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Thermography in plastics welding processes assessment

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Materials

ABSTRACT

Purpose: The purpose of this paper was to describe the possibilities of thermovision technique to evaluate temperature distribution on heating tools surfaces of plastics welding machines and temperature distribution on heated surfaces of welded parts.

Design/methodology/approach: Heating tools of butt fusion, socket fusion and infrared fusion machines were tested using thewrmovision camera. Interrelation was shown between temperature distribution on heating tools and welded parts surfaces.

Findings: The quality of ready welds is essentially dependent on uniform heating of welded parts. Achieved results shown that thermography may be applied as a tool to quick temperature distribution evaluation on heating elements and welded parts.

Research limitations/implications: In order to evaluate temperature distribution with thermovision camera complete surface of heating element must be "visible". The maximum angle between camera axis and line perpendicular do scanned surface is 30°.

Practical implications: Achieved results showed that thermography may be applied in industrial practice to test heating elements of plastics welding machines. Also welded parts may be scanned with this methodology.

Originality/value: The originality of the research comprises in evaluation of relation between temperature distribution on heating elements and temperature distribution on welded parts heated with given tools.

Keywords: Engineering polymers; Non-destructive testing; Thermography; Welding

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1. Introduction

In many industry fields plastic parts are applied more and more frequently. Very demanding criteria must now be fulfilled by parts made of polymeric materials and polymeric composites. For this reason new high performance polymeric materials are developed. Because of space limitations, especially in car industry, electronic and household equipment industries, very complicated parts are designed and produced. In many cases it is not possible to manufacture such parts as single elements. Usually they are assembled from two or more semi products. When leak proof and tough joints are needed common method used to join parts made of thermoplastic polymers is welding technology.

In many of welding procedures heating elements are applied. Their basic task is to heat welded surfaces to temperature above polymer melting point, dependant on type of joined polymer.

To achieve permanent and strong joints it is necessary to attain even temperature distribution over all welded surfaces [1, 2]. Many of welds defects such as discontinuities, leaks, brittleness, inner and outer bubbles, polymer degradation, too small strength etc. are caused by improper temperature level and uneven temperature distribution on welded surfaces. These temperature characteristics are directly dependent on temperature distribution on heating elements surfaces. Commonly used method of heating elements temperature evaluation is application of contact thermocouples. These apparatuses are very imprecision because contact between thermocouple tip and scanned surface is usually only punctual, air gap is formed on the rest of thermocouple probe surface and heat transfer is imperfect. Readings are in high degree dependent on mutual arrangement of heating element's surface and contact thermometer probe. Another disadvantage of this and many other temperature measuring techniques is impossibility to scanned temperature distribution over all heating surface in short time. Usually only few points are scanned. The method allowing scanning temperature distribution over all heating surface in very short time is thermography [3, 4, 5]. Thermography properly applied allows also to achieve much more precise temperature readings and first of all shows temperature differences. In many cases important is that thermography is non-contact technique and allow temperature measurement from distant.

Thermography is a technique allowing to see object properties that are not visibly using human eye. The basic idea of thermography is to apply infrared frequency range of all electromagnetic radiation (Fig. 1) emitted by object under research to obtain information concerning its selected physical properties, mainly surface temperature, or processes taking place within this object.

The first known from literature application of thermography methods took place at the beginning of twentieth century. In 1914 Parker patented the first infrared detector. In 1934 Barker proposed complete infrared system to detect forest's fires. In the next years many scientific and industrial applications of thermography were described.

Thermography evaluates the distribution of infrared radiation emitted by searched body surface. Scientific and industrial methods apply basic knowledge concerning relations between infrared radiation and temperature distribution on radiating body surface. Emissivity and other thermodynamic properties of body surface, important in radiation phenomena, are also taken into account. Depending on experimental conditions, temperature distribution can also be an information source about other object properties, especially these that are directly dependant on temperature.

