ANALYSIS OF INDUCTION IN THE PROCESS OF COMPONENTS OF ALUMINUM

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***Abstract**: In the hot junction processes the expansion of aluminum in the induction and estimation of the heat flux is considered a working with little development in the scientific area. Several studies have been undertaken in order to determine the correct rate of heat flux in the aluminum, its spreading and proportional growth. Researches in deformation and propagation of heat in workpieces of aluminum also have application in cases of hot junction due to the small percentage of its application in the assembly in the industries. In this work the heat flux and temperature in the junction area during its insertion is estimated by an electromagnetic current applied within an aluminum tube. An analytical methodology based on the propagation of heat and dilation was applied to find the coefficient of expansion. The temperatures were measured in part using a pyrometer infrared. The tests were carried out in injected alloy aluminum Copper. Thus, was possible determine and take account the best parameters of heating surface effect, electromagnetic effects, electromagnetic of effects ring and influence of the heat and electromagnetic parameters.*

***Keywords**: Thermal Expansion; Aluminum Electromagnetic Induction; Electromagnetic Effect; Temperature.*

1. INTRODUCTION

The technology of electromagnetic induction by heat treatment of materials have been used in various fields of engineering, as in the mineral industry, metallurgical industry, automobile industry and specifically in the joints in aluminum house for hydraulic steering mechanisms. The heat treatments aim to change the main physical and mechanical properties of metallic materials, and the steel ones that best respond to these processes. The aluminum hasn't significant nucleation to change its structure; its use in the process of electromagnetic induction is restricted to expansion followed by shrinkage, making it attractive for processes of the hot junction.

The heating provided by a high-speed electromagnetic inductions significantly alter the transformation temperatures of the aluminum would offer subtle way of the junction between two bodies due to the process of thermal expansion. The correlation between the temperature of electromagnetic induction, the temperature in the act of joining and heat treatment parameters on electromagnetic induction and the final properties are obtained that promote initial understanding of the phenomena involved and is an important area of research for the heat treatments. With tests that allow such correlation, this work was given the continued developments of the partnership between the Federal University of São João del Rei and TRW Automotive Ltda., Which were established the optimum parameters for induction heat treatment at the junction of two bodies aluminum cups for hydraulic steering.

1.1. Basic principles of heating by induction

An alternating electric current moving through a conductor always produces a magnetic field around the conductor. If the current flows in a conductor in the form of a spiral and is placed a metallic body in the magnetic field inside the helix, this field creates a force in the aluminum electrometric induced which produces an electric current (current or parasites Foucault) in order that would produce, in turn, induced a magnetic field that opposes the change in magnetic flux of the coil. This current can join Joule losses ($P = I^2R$), which will cause the energy injected into the system to create the magnetic field will in large part, transformed into heat. Besides the effect of heating due to losses by Joule effect, is caused by another phenomenon called hysteresis losses. The ferromagnetic elements, having a magnetic permeability on lesser than 1, show this effect in a field alternate. It follows from the fact that the magnetic material is composed of tiny elementary magnets arranged at random (Martins, 1975).

In the alternating magnetic field of the induction coil are continually forced to change its orientation to the rhythm of the frequency of circulating current in the coil. This change of direction causes a quantity of heat that increases with increasing frequency, but even for this high frequency heating is considerably low compared to the amount of heat due to Joule losses, since they increase with the square of the frequency. The hysteresis losses are to the point of Curie. Next to this point and above it on the magnetic permeability of the material then decreases to 1, while at temperatures below the Curie temperature is high (Martins, 1975).

A system for induction heating system, which consists of a cylindrical piece surrounded by an induction coil of several turns, is shown in Fig. 1.

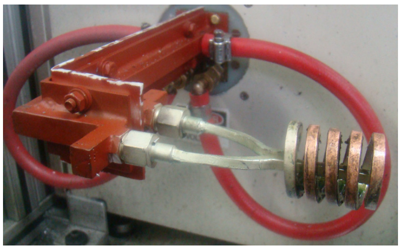


Figure 1. Detail of the induction heating system used in the experiments

Due to electromagnetic phenomena, the distribution of current within the inductor and the piece is not uniform. This non-uniformity of heat source generates a non-uniform temperature profile of the piece. A non-uniform distribution of current can be caused by complex electromagnetic phenomena, including: surface effect, proximity effect and effect of ring. These effects have an important role in understanding the phenomenon of induction heating (Rudnev, *et. al*. 2003).

