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Influence of induction heating of injection molds on reliability of electrical connectors

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Highlights

- The publication presents the problem of an exploitation of the rail-mounted electrical connectors.
- Experimental studies and obtained results are shown.
- Selective induction heating process resulted in a decrease in damaging of the plastic parts.

Abstract

Continuous increase in demand for electricity causes that electrotechnical industry is relentlessly under pressure of technological development. It is necessary to reduce costs while increasing a reliability of manufactured products. Common miniaturization of products mounted in land vehicles, vessels and airplanes along with limitation of their weight requires the use of innovative production methods. This publication presents the problem of exploitation related with reliable assembly and disassembly of rail-mounted electrical connectors. In order to improve the reliability of injected electrical connector housings, the authors proposed the selective induction heating technology as a heating method of injection mould. To reveal the origin of the problem, in case of this work, the simulation studies of filling the mould cavity were carried out. They show an incorrect localization of polymer streams weld line. Then the results of the simulation and induction heating experiment are presented. They were necessary for the proper design and make of the injection mould. In the final stage, the experimental tests of the manufactured housings assembly and disassembly were performed in conditions corresponding to the actual conditions. The obtained results show, that selective induction heating technology has significantly improved the reliability of rail-mounted electrical connector housings.

Keywords

injection mold, induction heating, maintenance and reliability of moldings, electrical connectors.

1. Introduction

Electrical and electronic parts are nowadays integral components of mechanical engineering, vehicles and devices. Given that those parts are often responsible for the user's safety, they are required to have a high reliability [28]. Because of continuous pursuit of miniaturization, the amount of problems related to maintaining the reliability of these elements still increases [25, 30]. The authors, B. Sun, A. Wymysłowski et al. examined the exploitative problems of electronic components which are caused straight by miniaturization. The miniaturization problems do not only concern electronics. Limitation of weight and overall dimensions acts as a barrier for housings constructors and contractors, which are usually made of polymer material using injection molding technology [24]. Due to its insulating properties, ease of molding and low price, plastics have become the basic materials used in the production of housings precisely in injection molding technology.

Of all the injection molding parameters, the key is the temperature of the forming surfaces when filling the cavity with the flowing material [1, 2, 20, 27]. In a publication [17] there was shown an effect of induction heating on thin-walled, plastic products manufacturing process. Likewise, Chang et al. proved, that the use of high mold's cavity temperature allows to produce elements with good aesthetic [5-8]. During conventional process of injection molding, the constant-temperature injection molds are used. The difference in temperature between the flowing plastic stream and the forming surface causes, that the polymer melt cools down and its viscosity increases with the distance travelled. On the other hand, in a publication [26] it was noticed, that the heat loss of injected polymer melt decreases with an injection velocity increase, what prove about importance of that parameter in a context of the conventional process. The creation of frozen layers reduces the cross-section of the mold cavity, what prevents filling the forming areas which are the furthest from the injection point. Problems with incomplete filling of the mold cavity appear in particular while processing plastic materials with increased viscosity or containing various types of filling agents (strengthening fibers, magnetic powders, talc, flame retardants, etc.) [32]. Very often this phenomenon is accompanied by microstructure mapping errors and

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defects related to incorrect shaping of flowing polymer melts' weld lines [3, 13]. Defects which are caused by too low mold temperature and increased injection pressure can be removed in additional processes. It is appropriate to take into account, that from an economic and ecology manufacturing point of view, conducting complex production included in one operation of injection molding is more beneficial.

