Assessment of thermal behavior of a cooling system to reduce thermal fatigue cracks in aluminum injection molds

Avaliação do comportamento térmico de um sistema resfriado para reduzir trincas por fadiga térmica em molde de injeção de alumínio

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Abstract

The present article aimed to test changes in cooling water temperatures of males, present in aluminum injection molds, to reduce failures due to thermal fatigue. In order to carry out this work, cooling systems were studied, including their geometries, thermal gradients and the expected theoretical durability in relation to fatigue failure. The cooling system tests were developed with the aid of simulations in the ANSYS software and with fatigue calculations, using the method of Goodman. The study of the cooling system included its geometries, flow and temperature of this fluid. The results pointed to a significant increase in fatigue life of the mold component for the thermal conditions that were proposed, with a significant increase in the number of cycles, to happen failures due to thermal fatigue.

Keywords: Thermal fatigue. Aluminum injection mold. Goodman.

Resumo

O presente artigo objetivou testar alterações em temperaturas da água de resfriamento de machos, presentes em moldes de injeção de alumínio, como meio para reduzir falhas por fadiga térmica. Para realizar este trabalho, sistemas de resfriamento foram estudados, incluindo suas geometrias, gradientes térmicos e a durabilidade teórica esperada com relação à falha por fadiga. Os testes do sistema de resfriamento foram desenvolvidos com auxílio de simulações no software ANSYS e com cálculos de fadiga, utilizando o método de Goodman. O estudo do sistema de resfriamento incluiu suas geometrias, vazão e temperatura desse fluído. Os resultados apontaram para um significativo aumento da vida em fadiga do componente do molde para condições térmicas que foram propostas, com um aumento significativo do número de ciclos, para ocorrer falhas por fadiga térmica.

Palavras-chave: *Fadiga térmica. Molde de injeção de alumínio. Goodman.*

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1 Introduction

Die casting is an economic method to produce products with complex geometries, close to their final shape, with narrow tolerances and excellent surface finishing. It has a high-volume production process, generally reaching a production rate of 200 parts per hour and production batches of 300,000 parts. Low cycles demand high speed flows of injected material and rapid metal solidification (high thermal gradients). For example, during the casting process, molten aluminum (670 –710°C) is injected into the mold at speeds of 30 to 100 m/s. These severe conditions limit the life of the molds. Thermal processes are responsible for 70% of premature failures in molds and cause significant loss in the industry due to the high maintenance cost and production downtime as a result of inactivity. Therefore, this has become a major research topic to obtain an increased resistance to thermal fatigue of die steels for hot work.

Computational systems and practical tests have been constantly developed to verify the fatigue life of tool steels. To minimize the damages caused by thermal processes, different approaches are applied. The use of surface coatings is an example; they minimize corrosion (figure 1b), welding and erosion, but provide this surface low resistance to thermal fatigue (CHEN *et al.*, 2016).

During the process, the mold surface suffers strong alternating heating and cooling cycles, respectively in the injection and extraction stage, during which the part is ejected. Then, release agent/lubricant is sprayed over the mold surface. As a result of these transient high thermal gradients, the thermal tensions are induced on the surface of the mold cavity where cracks are initiated by low anisothermy and fatigue process due to the low cycle. The microcracks grow to form a network, whether multiaxial on flat surfaces (figure 1d) or uniaxial in geometric singularities (figure 1e), (SALEM *et al.*, 2019).

Figure 1 – Observations in steel X38CrMoV5 (AISI H11). Aluminum alloy high pressure casting mold AlSi9Cu3: undamaged areas (a), oxide (b) and aluminized (c); multiaxial (d) and uniaxial (e) network
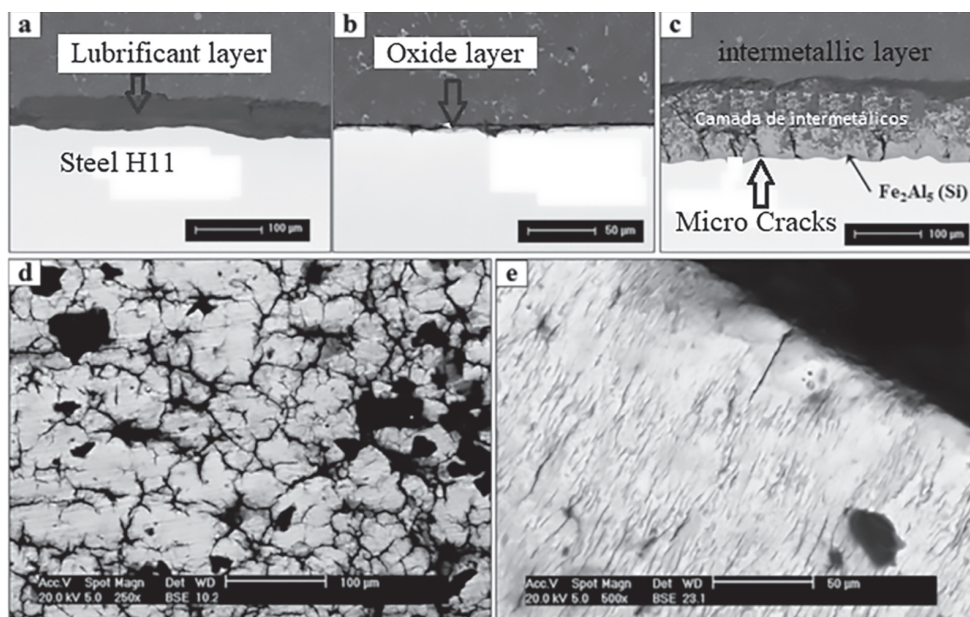
Source: Adapted from Salem *et al.* (2019, p. 2).