In physical theory of radiation emission the key concept is the *black body* model. A black body is a purely theoretical object that absorbs 100% of the radiation that hits its surface. Therefore it reflects no radiation and appears to be perfectly black. The basic physical laws describing radiation emission are [6, 7]:

- The Kirchoff law stating that the ratio of emission to absorption capability of given surface is constant independently on temperature;
- The Planck law describing radiation distribution of black body;
- The Wiena law describing the relation between wavelength of maximum emitance and surface temperature;
- The Stefan-Boltzman law describing the relation between total emitance and surface temperature.

These laws constitute experimental basis for evaluation of surface temperature distribution using thermographic images.

Knowing the body surface temperature distribution or temperature distribution changes one can formulate the inverse problem: What are the physical reasons of achieved surface temperature state or given process of surface temperature changes? Especially interesting is what material properties and structural characteristic of experimentally tested material can influence temperature distribution of surface scanned with thermovision camera.

There are many different thermographic methods (techniques) classifications, depending on class of researched objects, on factors chosen as essential for thermal processes in given experimental programme, on way of thermal activation of investigated object and on many other criteria.

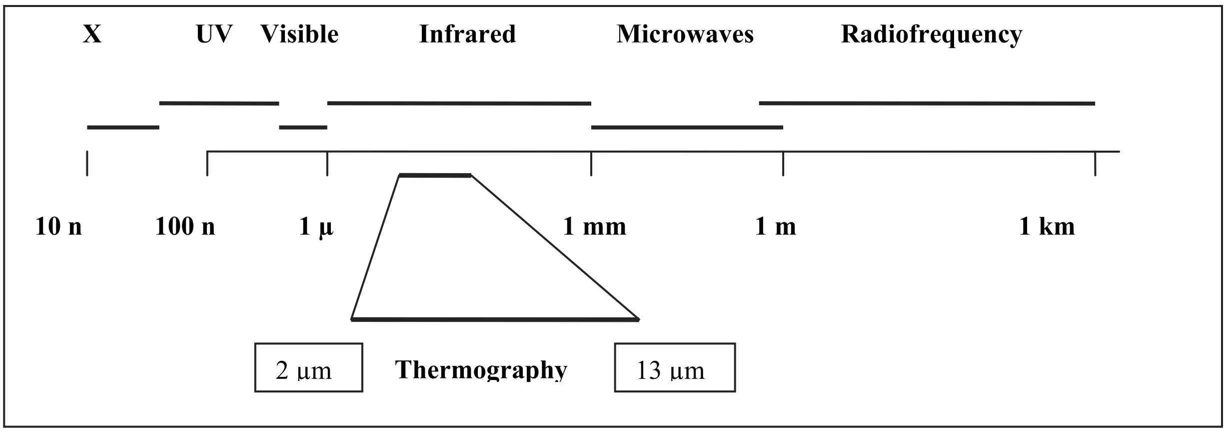

Fig. 1. Range of wave length of all electromagnetic radiation scale applied in thermographic techiques

The most frequently cited classification is on the way of searched body thermal activation. Taking into account this criterion thermography methods are divided into active and passive. Passive thermography is limited to recording of temperature states and processes on researched surfaces without any additional thermal activation and without any researcher interference. On the other hand in active thermography researcher initializes thermal processes and records surface temperature distribution and its changes.

There are known many different scientific and industrial fields of application of passive thermography. These methods are effectively applied in research programmes and in ordinary practice, not only industrial, for such demanding spheres as cosmonautics, aviation, marine, fire service, military service, police, medicine, life rescue, environment conservation, electronics, machine building, steel and iron industry and many others [8-18]. Because of possible different ways of thermal activation of searched objects, active thermography has even more interesting possibilities. The object activation processes can be static or dynamic in their nature. The most popular activation methods are: thermal pulse activation (pulsed thermography), modulated heating (lock-in termography with modulated heating), pulse-phase heating (pulsed-phase termography). The most frequently in practice used is radiation activation of observed surface. Information concerning surface or thin surface layer of tested material is subsequently gathered and analysed.