In the case of dynamic mold temperature change technology, mold cavity doesn't have one, constant work temperature. The temperature in the mold is changed intentionally in the way synchronized with the work of the injection machine, in accordance with the profile selected by the technologist. At the moment of injection, forming surfaces are heated to the temperature near to the injected polymer melt's temperature. After injection the intense mold cooling process begins. Thanks to that, it is possible to produce elements with high gloss, without deformations or visible flow lines [31] and thin-walled elements, which are often subjected to incomplete filling of the mold cavity. The rheology of the polymer materials, due to their non-newtonian character, is directly related to the processing temperature [33]. In opposite to newtonian liquids, in isobaric conditions the viscosity of the flowing melt is not a constant value, but it changes with the shear rate [34]. Techniques of the cyclic regulation of mold's cavity temperature gives the manufacturer a possibility of aware influence on waveform and distribution of temperatures in the cavity. According to Huang et al. study, the process of premature polymer melt cooling is stopped by increased temperature of the forming walls, which enable complete filling of the cavity and provide high quality of microstructure mapping [14, 19]. It helps to obtain more accurate map of the surface with significantly lower mold filling resistance during the injection process [29]. The quality of surface reproduction is nowadays a growing challenge [11]. However, during the holding phase there is better pressure propagation in the whole volume of a molded piece. This means that there are smaller pressure gradients between the injection point and the furthest areas from it in the plastic flow path. In accordance to the analysis carried out by Liparoti et al., it results in a decrease of frozen stresses in molded part and lower values of shrinkage and its various orientations [15]. This benefit becomes noticeable especially when the cyclic regulation of mold's cavity temperature involves both halves of the mold. Of the many rapid heating methods, the induction heating offers many advantages [9]. The main advantage of high-frequency induction heating is, first of all, possibility of surface heating (without large volumes), which is called the skin effect. There are many publications describing the influence of induction heating on the quality of molded parts and the production process [22, 23]. Mechanisms for the formation of weld lines of flowing plastic streams are also widely tested [3, 4]. However, the literature is devoid of studies on the impact of induction heating on the exploitation and reliability of plastic products. As part of the work, the authors undertake to define the problem of exploitation of the rail-mounted electrical connector housings. The study contains simulation tests of housings manufacturing process, induction heating of chosen forming areas and experimental tests involve production and exploitation of a group of 1000 test samples (mold parts).

2. Problem definition

In the figure 1 the process of electrical connector assembly and disassembly on the rail was shown. The connector housing was fitted with a closed flexible clip, which is widely used in the electrotechnical industry.

Pressing the housing to the rail causes temporary elastic deflection of the foot (fig. 1a). Disassembly is done by pulling the clip away with a screwdriver or other tool (fig. 1b). As can be seen (fig. 1c), the highest stresses are accumulated in the foot area (stress simulation tests were presented as a guide). The problem is that the place of joining

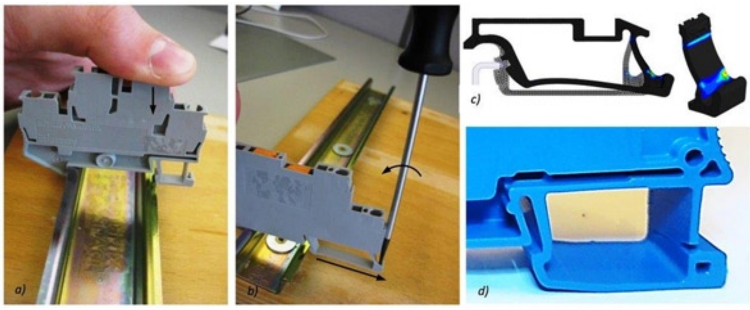

Fig. 1. Example of an electrical connector fitted with a flexible clip: a) assembly of connector on the rail, b) disassembly of the product using a screwdriver, c) stress concentration in the flexible clip during disassembly process, d) the problem of cracking of the installation foot during deformation of the clip

of flowing plastic streams becomes the area of stress concentration. In case of too cool fronts of polymer melt meet, it is impossible to create sufficiently strong polymer bindings. It results in cracking of the clip while disassembling, what, in effect, disqualifies the product from a further use (fig. 1d). The mold part shown in the figure 2 is a prototype of electrical connector housing. A dense ribbing allows to obtain high stiffness of the part and enables the assembly of conductive elements.