The casting die's life under pressure can be lengthened through lower thermal gradients, that is, with the diminution of thermal tensions. They can be reduced by an appropriate die design (without sharp edges or corners and with adequate cooling channels distribution). The selection of appropriate die material and its heat treatment allow higher resistance to temperature variation and greater resistance to tempering during the operation. The fabrication of dies, without surface deformation and temperature

development during mechanical machining, grinding or electro-discharge machining, which cause phase and residual transformations, also contribute towards stress decrease and the appearance of surface cracks (KLOBCAR *et al.*, 2012).

This research aims to verify the relevance of the flow parameters and fluid temperature so that a mold cooling system can be energetically efficient and contribute to its components' durability. Searching for positive results, the cooling water flow

and temperature were increased gradually, so that thermal tensions caused by the thermal gradients were reduced, and so the possibility of thermal cracks happening is decreased. To test these conditions, a mold aluminum injection core, cooled with water and having a waterfall cooling system, was selected. The results of the thermal conditions are presented in forms of tables, thermal images and graphs.

2 Molds and termal processes

2.1 Die Casting injection mold

The injection molds are fairly complex, made up of many parts with defined functions that relate to each other. The figure 2 presents a typical example of an injection mold and its main parts.

Figure 2 – Generic representation in cut of an injection mold
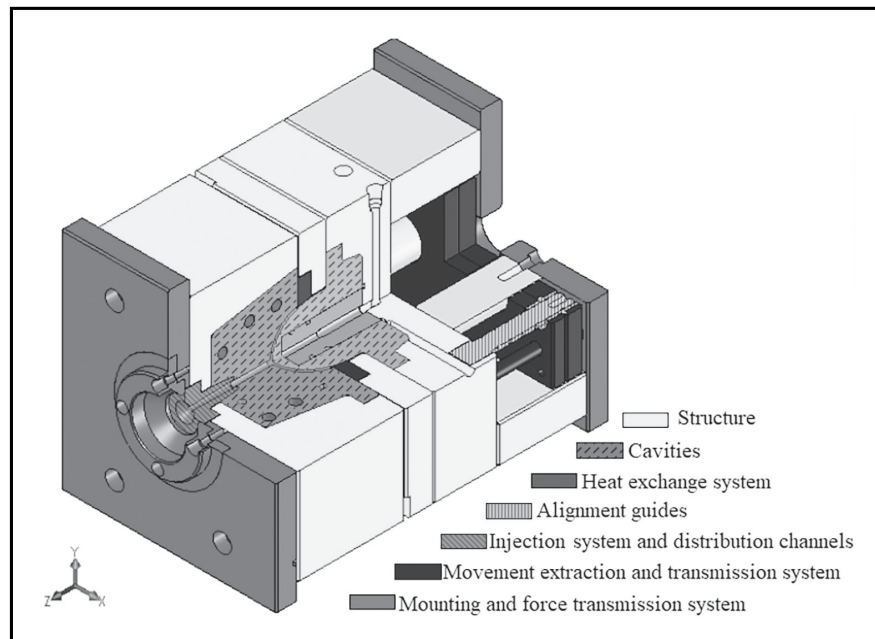
Source: Bareta (2007, p. 32).

Many knowledge areas are involved in the project of a mold, especially heat transference, fluid mechanics, tribological aspects, materials, all with a high degree of interaction with each other (BARETA, 2007). The molds for the injection process under pressure are subject to a high performance requirement demand where high work cycles subject the die to high levels of wear and thermal stress (CONCER, 2011).