Dynamic thermography is yet another class of methods in which energy (mainly in form of mechanical vibrations) is transferred to tested object and response in the form of heat emission is observed (vibro-thermography). This technique is usually realized by forcing harmonic mechanical oscillations of researched object and simultaneous surface temperature measurement with thermovision camera. The forced mechanical vibrations have in this case only a character of diagnostic tool. Temperature measurements are usually performed using very sensitive (with resolution up to 20 mK) and quick (up to 25 000 images per second) thermovision cameras. In recent year cheap and simple thermovision cameras are produced but they are not used in science and in demanding industrial applications. Apart from described methods new thermographic techniques, sometimes specific for individual problem, are elaborated and applied.

In presented research an attempt was undertaken to use thermovision camera to evaluate temperature distribution on surfaces of welder's heating elements applied in three different plastics welding techniques and to evaluate temperature distribution on surfaces of welded parts. The interrelation between these two classes of temperature distributions and interrelations between temperature distributions and quality of welds produced with scanned heating elements were analysed. Performed analysis allowed to draw conclusions concerning possibilities of applying thermovision in qualification of heating elements.

2. Experimental

2.1. Materials and methodology

In experimental part three welding technologies were applied: butt fusion, socket fusion and welding with infrared emitter. Temperature distributions on heating elements surfaces were scanned and then on surfaces of welded parts directly after heating. Finally quality of ready welds was evaluated.

Using butt fusion technique high density polyethylene pipes sections were welded. Polypropylene parts were welded with socket fusion and infrared fusion technologies.

In butt fusion and socket fusion methods welded parts were heated through direct contact with heating elements. In infrared method welded parts were heated due to emission of infrared radiation from emitter placed 3mm apart from the welded surfaces.

Thermographic research was performed using thermovision system ThermaCAM SC640 (Flir Systems A.B.).

Photographs and video films together with the rest of information registered by thermovision camera were transferred to computer and analysed using ThermaCAM Researcher software. This computer programme allows to perform very sophisticated procedures of temperature and temperature distribution analysis. Thermovision camera SC640 was equipped with micro-bolometric matrix FPA (Focal Plane Array) working with resolution 640 times 480 pixels in radiation spectrum 7.5-13 um. The camera works in three temperature ranges: from minus 40 °C to plus 120 °C, from 0 °C to 500 °C and from 300 °C to 2000 °C. In every of these ranges it is possible to electronically narrow searched temperature span to 1 °C, what facilitate analysis of achieved results and increase measurement precision. In all measurements, apart from infrared emitter scanning, 0 °C to 500 °C temperature range was applied. It allowed to registered full range of temperatures observed on scanned surfaces. 15 images were taken every second. This camera speed allowed to register temperature distribution on welded parts in time shorter than 0.5 second after the end of heating process. It was not necessary to use higher speeds because searched processes were not dynamic. In the case of infrared emitter temperature scanning a broader temperature range from 300 °C to 2000 °C was applied. For this range measuring precision was ± 2 °C. All tests were performed in laboratory conditions to guarantee constant environmental conditions. Air temperature was 21 °C, there was no significant air flow, air humidity was about 50%. In this way there were no factors negatively influencing infrared radiation and measuring precision. In industrial and field tests it is necessary to assure similar conditions. If conditions are not stable it can influence temperature readings but measured temperature differences will not be changed essentially. It is important because in welding technologies more essential are temperature differences.