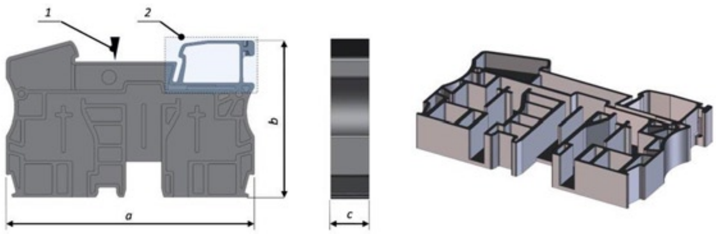

Fig. 2. The model of the electrical connector fitted with flexible joint parts: a = 80,2 mm, b = 50,6 mm, c = 12,2 mm, 1 – injection point, 2 – the forming area of the flexible installation foot qualified for selective induction heating

The product was designed to reduce its weight as much as possible. The upper part of the molded piece is fitted with a mounting unit. The flexible installation foot allows the connector to be clipped in and out on the mounting rail.

3. Simulation tests for the filling of the mold cavity

In order to correctly read the problems related to the assembly and disassembly of the electrical connectors, it was necessary to simulate the flow of the plastic melt inside the mold cavity. To make that, the Cross-WLF model was used. Melted polymers are non-newtonian liquids and their properities are strictly dependent on the temperature [33]. Contrary to newtonian liquids, polymer melts viscosity η is not constant and it depends on shear stress τ and shear rate $\dot{\gamma}$ (1):

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{1}$$

The viscosity of polimers η decreases with growth of the shear rate $\dot{\gamma}$ [10, 34]. To determine the viscosity, the Cross model was used (2):

$$\eta = \frac{\eta_0}{1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{2}$$

To determine the relation between the viscosity η and the temperature T, the Williams-Landel-Ferry equation was used (3):

$$\eta_0 = D_1 exp\left[-\frac{A_1\left(T-T^*\right)}{A_2+\left(T-T^*\right)}\right] \quad (3)$$

where D_1 A_1 A_2 are material constants, T^* is a reference temperature. Equations 1-3 are called Cross-WLF model.

Simulation studies were conducted using Autodesk Moldflow Insight 2013 program. The parameters for simulation tests of the mold cavity filling are shown in Table 1.

Table 1. Output parameters for simulation tests for the third test model

	Conventional technology	Induction heating
Injected material:	PA 66 (Frianyl A63 RV0 Frisetta)	PA 66 (Frianyl A63 RV0 Frisetta)
Material temperature [°C]:	270	270
Mold temperature [°C]:	70 – the whole cavity	70 - cavity/ 130; 150; 170 - induction heating
Filling time [s]:	0,8	0,8
Holding time [s]:	2	2
Cooling time [s]:	8	8.1
Injection pressure [MPa]:	37	36.6; 35.9; 33.6
Holding pressure [MPa]:	29.6	28.7

The plastic flowing streams at first fill the body of the molded part, and in the final phase is the installation foot formed. The foot is a closed loop, which means that the two streams merge in its circumference (fig. 3).

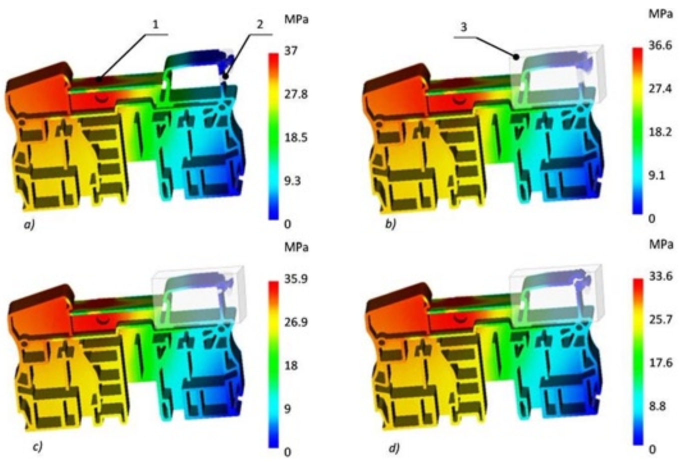

Fig. 3. Simulation tests of filling the mold cavity for electrical connector housing, a) conventional process with constant mold temperature, b) temperature of induction heated area is 130°C, c) temperature of induction heated area is 150°C, d) temperature of induction heated area is 170°C, 1 – injection point, 2 – the place of joining of flowing plastic streams, 3 – the mold area heated by induction heating