2.1.1 Mold cooling systems

According to Cruz (2002), cooling in the mold is extremely important for directly influencing the quality of the injected part, it can be responsible for the presence of defects, deformities, product extraction difficulties, as well as in the dimensional and structural stability of the mold. The cooling doesn't apply to the entire mold, but to the cavities and cores, in which it helps maintain the temperature stabilized. The cavities and cores keep direct contact with the injected material and are subject to suffering a higher heating, wear and crack appearance. Different parts demand different cooling characteristics: there are cases in which it is done with room temperature water, cold water and in some cases hot oil.

There are seven kinds of mold cooling systems. They are: in line, circular, helical, blade or baffle, waterfall or bubbler, thermal pin and adapted to the contour of the part (SACCHELLI, 2007). Each type is used according to the specific necessities of each project of the cooling system, according to a more appropriate model of the cavity drawing and the size of the mold (BRITO; ARAÚJO; PONTES, 2004). In schematics, the figure 3 presents different techniques applied to cooling circuits.

For each mold project, a careful assessment must be made to identify which cooling process will offer the best result; the histories of previous molds that have already been tested and the positive results that have already been verified may be included in this evaluation. The time of each cycle, including the cooling one, may vary depending on the thickness of the injected part, the pressure of the injection, room temperature, among others (CORAZZA, 2012).
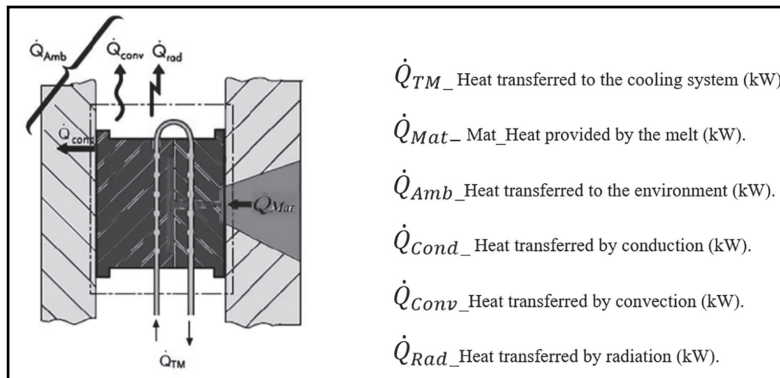
Figure 3 – Types of mold cooling systems
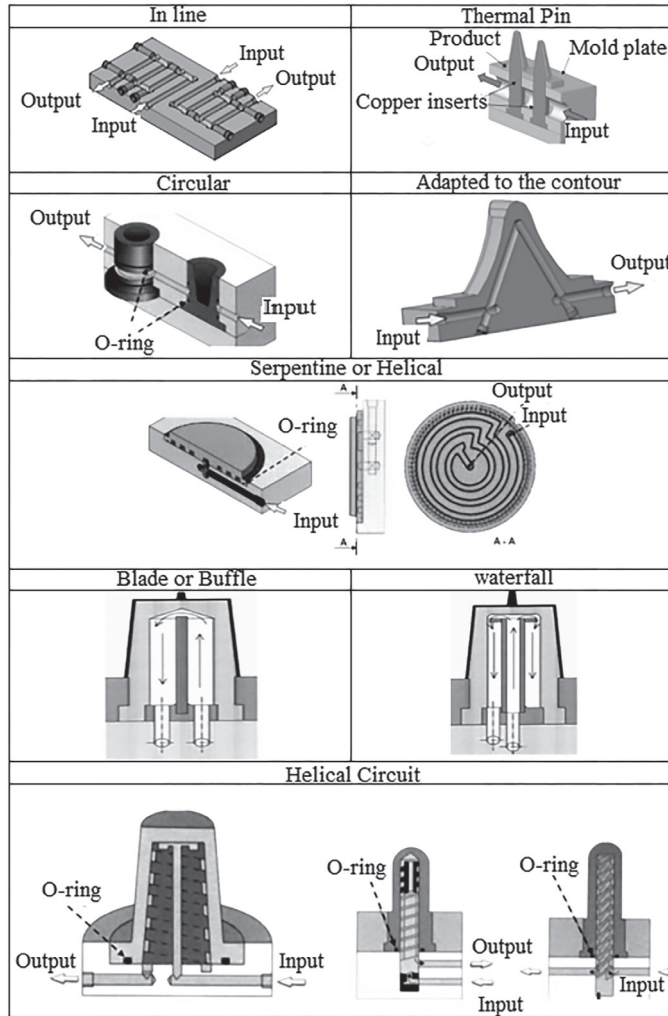
Source: Adapted from Basso (2013).

2.1.2 Heat transfer in injection molds

A mold can be considered an exchanger of heat, where conduction and convection are predominant (BASSO, 2013). The figure 4 illustrates the means of transportation of heat that are present in a mold. The cavities and cores maintain direct contact with the injected material and are subject to greater heat, wear and cracking (CRUZ, 2002).