2.2. Results

Butt fusion welding

High density polyethylene (PE-HD) pipe's sections 200 mm long with diameter 63 mm and wall thickness 5.8 mm were welded. PE-HD with MRS 10.0 MPa (PE 100) was used. According to generally accepted and commonly applied in plastics welding practice DVS (Deutsche Verein für Schweisstechnik) recommendations [19], the following main welding parameters were accepted: heating plate temperature setting – 210 ºC; initial bead thickness – 0.5 mm, heating time – 58 sek; cooling time – 8 min; welding pressure – 0.15 N/mm^2, heating pressure – 0.01 N/mm^2. Heating plate, after reaching set temperature, was thermally stabilized in 15 minutes time before welding. Next the temperature of plate surface was scanned. The thermographic image presenting temperature distribution on one side is shown in Fig. 2. Similar temperature distribution was registered on the other side of the plate. Very even temperatures profile was observed on all surface apart from edges of heating plate, where temperatures were lower about 3-5 ºC. It is known from industrial practice and because of this it is recommended to weld parts with maximum dimensions of cross section smaller than dimensions of heating plate. Usually about 2 cm margin is proposed. Even with these differences temperature distribution fulfil DVS recommendations, which allow temperature differences not greater than 10 ºC. The recommended mean temperature in heating plate welding region ought to be 210 ºC ± 10 ºC. In our case the mean temperature in this region was 208.9 ºC and differences were not greater than 2 ºC.

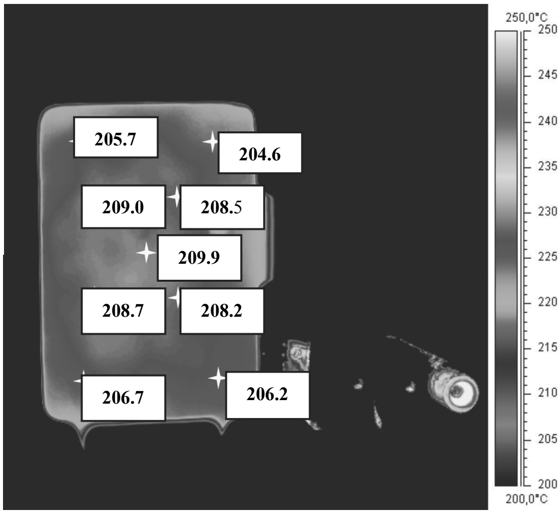

Fig. 2. Temperature distribution on surface of butt fusion heating plate

With plate prepared in this manner pipe's fronts were heated under heating pressure. Temperature of heated surfaces were scanned 5 seconds after the end of heating process. It was the time needed to remove heating device from among pipes and fix pipes axially with thermovision camera. Thermographic image presenting temperature distribution on one of scanned surfaces is shown in Fig. 3. The second image was very similar to the presented one. Achieved temperature distribution was very even, temperature differences in middle region of pipe wall were not greater than 6 ºC. It is obvious that due to rapid heat outflow from wall edges temperatures in these regions were lower. In the next step full welding procedure was performed without temperature scanning to produce proper weld. The photograph of a fragment of ready weld is presented in Fig. 4. The weld was evaluated according to DVS recommendations [20, 21]. The weld was accepted as fulfilling DVS requirements.