1.2. Surface effect

When an alternating current through a conductor is generating the distribution of current is not uniform. The maximum current density is always located on the surface of the driver and reduces the surface to the inside (toward the center). This phenomenon of uneven distribution of current within a section through the driver is called the surface effect. This effect always occurs in isotropic conductors in its straight section and is also found in the part located inside the coil, according Fig. 1. Due to the surface, approximately 86% of the current concentrates on the superficial layer of the driver, in a region called the reference layer and penetration in depth. δ In alternating current, the degree of the surface effect depends on the frequency of alternating current and the properties of the heated material, such as electrical resistivity and magnetic permeability on (Rudnev *et. al*., 2003). The surface effect can be described by a differential equation, whose solution shows that the current induced on flat surface decreases exponentially toward the center of the piece. The depth of penetration of current in one piece of treatment is defined by the limit in which the density reaches 37% of current value of the surface **(**Loveless *et. al.,*1995a, 2000b), as can be calculated by the Eq. 1(ASM, 1991).

$$\delta = \left(\frac{\rho}{(\pi.\mu_0.\mu.f)} \right)^{1/2} \qquad (1)$$

Where:

δ = Depth of penetration;
ρ = Electrical resistivity of the workpiece;
μ_0 = Magnetic permeability in vacuum;
μ = Magnetic permeability of the piece;
f = Frequency of the alternating magnetic field of the coil.

The layer with the thickness fired approximately 87% of all heat. Consequently, the depth of penetration of current δ, and decreases with the increase of its frequency. In practical calculations, the magnetic permeability of a non-magnetic piece, μ, is close to the air and takes value 1. This applies to steel above the Curie temperature. The relative magnetic permeability of aluminum commonly used for heating by induction may vary from small values of μ_r (μ_r = 2 or 3) the high values of r (over 500), depending on the intensity of the magnetic field and temperature (Rudnev, *et. al*., 2003).

The depth of penetration is also function of temperature. At the beginning of the cycle of warming, the penetration of aluminum in the current increases, due to the increase of electrical resistivity of the material with temperature. Near the critical temperature Tc (Curie temperature) the permeability drops sharply to a unit, because the material becomes paramagnetic, further increasing the depth of penetration. After heating above the critical temperature Tc, the depth of penetration will increase due to the increase in electrical resistivity of the material, however, the rate of growth will not be as significant, as it occurs in the transition through the Curie temperature, it can is shown in Fig. 2 (Rudnev *et. al*. 2003).

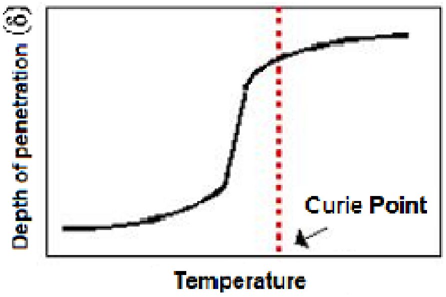


Figure 2. Determination of the Curie point

1.3. Electromagnetic effect of proximity and effect of ring

When an electric current in opposite directions is conducting in two parallel wires, a strong magnetic field is formed in the region between them. The magnetic field lines, which are produced in parallel bars, have the same direction, making the magnetic field resulting from the bar is very strong. If the currents have the same direction, then the lines of magnetic field have opposite directions in the area between the bars, so they cancel. Increasing the distance between the bars decreases the power of the effect of proximity (Rudnev *et. al*., 2003).

The induction system consists of two drivers: one is the inductor carrying a current source and the other is located next to the piece inducer. Parasitic currents are induced in part by an external alternating magnetic field. Due to the effects of proximity of the currents induced in the coil and the piece will focus on the facial areas from one to another. If the bar is driving curve, in the form of ring also occurs a redistribution of power. The line of magnetic flux is concentrated inside the ring and thus the density of the magnetic field is high in this region. As a result, most of the current flow within a thin surface layer internal. Effect of this ring is similar to the effect of closeness and the concentration of current causes the inner surface of the induction coil (Rudnev *et. al*., 2003).