Figure 4 – Heat transports in an injection mold

$\dot{Q}_{TM}$_ Heat transferred to the cooling system (kW).

$\dot{Q}_{Mat}$_ Mat_Heat provided by the melt (kW).

$\dot{Q}_{Amb}$_Heat transferred to the environment (kW).

$\dot{Q}_{Cond}$_ Heat transferred by conduction (kW).

$\dot{Q}_{Conv}$_Heat transferred by convection (kW).

$\dot{Q}_{Rad}$_Heat transferred by radiation (kW).

Source: Basso (2013, p. 91).

Conduction occurs through the components of the mold and reaches the channels, where the cooling liquid circulates. Convection can be natural, on the outside of the mold, or forced, when cooling liquid circulates through the cooling channels, being responsible for removing most of the heat.

In the thermal balance in the mold, received heat is considered positive and transferred heat is negative. The thermal balance is expressed through equation (1) where, if the heat supplied by the material is higher than the amount of heat removed by the environment and the cooling system, the accumulated heat will increase and generate problems in the process of solidification and extraction of the product from the mold (POLYTECHNIC INSTITUTE OF LEIRIA, 2007),

$$\dot{Q}_{Mat} + \dot{Q}_{Amb} + \dot{Q}_{Ref} = \dot{Q}_{Acum} \qquad (1)$$

Where:

$\dot{Q}_{Mat}$ _ Heat supplied by the material injected into the mold (kW);

$\dot{Q}_{Ref}$ _ Heat transferred to the cooling fluid (kW);

$\dot{Q}_{Amb}$ _ Heat transferred to the environment (kW);

$\dot{Q}_{Acum}$ _ Heat accumulated in the mold (kW).

An effective cooling system leads to an uniform distribution of the different temperatures that arise during the cycle time. Some of the factors that influence the cooling process are: the geometry of the component of the die, the temperature of the mold, the disposition of the cooling channels, the temperature of the cooling fluid and the flow speed. The amount of heat removed by the cooling system is given by equation (2). This equation is adapted from Incropera *et al.* (2008),

$$Q_{resf} = m_a . C p_a . (T_s - T_e) \qquad (2)$$

where:

Q_{resf} _ Amount of heat removed by the cooling system (kW);

m_a _ Mass flow of water (kg/s);

C_{p_a} _ Specific heat of the cooling water (4,18 kJ/kG. K);

T_s _ Outlet cooling water temperature (°C);

T_e _ Inlet cooling water temperature (°C).

The bigger the flow rate of the fluid, the bigger the amount of heat removed by the cooling system will be. Another important factor to be considered is the area of thermal exchange, that is, the area, where the fluid comes into contact with the surface that will cool. The larger it is, the bigger the efficiency of the cooling system will be.

2.1.3 Thermal fatigue in molds

Thermal fatigue is the biggest responsible for the initiation of cracks. It is estimated that they might represent approximately 80% of the origin of thermal caused cracks (CONCER, 2011). During heating, the surface of the cavity undergoes an increase in temperature, causing a volume expansion and, so, resulting in a state of compressive stress on the surface of the die. When the generated stress is superior to the limit of the flow, the material plastically deforms. The higher the temperature, that is reached, the bigger the dilation will be. As the resistance of the material is smaller, there will then be a bigger plastic deformation. During subsequent cooling, the material will then deform under a state of tension stress and at a temperature of less ductility. Depending on the level of these stresses and the number of cycles, thermal fatigue cracks can then appear (FERREIRA, 2001).

The subject of thermal stress is very difficult from a mathematical point of view, so, to deal with that, only simplifying assumptions are made. The simplifications, however, allow the order and magnitude of the stresses to be estimated. A formula (equation (3)) was derived from the stress, after assuming that the surface is a plane of infinite extension that continues from an infinite distance in a normal direction to that plane (SABHARWAL, 1969). This equation takes into account that a surface with a high temperature exists on a mold, as well as another surface with a milder temperature resulting from a cooling process, while both surfaces are parallel at a short distance from each other,

$$\sigma = -\frac{m.E}{m-1} . \alpha . (T_1 - T_2) \qquad (3)$$

Where:

σ _ Stress (MPa);

m _1/Poisson Coefficient of the material (10/3 for steel);

α Linear dilation coeficiente of the material (12,6.10-6/°C for steel);

E _ Elasticity module of the material (medium value, 206,800 MPa);

T_2 _ Temperature at the limit/upper face (°C);

T_1 _ Temperature at the limit/upper face (°C).

Figure 5 shows a crack caused by stresses from the thermal injection process of molten aluminum and the cooling system. In the figure, the region outlined by the biggest circle (1) indicates the region surrounded by molten metal, the region (2), at the center of the figure, indicates the channel, where water circulated (50°C), the arrow indicates a crack that passes through the section of the core wall.