Because this process takes place in the last phase of injection, their fronts are that much cool, that there is no possibility to create strong polymer bindings. As this area is exposed to a stress concentration during assembly and disassembly of the product, it is often cracked. In theory, the solution of this problem would be to locate the gate directly on the installation foot, but for technological reasons this is economically unjustified. This type of electrical connectors is produced in a such big amounts, that the cold channel injection system has been displaced by the direct (hot channel) injection system. For economic reasons, a cold channel system was used for the experiment. On the basis of the carried out simulation studies, it was found that a local increase in temperature in the forming area of the installation foot caused the weld line to move outside the stress concentration area. There has been a slight reduction in pressure, which is due to the small proportion of the area with increased temperature to the entire area of the mold cavity. The results show, that exploitation of the electrical connectors should be improved after heating the installation foot forming area to 170°C.

4. Induction mold heating tests

The design and building processes of injection mold dedicated to produce electrical connector housings (fig. 2) required simulation and experimental tests of the induction heating process. The simulation analysis was carried out using the Finite Element Method (FEM) implemented in the QuickField 6.3.1 package. All tests were performed in 2D space (xy) in AC Magnetics modules (electromagnetic analysis) to determine current density, magnetic field strength and magnetic flux density on the surface of the metal insert, followed by Transient Heat Transfer (non-stationary thermal analysis) to determine surface temperature changes as a function of time. The 2D model is a cross-section through a heated insert and induction coil in a plane perpendicular to the direction of current flow through the coil. Due to the multitude of non-linear relationships between individual parameters, it is difficult to predict the exact temperature value during induction heating [21]. Moreover, not only material properties have an influence on the induction heating process. Stresses caused by machining and heat treatment can influence on the induction heating process significantly. The basis for solving problems with electromagnetic phenomena are Maxwell equations (4-7) [12, 16, 18]:

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (4)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} = J_s + J_e + \frac{\partial D}{\partial t} \quad (5)$$

$$\nabla \cdot D = \rho \quad (6)$$

$$\nabla \cdot B = 0 \quad (7)$$

where E is the intensity of the electric field, B is the density of the magnetic flux, H is the intensity of the magnetic field, J is the density of the current, D is the density of the electric flux, J_s is the source current vector, J_e is the induction vector, ρ is the density of the electric charge.

Induction coil in shape of closed loop was positioned in the way, which determine the forming insert as a heated core (fig. 4a). It is the most effective method of induction heating, because the magnetic flux penetrates in direction perpendicular or close to perpendicular to the surface of heated insert. As assumed, very high temperature increases were achieved in a short time (fig. 4b). The average velocity of heating after 2,5 s was 210°C/s. In 1 s the character of

Table 2. Material data for simulation tests

Material	1.2343	Fluxtrol A	Cu	Water	Air
Relative magnetic permeability μ_r	55	130	1	1	1
Electrical conductivity $\sigma\left[\frac{s}{m}\right]$	1e7	5e-5	5,6e7	2e-4	5e-15
Thermal conductivity $K\left[\frac{W}{mK}\right]$	45	23	380	0,58	0,025
Density $\rho\left[\frac{g}{cm^3}\right]$	7,8	6,6	8,7	1	0,001
Specific heat $C\left[\frac{J}{kgK}\right]$	460	430	380	4190	1005

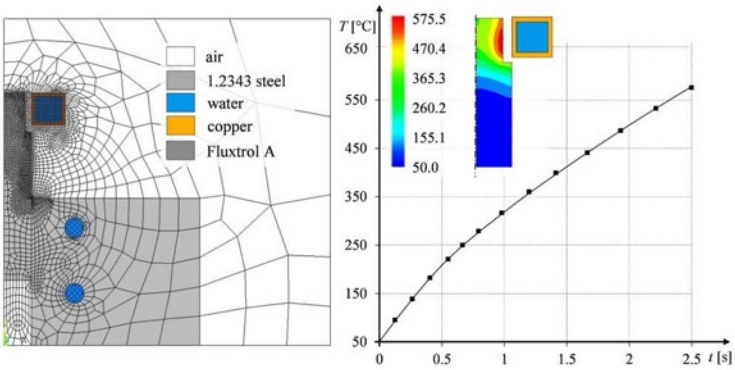

Fig. 4. Simulation tests of induction heating process carried out on the insert which forms the molded part's clip: a) a diagram with a preset discretisation in a QuickField program b) obtained results