1.4. Influence of the transfer of heat and parameters electromagnetic

The nature of heating by induction is a combination of two phenomena: heat transfer and induced current. They are closely inter-related, because the physical properties depend on two phenomena, the magnetic field intensity and temperature (Loveless *et. al.,* 1995). In induction heaters, the three forms of heat transfer are present: conduction, convection and radiation. In general, the problems of transient heat conduction of the conductive piece can be described by the equation of Fourier. Due to the phenomenon of heat transfer by conduction, heat is conducted in the region of high temperature of the piece toward the region of low temperature. The ratio of heat transfer is proportional to the gradient of temperature and thermal conductivity of the material. Due to non in the thermal properties of the piece, such as thermal conductivity and specific heat, the problem of heat transfer is not linear (Loveless *et. al.* 1995).

The design of the coil based on the crude approximation of the thermal conductivity can lead to significant errors in predicting the temperature profile of the piece. Not accurate approximation of the specific heat can not only lead to incorrect profiles of temperature, but can also create a significant error in the choice of power required. Usually the problems of heating by induction are affected by the loss by convection and radiation. Losses of heat by the surface of the piece are clearly variables due to non constant of losses by convection and especially the losses by radiation. In tests performed for low temperatures, applications of induction heaters, convection losses are a significant part of total heat loss, but in applications to high temperature radiation losses are the most losses of heat. Transfer of heat by radiation and convection are usually negative factors in the conventional heating by induction, because they reflect the value of the loss of heat. In addition, as a result of these factors in induction heating by the piece, is the undesirable non-uniform temperature profile (Loveless *et. al.,*1995).

2. EXPERIMENTAL WORK

The experiment were carried out to determine the optimum temperature for conducting the process of junction between two bodies of aluminum with cylindrical dimensions of 41mm by 45 mm in length, using a total length of 500 mm after the junction, as shown in Fig. 1. The chemical composition of aluminum is the object of study: Copper (Cu 3-4%), Silicon (Si 7.5 and 9.5%), Iron (Fe 1.3% max), and manganese (Mn 0.5% maximum), Magnesium (Mg 0.3%

max), Zinc (Zn 1.2% max), Nickel (Ni 0.5% maximum), Tin (Sn 0.35% maximum), Other (0.5% maximum) and Aluminum (Al 81.8% approximately).

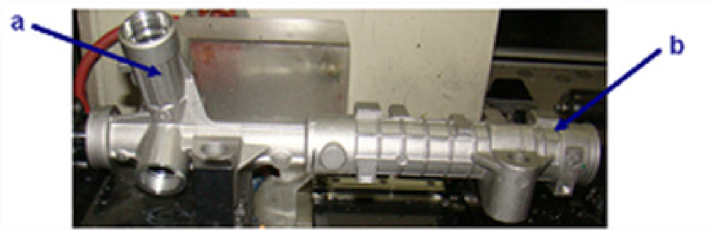
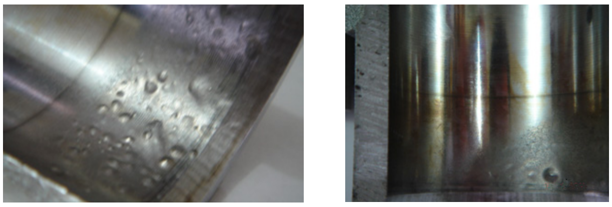


Figure 3. Steering hydraulic gear – (a) Housing, (b) Tube

Figure 4 shows the factors that were considered as anomalies of the process, bubbling in the internal diameter of the tube come from greater exposure to the process of electromagnetic induction. The electromagnetic effect known as the proximity and trademarks in internal diameter of the tube were resulting from low exposure to the process of electromagnetic induction. To determine which parameters are appropriate procedures for the implementation of this operation can take Table 1 as a starting point:



4 (a) 4 (b)