Figure 5 – Crack in an injection mold
core of aluminum cooled with water
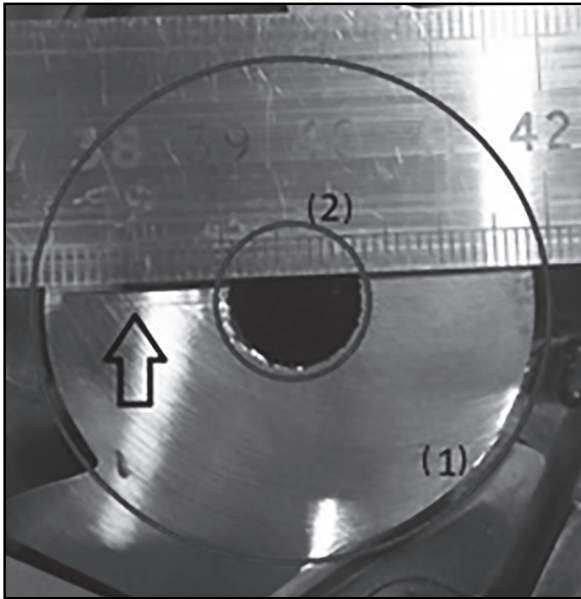
Source: The authors (2018).

Norton (2013) describes that any load that varies with time may potentially provoke a fault due to fatigue. The behavior of this type of load varies a lot from one application to the other. Loads tend to vary in amplitude and frequency over time and may even be random. Thus, the schematic function is described as a sine wave or as a shape of sawtooth. Significant factors are amplitude and the medium value of the stress-time wave, or deformation time, and the total number of stress/deformation cycles the part is subjected to.

The figure 6 illustrates the typical stress cycles in fatigue. Figure 6(a) illustrates a cycle of alternating sinusoidal stresses, in which the maximum and minimum stresses are the same. Figure 6(b) shows a cycle of fluctuating stresses, in which the maximum and minimal stresses are different. Figure 6(c) illustrates a complicated stress cycle found in a material subject to unpredictable periodical overcharges, like in airplane wings exposed to air currents (NASCIMENTO, 2015).

Figure 6 – Typical stress cycles to the occurrence of fatigue
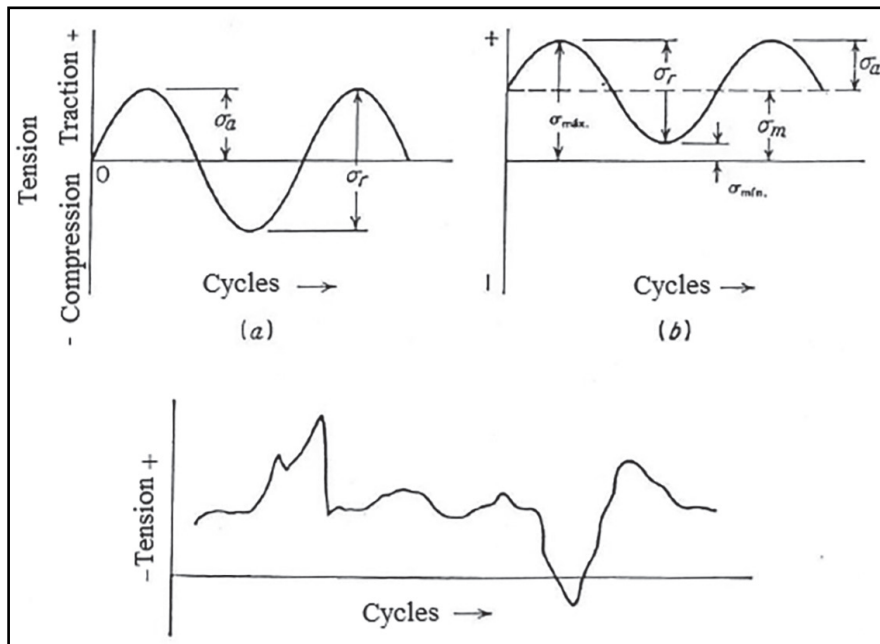
Source: Nascimento (2015, p. 58).

The main parameters of a stress cycle are:

σ_{max} – Higher algebraic value of the stress cycle;

σ_{min} – Lower algebraic value of the stress cycle;

σ_m – Medium value of the maximum and minimum stresses;

σ_r – Stresses interval;

σ_a – Cycle stress amplitude or alternating stress;

R – Ratio between minimum and maximum stress.