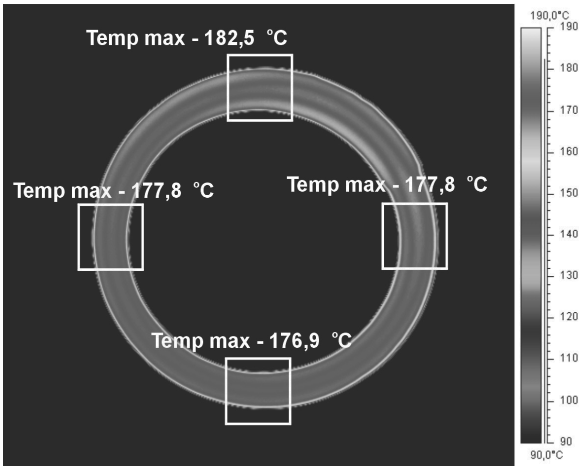

Fig. 3. Temperature distribution on heated surface of welded pipe

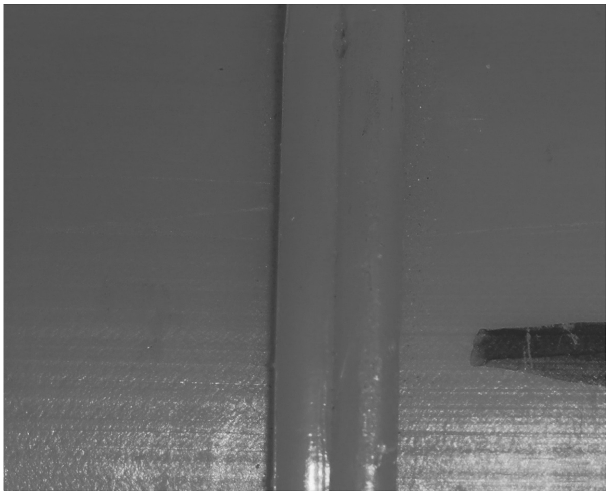

Fig. 4. The shape of beads of butt fusion welded pipes

Socket welding

Polypropylene muff with nominal diameter 20 mm was welded with polypropylene pipe with the same nominal diameter and with 3.4 mm wall thickness. Both welded parts were produced from random polypropylene copolymer (PP-R). According to DVS recommendations [22] the temperature was set to 260 ºC. Also in this case the temperature was stabilised in 15 minutes time after reaching set value. After that temperature distribution of heating elements was scanned with thermovision camera. Achieved temperature distribution is presented in Fig. 5.

As can be seen temperature of heating elements was lower then temperature set in the temperature control of aluminium plate to which heating elements were assembled. Temperature differences on heating elements were not higher than 12.5 ºC. Inspection of heating elements showed that cooler places were observed where anti-adhesion coating was damaged.