Figure 4. Example of bubbling in diameter

Table 1. Experimental conditions chosen to begin experiments

Tx	V @ Tx	Delta V	Delta S	S final	Dint final	Incremento Dia/100	Energia Entalpica	Kwsgerador	Tempo	S @ Tx	Dext @ Tx	Delta diaext/100
°C	mm3	mm3	mm2	mm2	mm		kWs			mm2	mm	mm
	$\Delta V = \beta V \Delta T$	$\Delta V = Vf - Vi$	$\Delta S = \frac{\Delta V}{L}$	$Sf = \Delta S + Si$	$d = \sqrt{\frac{4}{\pi} Sf}$	$\Delta d = (df - di)100$ $[mm \times 10^{-2}]$		$E_{gerador} = \frac{E_{entalp}}{n}$	$t = \frac{E_{gerador}}{P}$ $\left[s = \frac{kWs}{kW}\right]$			
25	35293,1	0,0	0,0	1336,4	41,3	0,0	2,3	6,5	1,0	840,3	52,66	0,78
30	35305,5	12,4	0,3	1336,7	41,3	0,5	2,7	7,8	1,2	840,6	52,66	1,50
35	35317,8	24,8	0,6	1337,0	41,3	0,9	3,2	9,1	1,4	840,9	52,67	2,21
40	35330,2	37,2	0,9	1337,3	41,3	1,4	3,7	10,5	1,6	841,2	52,68	2,92
45	35342,6	49,6	1,2	1337,6	41,3	1,8	4,1	11,8	1,8	841,5	52,69	3,64
50	35355,0	61,9	1,5	1337,8	41,3	2,3	4,6	13,1	2,0	841,8	52,69	4,35
55	35367,4	74,3	1,8	1338,1	41,3	2,7	5,0	14,4	2,2	842,1	52,70	5,06
60	35379,8	86,7	2,1	1338,4	41,3	3,2	5,5	15,7	2,4	842,4	52,71	5,78
65	35392,2	99,1	2,4	1338,7	41,3	3,6	5,9	17,0	2,6	842,7	52,71	6,49
70	35404,6	111,5	2,7	1339,0	41,3	4,1	6,4	18,3	2,8	843,0	52,72	7,20
75	35416,9	123,9	2,9	1339,3	41,3	4,6	6,9	19,6	3,0	843,3	52,73	7,91
80	35429,3	136,3	3,2	1339,6	41,3	5,0	7,3	20,9	3,2	843,6	52,74	8,63
85	35441,7	148,7	3,5	1339,9	41,3	5,5	7,8	22,2	3,4	843,9	52,74	9,34
90	35454,1	161,0	3,8	1340,2	41,3	5,9	8,2	23,5	3,6	844,1	52,75	10,05
95	35466,5	173,4	4,1	1340,5	41,3	6,4	8,7	24,8	3,8	844,4	52,76	10,76
100	35478,9	185,8	4,4	1340,8	41,3	6,8	9,1	26,1	4,1	844,7	52,76	11,48
105	35491,3	198,2	4,7	1341,1	41,3	7,3	9,6	27,4	4,3	845,0	52,77	12,19
110	35503,7	210,6	5,0	1341,4	41,3	7,7	10,1	28,8	4,5	845,3	52,78	12,90
115	35516,0	223,0	5,3	1341,7	41,3	8,2	10,5	30,1	4,7	845,6	52,79	13,61
120	35528,4	235,4	5,6	1342,0	41,3	8,6	11,0	31,4	4,9	845,9	52,79	14,32
125	35540,8	247,8	5,9	1342,3	41,4	9,1	11,4	32,7	5,1	846,2	52,80	15,03
130	35553,2	260,1	6,2	1342,6	41,4	9,6	11,9	34,0	5,3	846,5	52,81	15,75
135	35565,6	272,5	6,5	1342,9	41,4	10,0	12,3	35,3	5,5	846,8	52,81	16,46
140	35578,0	284,9	6,8	1343,2	41,4	10,5	12,8	36,6	5,7	847,1	52,82	17,17
145	35590,4	297,3	7,1	1343,5	41,4	10,9	13,3	37,9	5,9	847,4	52,83	17,88
150	35602,8	309,7	7,4	1343,7	41,4	11,4	13,7	39,2	6,1	847,7	52,84	18,59
155	35615,2	322,1	7,7	1344,0	41,4	11,8	14,2	40,5	6,3	848,0	52,84	19,30
160	35627,5	334,5	8,0	1344,3	41,4	12,3	14,6	41,8	6,5	848,3	52,85	20,01
165	35639,9	346,9	8,3	1344,6	41,4	12,7	15,1	43,1	6,7	848,6	52,86	20,72
170	35652,3	359,2	8,6	1344,9	41,4	13,2	15,6	44,4	6,9	848,9	52,86	21,44
175	35664,7	371,6	8,8	1345,2	41,4	13,6	16,0	45,7	7,1	849,2	52,87	22,15
180	35677,1	384,0	9,1	1345,5	41,4	14,1	16,5	47,0	7,3	849,5	52,88	22,86
185	35689,5	396,4	9,4	1345,8	41,4	14,5	16,9	48,4	7,5	849,7	52,89	23,57
190	35701,9	408,8	9,7	1346,1	41,4	15,0	17,4	49,7	7,7	850,0	52,89	24,28
195	35714,3	421,2	10,0	1346,4	41,4	15,5	17,8	51,0	7,9	850,3	52,90	24,99
200	35726,6	433,6	10,3	1346,7	41,4	15,9	18,3	52,3	8,1	850,6	52,91	25,70
205	35739,0	446,0	10,6	1347,0	41,4	16,4	18,8	53,6	8,3	850,9	52,91	26,41
210	35751,4	458,4	10,9	1347,3	41,4	16,8	19,2	54,9	8,5	851,2	52,92	27,12
215	35763,8	470,7	11,2	1347,6	41,4	17,3	19,7	56,2	8,7	851,5	52,93	27,83