The calculation of the number of cycles N describes, in a theoretical value, the moment in which a fatigue crack may start. The resistance limit to fatigue

$S_{e'}$ for steels, equation (4), may be estimated as half of the value of the Sut tensile resistance limit of steel (SANTOS JUNIOR, 2002).

$$S_{e'} = 0{,}5.S_{ut} \quad (4)$$

For the theoretical calculation of the fatigue limit some corrections must be made taking into consideration a group of resistance reduction factors. It takes into account the effects of loading (C_{carr}), size (C_{tam}), surface effects (C_{sup}), the temperature factor (C_{temp}) and the reliability factor (C_{conf}) (NORTON, 2013).

Considering the resistance's correction factors, equation (5) presents the resistance limit (S_e) corrected for a specific application.

$$S_e = C_{carr}.C_{tam}.C_{sup}.C_{temp}.C_{conf}.S_e \quad (5)$$

The number of cycles *N* is defined by equation (6) as:

$$N = \frac{10^{\frac{b}{m}}}{\sigma_a^{\frac{1}{m}}} \quad (6)$$

To obtain values of *b* and *m*, equations (7) and (8) are used.

$$m = \frac{1}{3} log \left(\frac{0{,}9.S_{ut}}{S_e} \right) \quad (7)$$

$$b = log \frac{(0{,}9.S_{ut})^2}{S_e} \quad (8)$$

Castro *et al.* (2008) defines that, for calculations of thermal fatigue, the value of nominal stress σ_0 is equal to the maximum value of stress obtained by the temperature gradient observed through the section of the wall, where the cooling liquid circulates and the wall is submitted to heating ($\sigma_0 = \sigma_{max}$). The same author defined the concentration factor of the theoretical static stress, $K_t = 2$, as the minimum value for a fatigue crack to start in cylindrical tubes subjected to corrosion. These values are necessary to define the alternating stress, equation (9).

$$\sigma_a = k_f.\sigma_0 \quad (9)$$

The concentration factor of dynamic stress K_f is obtained by equation (10).

$$K_f = 1 + q.(K_t - 1) \quad (10)$$

The sensitivity factor to notch *q* is found taking into account the rounding radius *r* and the resistance limit of the material, S_{ut}.

All tables to determine the modifying factors of fatigue resistance and other tables used for calculations of the number of cycles are available in the book "Projetos de Máquinas" (NORTON, 2013). The method used for the calculation of fatigue life is the one proposed by Goodman.

2.2 Analysis by finite elements method (FEM)

According to Goes (2010), the FEM is a method capable of approaching and solving the equations that govern the behavior of any continuous physical system through its discretization in sub-regions that are named elements. The union between the elements is named knots. The method is mathematically complex and computationally intensive, requiring the solution by large dies. The number of points chosen can be such that the structure can be described within the desired accuracy.

The analysis through finite elements corresponds to the execution of 5 steps, as follows:

Pre-processing: Creation of the model and geometry by the user, involving knots and elements. Specification of material properties and boundary conditions.

Solution of analysis by the FEM: Solution of the equations and calculations of the results (temperature, displacement, stresses and reactions in the supports, for example) in the knots and elements.

Post-processing: The behavior of the model may be investigated, according to the user's need. The result is displayed graphically with the visualization of stresses, temperature gradients, displacements, etc.

2.3 Case study

The component chosen for the thermal behavior study is an aluminum injection mold core that presents incidence of thermal fatigue cracks. It is demonstrated in figure 7. In the injection process, due to being a component that makes the product's internal geometry, it is almost completely surrounded by the molten metal and ends up absorbing much of the supplied heat. It is estimated that the thermal load acting on the component is approximately 10kW and the permanence time of the injected metal in the interior of the mold is 8 seconds. The component presents a waterfall cooling system.

Historically, this component presents the appearance of cracks in initial stages, around its first 8000 cycles. Its complete disposal, due to advanced cracks, occurs at 64000 cycles. The component is built in Dievar steel, hardened with a hardness between 44 and 46 HRC, superficially treated with a nitriding layer and a later PVD layer.

The figure 8 shows, with more detail, the geometry of the mold core that is the object of this study.
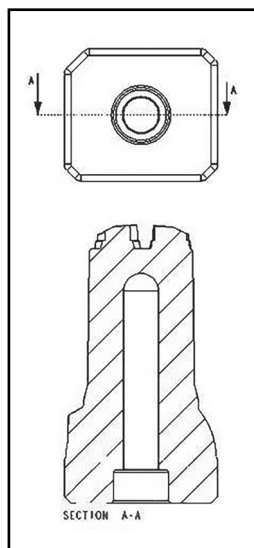
At the center, where the cooling water circulates, the channel geometry can be seen.