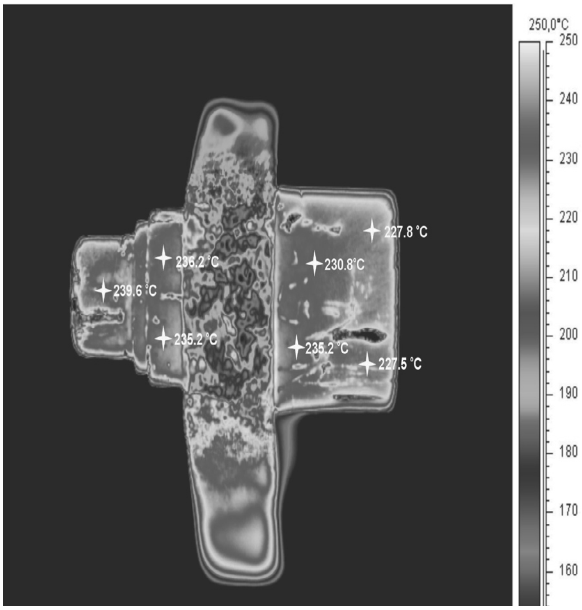

Fig. 5. Temperature distribution on surface of socket welding heating elements

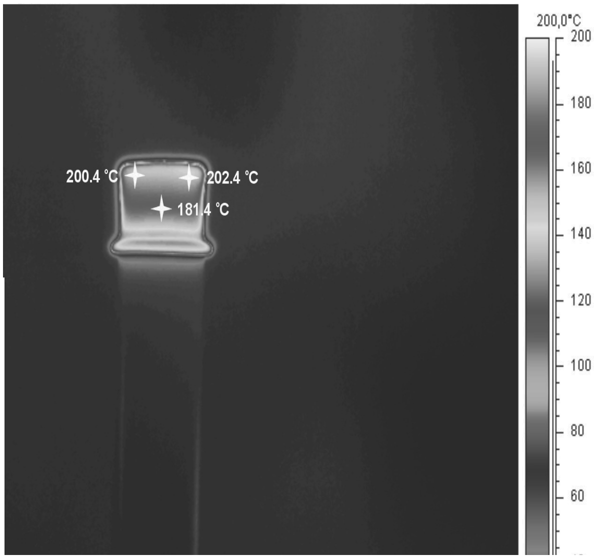

Fig. 6. Temperature distribution on surface of pipe heated to socket welding

After temperature stabilisation outer surface of pipe and inner surface of coupling were heated in 5 seconds time. Heating time was counted not before full insertion of welded surfaces into heating elements. According to DVS recommendations heating depth for elements with 20 mm nominal diameter was 14 mm. The temperature distribution on surface of heated end of pipe, 5 seconds after the end of heating, is shown in Fig. 6.

Achieved temperature distribution was very even over the circumference of the pipe. Temperature differences on pipe circumference were not greater than 2 ºC. Significant temperature differences were observed in axial direction. It is the result of heating time differences what is inseparable bounded with socket fusion welding procedure. In insertion stage of welding the end of the pipe and coupling were heated first.

It was not possible to scan temperature of inner surface of heated coupling. Only small outer part of fitting was visible.

In the following step new welding process was performed without temperature scanning. It allowed to achieved ready weld without process interruption. The photograph of socket weld is presented in Fig. 7. The weld was evaluated according to DVS requirements [20, 21] and was qualified as proper.

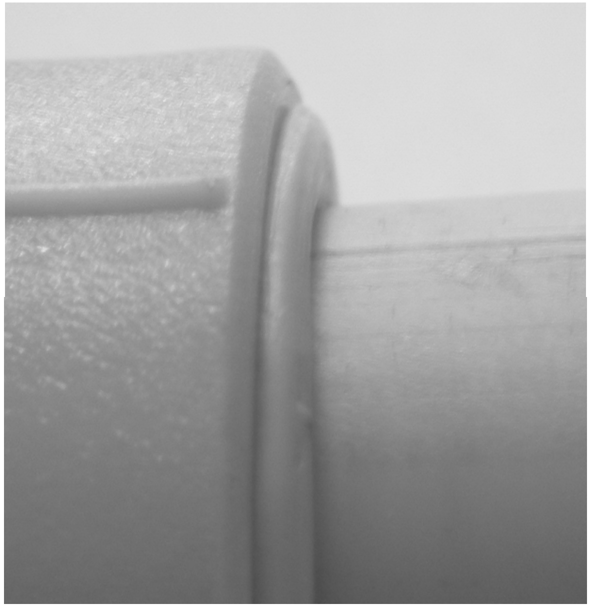

Fig. 7. View of socket welded polypropylene fitting and polypropylene pipe

Infrared welding

Two parts of polypropylene container were welded. Because of pressure application tightness and high weld's strength was demanded. Main process parameters were chosen according to machine producer instructions: heating time – 16 seconds; distance between infrared emitter and welded surface – 3 mm; joining time 10 second. As in previous welding methods, temperature of emitter was stabilised before welding. After temperature stabilisation the surface of emitter was scanned with thermovision camera. A part of thermographic image of emmiter is presented in Fig. 8. Because of dimensions and readability it was not possible to show all the photograph.

Very significant temperature differences, reaching 185 ºC, were observed in showed part. Even bigger temperature differences were observed for full area of the emitter. Similar but a little smaller temperature differences were observed for the second emitter.