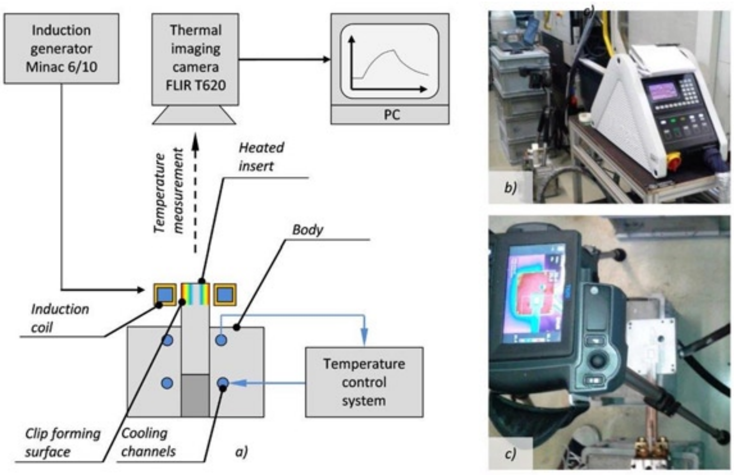

Fig. 5. Experimental tests of induction heating process carried out on the insert which forms the molded part's clip: a) a diagram b), c) the test stand

heating curve has changed. The obtained waveform is clearly close to the linear relationship.

To verify the results obtained by the simulations, before developing the construction and building the prototype of the injection mold, the experimental tests were carried out. For this purpose, a special test stand was prepared, which has included an EFD Minac 6/10 induction generator, two interchangeable induction coils, FLIR T620 thermal imaging camera, a computer, PSG temperature regulation system and a casing with interchangeable heated inserts (fig. 5).

Parameters used in the analyses are collected in Table 3.

The coil connected to the power supply and cooling system of the generator was positioned in relation to the heated surfaces according to the scheme shown in Figure 4. The thermal imagining camera, connected to results recorder which was installed on the computer, was placed on a tripod 700 mm from the heated surfaces. The injection mold body made from 1.2343 steel and interchangeable inserts made from the same material were covered with special chalk to obtain the same coefficient of emission on all measuring surfaces. The cooling system, which consisted of two rows of drilled channels with 6 mm diameter, was connected to temperature regulation system. Before the induction heating process, the body and the insert were heated to 50 °C. This temperature corresponds to the processing conditions for polyamide. The heating process, temperature and water flow through the coil rate were controlled from the generator's control panel. The temperature and the coolant flow through the body rate were determined from the PGS cooling system. The research process was carried out in the injection molding hall under conditions corresponding to actual production conditions (Fig. 5).

During the experimental studies, the measurement time was extended from 2.5 to 4.5 s to take into account the heat loss occurring during the withdrawal of the induction coil and mold closure, assuming that this time will be 2 s. The photographs of the measuring station are shown in Figures 5b and 5c.

The images recorded by the camera were sent to a PC on which the FLIR ResearchIR MAX software was installed. This program enables displaying of the results in temperature to time graph form. Similar to QuickField program, there is a possibility to select the points, for which values of the temperature increases are supposed to be read. The exemplary thermogram and the heating process graph for two reference points: P_1 – placed straight on the heated wall and P_2 – placed 1 mm into the material from the heated surface are shown in the Figure 6.

Table 3. Process parameters during experimental studies

Parameter	Wartość
Ambient temperature [°C]	24.8
Current in the coil [A]	828*
Coil cross-sectional area [m^2]	3,6e-5
Current density of the inductor $\left[\frac{A}{m^2}\right]$	3e7
Inductor frequency [kHz]	25
Water flow through the coil [l/min]	6
Water temperature at coil entry [°C]	35
Body and insert initial temperature [°C]	50
Water flow through the body [l/min]	6
Temperature at the entrance to the body [°C]	50
Diameter of cooling channels [mm]	6
Heating time [s]	2.5
Measurement time [s]	4.5

** The current values have been selected according to the induction generator manufacturer's recommendation for the particular coil type.*