Figure 7 – Aluminum injection mold male
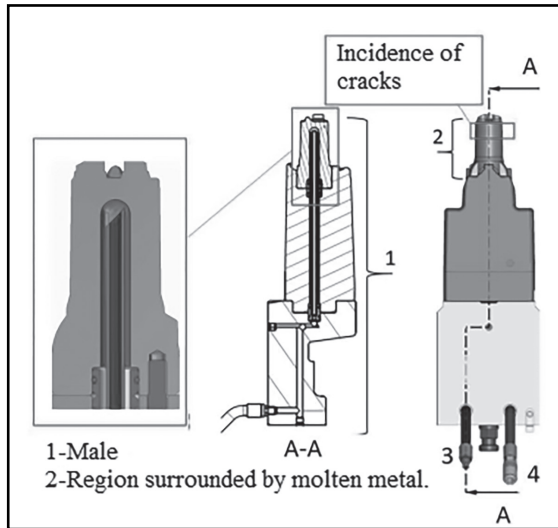
Source: The authors (2018).

Figure 8 – Component/aluminum injection mold core

Source: The authors (2018).

For this study of fatigue caused by thermal stresses, two temperature states are considered, one before the injection of the molten metal and another after the injection. It is considered that, after the extraction of the product from the mold, due to the period of time until the start of the next cycle and the cooling conditions, the balance of the temperatures between the cooled surface and the surface the molten metal comes into contact with occurs. This eliminates thermal stresses, as both walls are at almost the same temperature.

For carrying out the tests, ANSYS Fluent was used. In the software, the properties of Dievar Steel and the water in its liquid state were considered. The table 1 shows the temperatures of the cooling water used in the tests.

Table 1 – Testing conditions

	Geometry		Fluid
	Thermal exchange area (cm²)	Flow l/min	Inlet temperature (°C)
Test (A)	55	1,5	50
Test (B)	55	2	100
Test (C)	55	2,5	130
Test (D)	55	3	160
Test (E)	55	3,5	190

Source: The authors (2018).

2.4 Results and discussion

The figure 9 shows the evolution of the temperatures from tests (A) to (E). The simulations developed on ANSYS Fluent show the decrease of the thermal gradient through the section of the wall, as the flow and inlet temperature of the cooling water are increased. The horizontal line in the thermal images serves as an indicator of the point of study of the stresses. Through this line, the temperature curves in graph 1 were extracted.

The table 2 indicates the differences in temperatures, through the section of the wall of the region indicated by the horizontal line, in figure 9 from (A) to (E). This is the state of the temperatures, after the injection of aluminum into the mold.

Table 2 – Differences in temperatures through the section of the wall

	Internal temperature T1 (K)	External temperature T2 (K)	ΔT
Test (A)	420	500	80
Test (B)	445	500	55
Test (C)	450	500	50
Test (D)	465	503	38
Test (E)	485	505	20

Source: The authors (2018).

The graph 1 shows, with more details, the profiles of the temperatures found through the section of the wall. The beginnings of the curves to the left of the graph indicate the internal temperatures, the ones on the right end show the external temperatures.
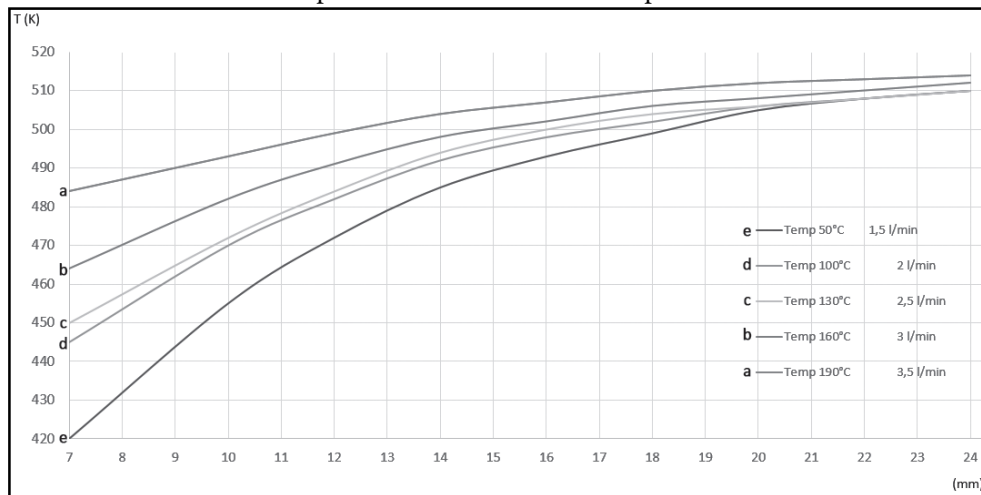
Figure 9 – Thermal profiles of temperatures from tests (A) to (E)
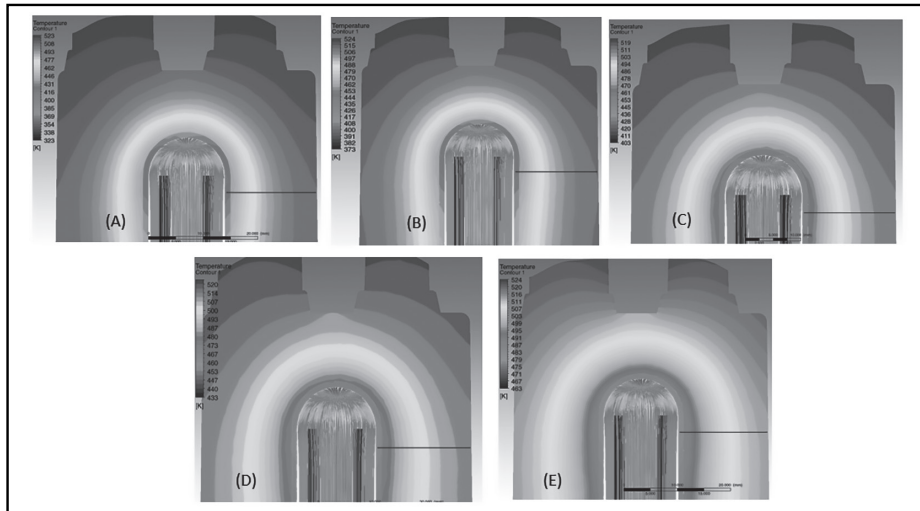
Source: The authors (2018).