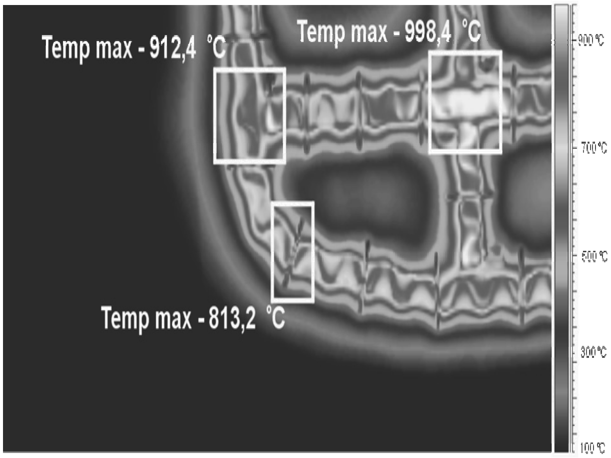

Fig. 8. Temperature distribution on surface of infrared radiator

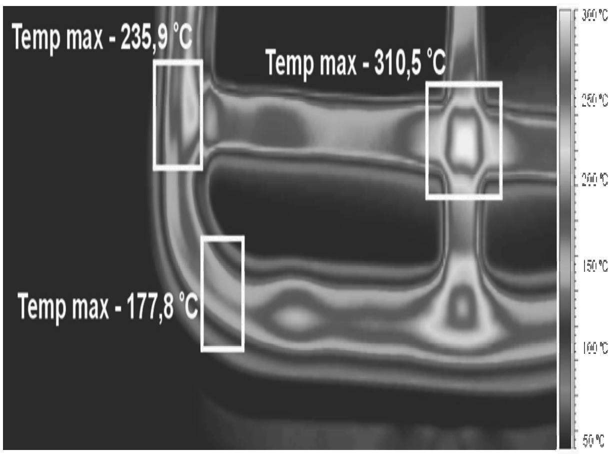

Fig. 9. Temperature distribution on welded surface heated with infrared radiator shown in Fig. 8

Using these emitters welding process was performed. At the beginning parts of container were heated and scanned. Thermographic image of one of heated part's area corresponding heater area in Fig. 8 is shown in Fig. 9. The image was taken 5 seconds after the end of heating. Temperature differences up to 130 ºC were noticed in the middle regions of heated walls.

After heating period regions of degraded polypropylene and regions with molten polypropylene flowing down container walls were observed. In few places polypropylene caught the fire and flame appeared. It was the result of heating polypropylene to temperature above 310 ºC. Next welding process was repeated with new parts and without temperature scanning. Finally weld with visible polymer degradation and weld discontinuities was made. A section of weld with visible polymer degradation and weld discontinuity is presented in Fig. 10. Similar result was achieved in other places where radiator temperature was very high.

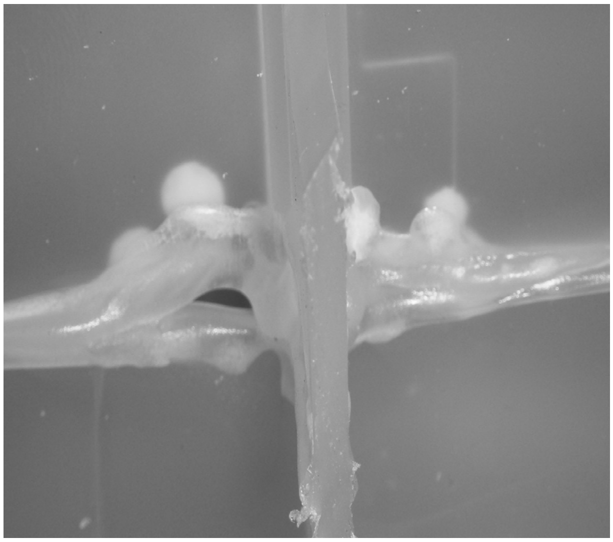

Fig. 10. View of weld in region corresponding to the highest infrared radiator temperature