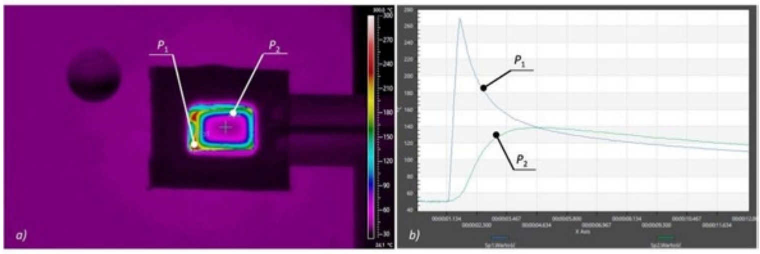

Fig. 6. Examples of results displayed in the FLIR Research MAX program: a) thermogram, b) graph, P_1 – placed straight on the heated wall and P_2 – placed 1 mm into the material from the heated surface

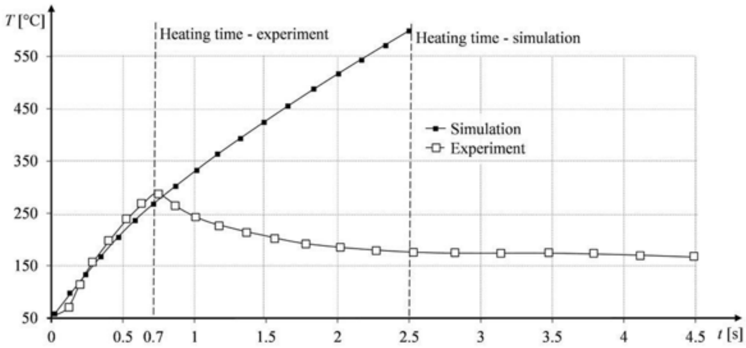

Fig. 7. Comparison waveforms of the heating process for simulation and experimental studies while keeping 1 mm gap between induction coil and the heating surface

Fig. 8. Preparation of the mold cavity: a) making of ejector holes in wire electrical discharge machining technology, b) making of shapes which form a ribbing of the molded part

Table 4. Process parameters during the experimental studies

Parameter and unit	Value
Hopper temperature [°C]	75
Plastic temperature [°C]	275
Temperature of the mold – cavity [°C]	50
Temperature of the mold – core [°C]	50
Temp. of the mold – the forming area of the clip [°C]	130 / 150 / 170
Injection pressure – limit [MPa]	50
Holding pressure – limit [MPa]	400
Mold clamping force [kN]	250
Injection time [s]	0,62
Holding time [s]	1,5
Cooling time [s]	5,8

Contrary to experimental studies, simulation studies allowed to determine the temperature distribution in the cross-section of the heated insert. Therefore, the obtained graph (Fig. 4) shows maximum values of temperatures in the volume of the insert, while during experimental tests maximum surface temperatures were recorded (Fig. 6).

In simulation tests, the cooling process of the insert, which takes place after the heating process was completed, was not included. However, this process was recorded during experimental studies. After 2,5 s the temperature close to 600°C was obtained during simulation tests. To avoid damaging of the forming insert, the heating time was limited to 0,5 s during the first measurement. The 1.2343 steel is tempered at the temperature of 400 – 550°C, because of that in this purpose the maximum work temperature was set at 300°C. The second criterion was to obtain the temperature close to 150°C after 2 s from the end of the heating process. The assumptions were met for the heating time of 1 s, with maximum temperature of 278°C and 178,5°C after 2 s from the moment of switching off the inductor.

Small temperature differences in the simulation and experimental studies most probably result from the fact, that the theoretical model does not take into account the material parameters related to the previous heat and mechanical treatment. The non-uniformity of the crystallographic structures resulting from dislocations, residual stresses and physico-chemical composition defects hinder the movement of domain walls under the influence of changes in magnetic field. These phenomena cannot be determined in a simulative way, and use of the experimental methods to carry them out require the use of specialist laboratory equipment. However, the experimental studies reflect the relationships obtained by the simulation and a temperature above 270°C was reached after a time of 0.7 s.