3. RESULTS AND DISCUSSION

The first experiment was to set the equipment in time of induction in 3.6 seconds, 23.5% of the power generator using 8.2 $kW.s^{-1}$ by increasing the internal diameter of the tube at 0.059 mm. Figure 5 and 6 show the variation of temperature during the act of heating electromagnetic.

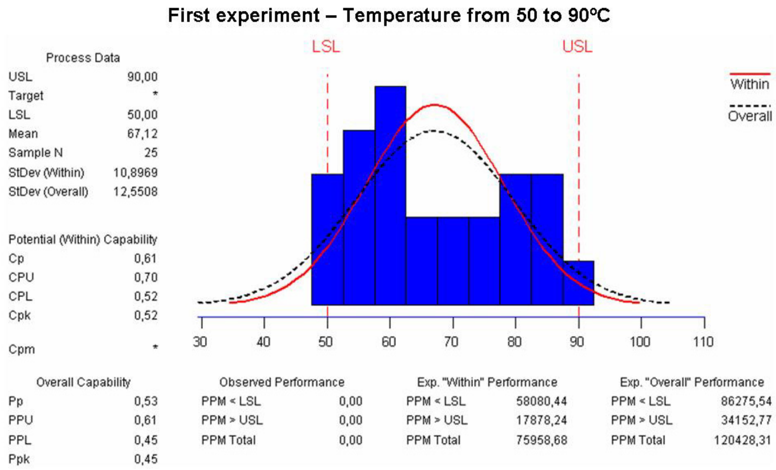


Figure 5. Normal distribution of temperature of heating (First experiment)