Graph 1 – Results of the thermal profiles

Source: The authors (2018).

The table 3 shows the results of the thermal stresses for each test done. It is possible to verify that, according to the increase in the flow and the temperature of the inlet cooling water, the stresses decrease.

The chart 1 shows the parameters used to determine the number of cycles.

Table 3 – Resulting stresses

Test	Flow l/min	Inlet Temperature (°C)	σ/σ0 (MPa)
(A)	1,5	50	297,79
(B)	2	100	204,73
(C)	2,5	130	186,12
(D)	3	160	141,45
(E)	3,5	190	74,45

Source: The authors (2018).

Chart 1- Parameters for the calculations of the number of cycles

S_{ut} (MPa)	1210,00
$S_{e'}$ (MPa)	605,00
S_e (MPa)	225,17
m	0,23
b	3,72
K_f	1,93
K_t	2,00
q	0,93

Source: The authors (2018).

The table 4 shows the result of the number of cycles for the testing conditions from (A) to (E).

Table 4 – Calculation of the number of cycles

Test	σa(MPa)	N
(A)	574,74	16460
(B)	395,13	85038
(C)	359,21	129129
(D)	273,00	429909
(E)	143,68	7162355

Source: The authors (2018).

According to Klobcar *et al.* (2012), the tools for under-pressure casting generally fail due to thermal fatigue cracks. During the cooling stage, a high in stresses is caused on the surface of the die, which in places with local plastic deformation provokes nucleation and the growth of cracks during the subsequent cycle. Long *et al.* (2012) also describes that elevated thermal gradients, during the cooling process of a die, provoke damage to its surface, especially when, in a process, water is used in cycles of heating and cooling.

Camargo (2018), in his study about thermal fatigue in molds, describes the cooling cycle in a mold, using low temperature water at the entrance of the system, produced high thermal stresses that caused cracks that increased with each cycle, leading to cracks of big depths that make it impossible for the mold to be used in the production of good quality parts.

This paper corroborates with the authors referenced in this chapter. Both argue that failure by thermal fatigue are caused by surface thermal stresses, provoked by thermal fluctuation processes, being the cooling process present in the mold of great importance and responsibility.

3 Conclusion

This article presented, in an objective way, the influence of flow and cooling fluid temperature in the fatigue life of a mold component. By this analysis, as the flow and the inlet cooling fluid temperature were increased, the decrease of the thermal gradients was observed, along of the section of the wall of the component. With the decrease of the thermal gradient, the thermal stresses also decreased, resulting in calculations of numbers of cycles gradually higher and, consequently, in a greater resistance of the mold component, in relation to failure from thermal fatigue. An increase in 435 times was obtained, in comparison with the tests - from test A to test E, for the number of cycles until thermal fatigue cracks started to appear. The Goodman model proved to be

an interesting tool to be used, because the theoretical calculated cycling (16460 cycles) and the real cycling observed in practice (8000 cycles) are close to the practical point of view. It serves as an indicator of the quality of the cooling process. One of the important factors for the good performance of the cooling system is that the specific heat of the water doesn't have great alterations between the temperature intervals that were analyzed here (minimum 50ºC and maximum 190ºC). In practice, it is necessary to keep the water circulating in a closed system and at saturation pressure. For example, for water at a temperature of 190ºC to stay in a liquid state, as it was studied here, it must be at pressure higher or equal to 12,6 bar, which is an acceptable value for some equipment used to circulate water in cooling systems.

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