5. Experimental studies

On the basis of simulation studies, a design and construction of the injection mold for the production of rail-mounted electrical connector housings was developed and built. The mold allows to manufacture products in conventional technology – with a constant temperature of the mold cavity or with use of the selective induction heating.

The mold cavity was designed to enable heating only of the selected forming area of the flexible clip to the desired temperature. The experimental samples were made on a Demag 35 injection molding machine with a screw diameter of 22 mm. The technological parameters are presented in Table 4. For research purposes, 1000 molding pieces were made (in 4 groups of 250 pieces, Fig. 9). The first group consists of housings manufactured in conventional technology using the constant temperature of the mold equal to 50°C (Fig. 9c). The second group is 250 parts made with use of the selective induction heating to temperature of 130°C in the forming area of the clip (Fig. 9d). In two subsequent groups, the clip forming area was heated to the temperatures of 150 and 170°C respectively (Fig. 9e, 9f). The products obtained, despite the use of different temperatures, did not show significant visual differences (Fig. 9c – 9f).

All products were conditioned at 25°C and 90 % humidity for 72 hours. The next step was to conduct the experimental tests on the assembly and disassembly of parts from the rails in conditions reflecting the actual exploitation of electrical connectors. For this purpose, a 35x7x500 mm rail fixed at both ends and a 6x1.5 mm flathead screwdriver were used. Each part was placed on a rail and disassembled. This cycle was repeated until the clip broke or 10 repetitions were achieved.

During disassembly, each clip was deformed to the same extent, which is ensured by the design of the product and the way the screwdriver is supported at two points in the final stage of

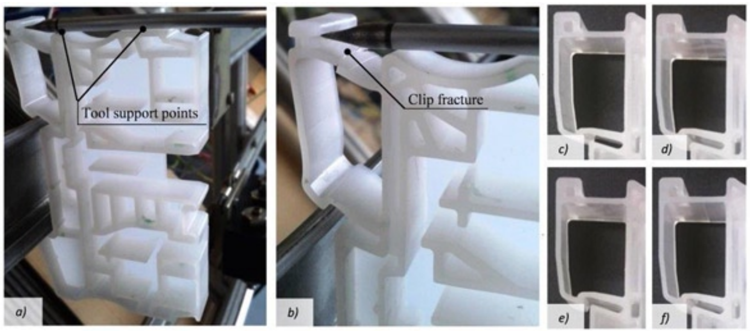

Fig. 9. Samples made for assembly tests: a) disassembly process of the housing from the rail, b) the phenomenon of cracking of the flexible clip during the disassemble of the housing, c) view of the clip made by using the conventional method, d) view of the clip made by using the induction heating, T = 130°C, e) T = 150°C, f) T = 170°C