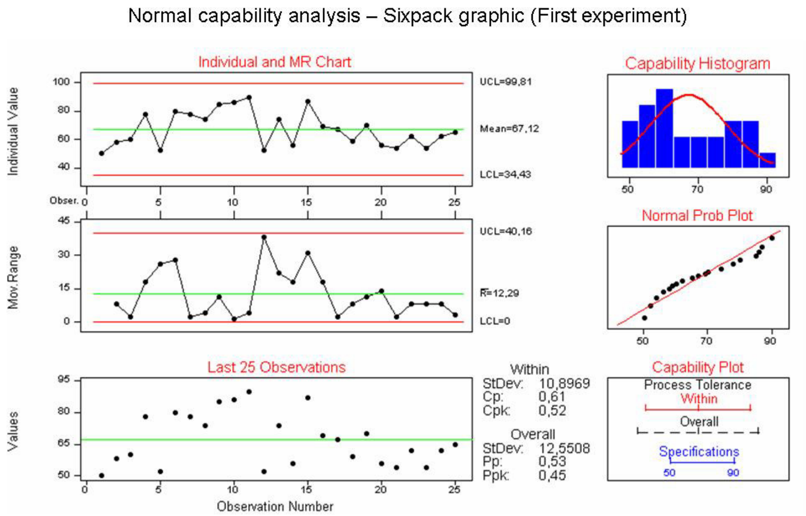


Figure 6. Magnitude and distribution of the normal temperature of heating (First experiment)

It can be observed that the parameterization used in first experiment caused malfunction in the junction, not allowing the perfect union between the two bodies, leaving 4 mm to the side of the carcass and side slopes of the tube is as shown in Fig. 7.

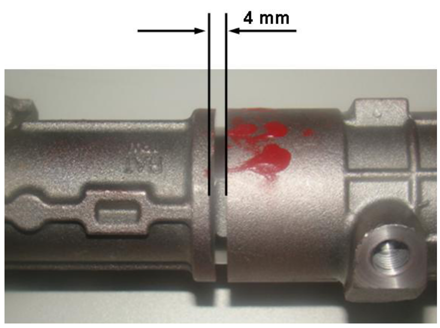


Figure 7. Junction between the tube and the body open

The second experiment was to set the equipment in time of induction in 7.3 seconds, 49.7% of the power generator using 17.4 $kW.s^{-1}$ by increasing the internal diameter of the tube at 0.15 mm. Figure 8 and 9 show the variation of temperature during the act of heating electromagnetic:

Second experiment – Temperature from 80 to 190 °C

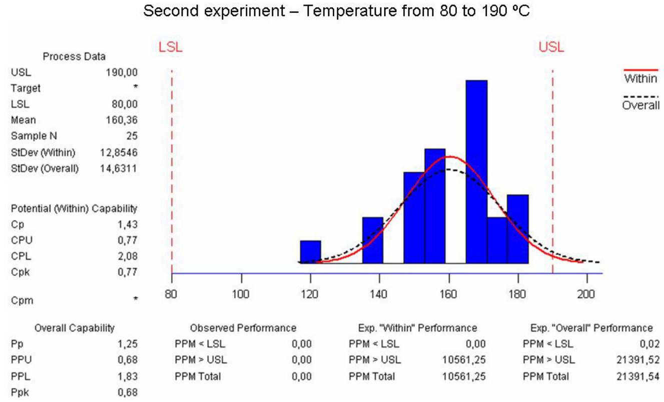


Figure 8. Normal distribution of temperature of heating (Second experiment)

Normal capability analysis – Sixpack graphic (second experiment)

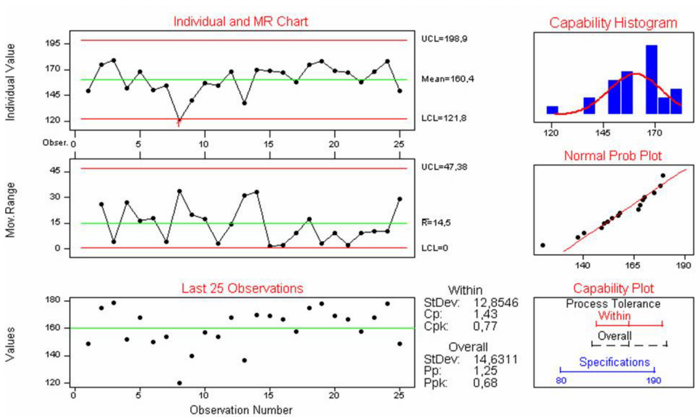


Figure 9. Magnitude and distribution of the normal temperature of the heating (Second experiment)

We note that the parameterization used in experiment 2 caused malfunction in the junction, causing bubbling in the internal diameter of the tube due to the high power applied to the inside diameter of the tube and electromagnetic effects of proximity, as shown in Figs. 4(a) and (b), respectively. The third experiment was to set the equipment in time of induction in 5.9 seconds, 37.9% of the power generator using 13.3 $kW.s^{-1}$ by increasing the internal diameter of the tube at 0.109mm. Figures 10 and 11 show the variation of temperature found in the act of heating electromagnetic:

