. Kunrath, D. Zhong, S. Meyres, B. Mishra, J.J. Moore, Development of multi-layered and graded die coatings for materials processing applications, Advances in Science and Technology 45 (2006) 1145-1154.
[5] S.N. Aqida, F. Calosso, D. Brabazon, S. Naher, M. Rosso, Thermal Fatigue properties of laser treated steels at semisolid processing temperatur, The International Journal of Material Forming 3/1 (2010) 797-800.
[6] A.R. Tassin, Technology of pressure die casting, aluminum its alloys and zamak, Molds Design, Brazil, 1995 (in Portuguese).
[7] S. Ott, M.D. Diehl, Study of the influence of molybdenum percentage on the thermal fatigue resistance of vermicularis

cast iron, Proceeding of the 53° Congress Anual ABM, Brazil, 1997 (in Portuguese).
[8] A. Fissolo, C. Robertson, V. Maillot, Prediction of crack initiation and growth under thermal fatigue, Chapter 3, Thermomechanical Fatigue and Fracture, M.H. Aliabadi (Ed.),WIT Press, Southampton, 2002.
[9] A. Persson, S. Hogmark, J. Bergstrom, Thermal fatigue cracking of surface engineered hot work tool steels, Surface and Coating Technology 191 (2005) 216-227.
[10] X.C. Wu, W.Y. Peng, Y.A. Min, Study on thermal fatigue behavior of boride layer of H13 steel, Materials Science Forum 475 (2004) 249-252.
[11] R.A. Mesquita, L.C. França, C.A. Barbosa, Cases of application of new tool steels for hot work, Tecnologia em Metalurgia e Materiais 2 (2005) 70-75 (in Portuguese).
[12] Villares Metals, Stainless steel for molds, H13 villares tool steels, Technical Catalog 1a, Brazil, 2007 (in Portuguese).
[13] S. Suresh, Fatigue of material, cambridge solid state science series, Paperback, USA,1998.
[14] R.B. Magnabosco, Fatigue life of carbon steel with ferrite-martensite biphasic structure, Proceeding of the 14º Congresso Brasileiro de Engenharia e Ciência dos Materiais Brazil, 2000 (in Portuguese).
[15] M.A. Meyers, K.K. Chawla, Mechanical behavior of materials, Cambridge University Press, New York, 1999.
[16] N. Cappetti, L. Garofalo, A. Naddeo, M. Nastasia, A. Pellegrino, A method for setting variables in Super Plastic Forming process, Journal of Achievements in Materials and Manufacturing Engineering 38/2 (2010) 187-194.
[17] A. Śliwa, L.A. Dobrzański, W. Kwaśny, M. Staszuk, Simulation of the microhardness and internal stresses measurement of PVD coatings by use of FEM, Journal of Achievements in Materials and Manufacturing Engineering 43/2 (2010) 684-691.
[18] M.J. Jackson, Numerical analysis of small recessed silicon carbide grinding wheels, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 27-37.
[19] W. Kapturkiewicz, A.A. Burbelko, E. Fras, M. Górny, D. Gurgul, Computer modelling of ductile iron solidification using FDM and CA methods, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 310-323.
[20] Abaqus/CAE, User's Manual, Version 6.9, 2009.
[21] http://www.SCHMOLZ-BICKENBACH.com.br/produtos/trabalho-a-quente.html, 2010.