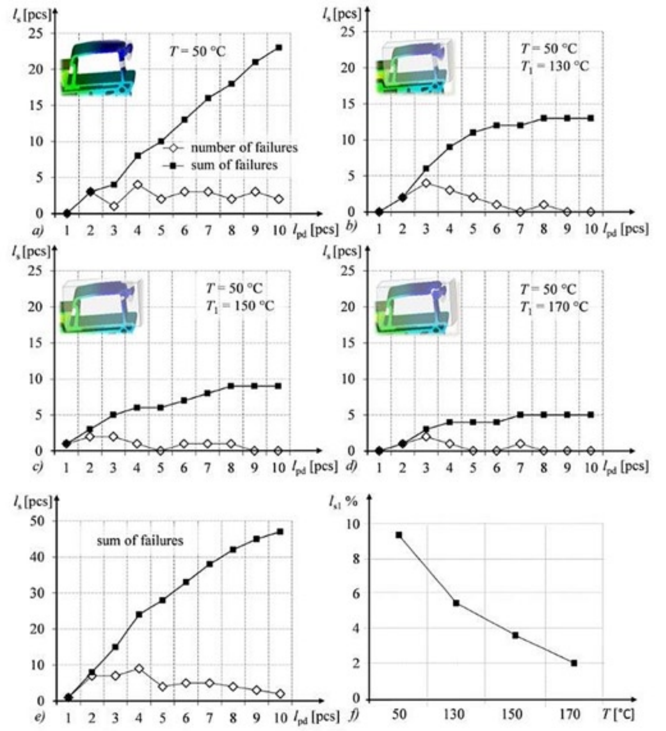

Fig. 10. The results of exploitation research – the amount of damaged housings during the disassembly process in function of number of performed cycles: a) group of parts made by using the conventional technology with a constant mold temperature, b), c), d) parts made by using the selective induction heating in clip forming area with temperature respectively 130, 150 and 170°C, e) a total damage to the clips for all temperatures as a function of the performed disassembly cycles, f) percentage distribution of damage to the clips depending on temperature; l_s - number of damaged pieces, l_{pd} - number of disassembly cycles, l_{s1} - percentage distribution of damaged parts depending on the tested group, T - temperature

movement. The obtained results show that the use of selective induction heating has had the effect of reducing damage to the housings during disassembly. During assembly, when the product was placed on the rail, there was no damage to the clip. This is the effect of less deformation of the clip when assembling the product than when disassembling it. In the case of the first group of products, made in conventional technology (Fig. 10a), there is a noticeable upward trend in damage with each subsequent assembly cycle. While testing of the first group of products, 23 clips were damaged, which is 9.2 %. The use of the induction heating and obtaining the temperature of 130°C in the clip area allowed to decrease the damage to 13 out of 250 tested samples (Fig. 10b). Also, the drop in damage can be observed at 150 and 170°C. It involves improving the conditions under which the two flowing plastic streams join together (Fig. 4). Increasing the temperature stops the material from cooling down and increasing its viscosity. It is confirmed by marginal decrease of the injection pressure for each temperature rise in clip forming area. The drop in damage to 4 per 250 specimens (1.6 %) in the latter case is also due to the moving of the weld lines outside the range of the greatest clip deformation occurring during disassembly. Figure 10e shows a total damage for all tested groups. The highest value of clip defects was recorded in the fourth disassembly attempt. On the basis of the last graph (Fig. 10f), a statement can be risk that tests at higher temperatures would result in an asymptotic distribution of clip damage.

The usage of induction heating has significant changed the distribution of damaged parts in relation to the number of repetitions of disassembly cycles. It is directly related to a reallocation of localization of creating the weld line in the clip.

6. Summary and conclusions

This publication presents the problem of an exploitation of the rail-mounted electrical connectors in terms of their reliability during assembly and disassembly. This topic was considered in response to manufacturing problems of one of the biggest producers of the electrical connectors in Europe.

The structural element of the connector that was analysed was its prototype housing fitted with a flexible clip. To show the genesis of the problem, in the first part of the study results of simulation studies of filling the mold cavity which formed the housing are presented. The attention was focused on the forming area of the clip, which is the key element determining the reliability of the housing. The obtained results showed, that the temperature increase of this area allows to move the place of creating weld lines of the polymer melt streams outside the arm of the clip, which is the most loaded place during the disassembly. After specifying the temperature as a 170°C the place of the two polymer melt streams meeting was moved from the critical product area. Additional, desired effect was to inhibit the increase in viscosity of the polymer melt on the stream front. As expected, this should contribute to improving the quality of the plastic weld lines and reducing damage during product disassembly.

Before the mold was made, the design of the mold based on simulation and experimental studies of the induction heating was developed. On the basis of series of measurements, the characteristics of the heating process were obtained and the results of experimental studies confirmed the results obtained by simulation. After 0.7 s the temperature on the clip forming surface was 272°C. After 2 s from the beginning of the heating process, the temperature was 175°C after disconnecting the inductor in 0.7 s. Using the prototype of the injection mold, 1000 molded parts in 4 groups with various clip forming surface temperature were made. Experimental studies and obtained results show, that the selective induction heating process resulted in a decrease in damaging of the housings during disassembly. The dynamics of the induction heating shows, that higher mold temperatures can bring about a decrease in molded parts failure rate with a slight increase in the cycle time. A higher mold temperature will not influence the cooling time of the mold because only the surface layers of the mold cavities are heated, which directly results from the skin effect of the induction heating process [18].

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2. INNOTECH-K2/IN2/60/182932/NCBR/13, 2013 – 2015

3. 0614/SBAD/1529, 2020

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