Third experiment – Temperature from 80 to 160ºC

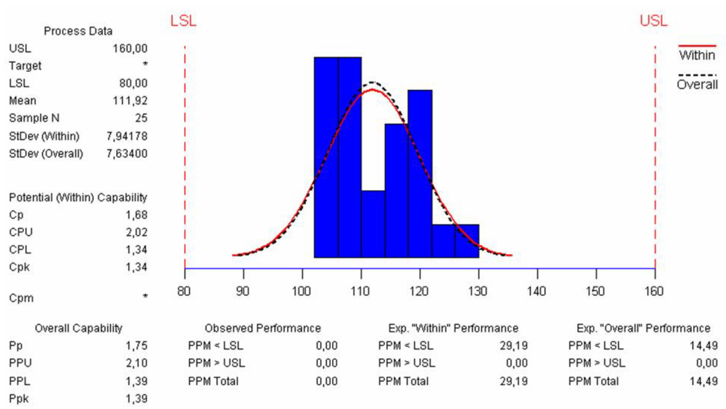


Figure 10. Normal distribution of temperature of heating (Third experiment)

Normal capability analysis – Sixpack graphic (Third experiment)

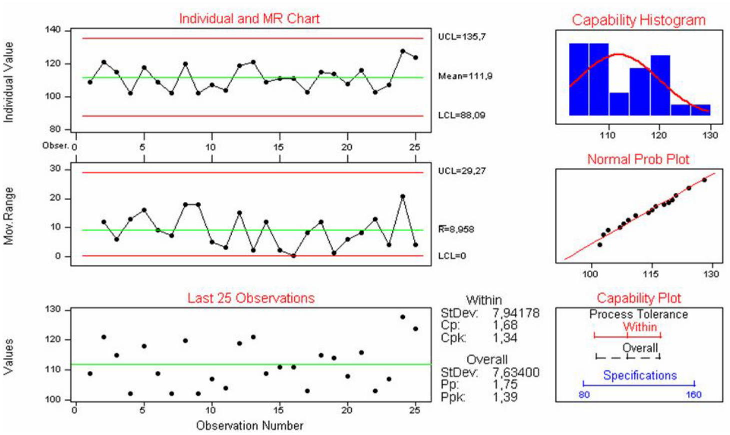


Figure 11. Magnitude and distribution of the normal temperature of heating (Third experiment)

We note that the parameterization used in experiment 3 was suitable for the process of union of parts, not causing abnormalities in everything and in the carcass, as shown in Fig. 12.

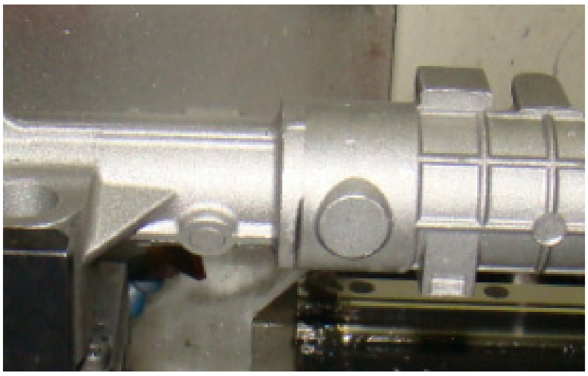


Figure 12. Junction between housing and everything

4. CONCLUSIONS

The following final conclusions are summarized below:

- When comparing different power converter, the greater time of exposure to electromagnetic current, increase the dilation of the internal diameter of the tube to the limit of present diseases known as surface effect;
- The shorter time of exposure to electromagnetic current, reduced the dilation of the internal diameter of the pipe, disabling the perfect junction between components, leading to loss process;
- The electromagnetic current spread uniformly from within everything out of everything, and time that separates the heat until the junction has no loss of heating and expansion by the addition of components;
- The balance of power, time of exposure to electromagnetic current and proximity effect, observed in third experiment was considered appropriate, not presenting any anomaly during and after the process of joining of aluminum components.

5. ACKNOWLEDGMENTS

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