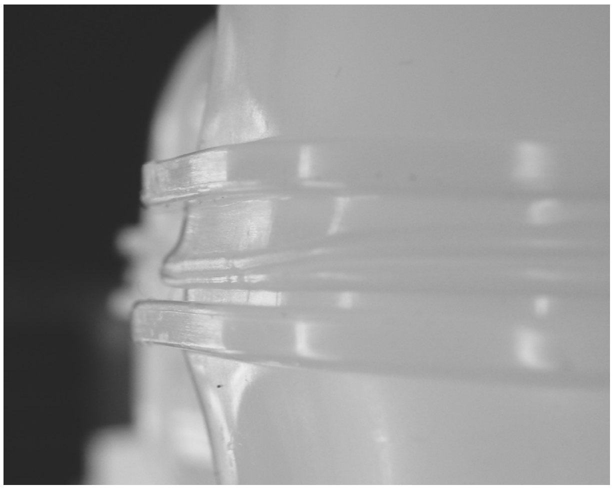

Fig. 11. View of weld's beads where the polymer was overheated

In many places, especially in regions of high temperature and polymer overheating, significant weld's beads deformations were observed. Fig. 11 presents an example of such deformations.

On the other hand there were places where polypropylene was not melted in needed extend and parts were not joined at all or only very weakly. In other places proper welding conditions were achieved and resultant weld seemed to be proper (Fig. 12). There were no possibilities to prove it with pressure test.

General opinion about weld produced with scanned infrared emitter was negative.

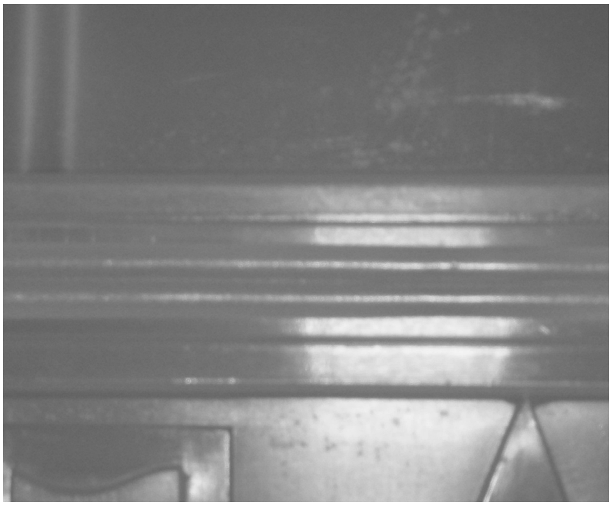

Fig. 12. Correct shape of weld's beads

3. Results analysis

Performed welding procedures and evaluation of ready welds proved that in tested welding techniques very important is not only mean temperature of heating elements but even more important are temperature differences on these surfaces. Big temperature differences on surfaces of heating elements result in unallowable differences of heated surfaces of welded parts. Places with maximum temperature on heating element correspond to such places on heated surfaces. Achieved smooth temperature distributions on butt fusion and socket fusion heating elements allow to properly heat welded parts and finally to form correct ready welds. Small temperature differences, not greater than 10 ºC, observed on heating and heated surfaces did not influence substantially the quality of made welds. In infrared welding method mean temperature on emitter surface is less important because it is possible to control degree of polymer plasticization by changing distance between emitter and heated surface and by regulation of heating time. Unfortunately it is not possible to compensate big temperature differences by changing these and other parameters. Welds produced with emitter with very big temperature differences (about 200 ºC) only partly were proper, in the rest of welding line polymer was overheated and degraded or even caught fire or was not heated sufficiently to allow diffusion. Places where parts were not joined at all were also observed. Realized additionally numerous trials to change welding parameters in order to improve infrared welds were not effective.

Performed research showed that thermovision technique may be very useful and effective in evaluation of heating elements temperature distribution. It is recommended to apply thermographic methods already on welding machines heating elements manufacture stages. Proper application of thermography in manufacture process can eliminate heating elements defects and in consequence faults of welds produced with these heating elements. It is also possible to apply thermography to test heating elements in industrial welding process and in service operations. In many cases welds imperfections are not so visible as in presented example but in exploitation lead to joints damages and leakiness. Periodic tests of temperature distribution on heating elements surface will allow to avoid weak and incorrect welds.

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