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Determining threaded machine element fabrication technology by pulsed thermography

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Abstract

Non-destructive testing methods, including pulsed infrared thermography, have become quite common in materials evaluation. The method is suitable for checking the quality of the surface treatment of the material structure up to a certain depth and is increasingly applied in the areas of system maintenance and condition assessment of machine elements. Thus, when installing spare parts (screws) for military purposes, for example in airplanes, helicopters, tanks, or armored vehicles, as well as for commercial purposes, for example, excavators or other machines, it is necessary to inspect these parts additionally to be sure of their quality. The paper discusses the applicability of pulse infrared thermography in the quality control of screws, through the determination of the technology of making standard threaded joints (by rolling or cutting), as well as the technology of the final surface treatment of screws with a cadmium layer.

Keywords: *Pulsed IR thermography; Screw thread; Nondestructive Testing and Evaluation.*

1. Introduction

Thermal imaging is becoming increasingly popular due to the continually improving quality and affordability of thermal imaging equipment used as a contactless means of estimating temperatures and recording surface temperature distributions [1, 2]. Today, it has an extensive range of applications and there is virtually no area in industry or science where it is not used: to locate warm objects and living beings or parts thereof [3-5]; to detect energy losses [6]; to control or monitor various technologies [7, 8]; to detect gases [9]; and even to investigate cultural heritage [10].

Active thermal imaging methods have recently been widely applied in nondestructive testing of materials [11, 12], as corroborated by numerous published works on the subject: to assess the quality of materials [3]; to detect surface and subsurface defects [13-16]; to monitor the status of technical systems [8]; to check the quality of machine elements [17]; and the like.

Quality control of machine elements includes inspection of components of airplanes, helicopters, tanks, armored vehicles (for military purposes), excavators, conveyor belts, or other machines (for commercial purposes) [18, 19]. Issues associated with the maintenance of such machinery, calendar-wise, are their long-life cycle and, above all, problems related to procuring original spare parts. This situation is even more complex if the manufacturer is out of business. Maintenance managers, under pressure from corporate management that imposes strict deadlines for the return to service of aircraft, armored vehicles, rotary excavators in mines, or other machinery, often look for solutions by approving the installation of commercially available but inadequately documented spare parts. As such, the danger of installing spare parts in an operating aircraft, armored vehicle, excavator, or other machine, that have not been fabricated following adequate, manufacturer-recommended procedures, should be avoided.

Modern equipment for pulsed thermal imaging, including a thermal camera, flashlight as a pulsed heat source for controlled heating of the test object, and suitable software, along with trained operators and engineers, supports rapid and low-cost evaluation of the surface and subsurface status of the tested machine element. Therefore, the paper discusses the applicability of pulse infrared thermography in the quality control of screws, through the determination of the technology of making standard threaded joints (by rolling or cutting), as well as the technology of the final surface treatment of screws with a cadmium layer.

Also, the paper gives an example of the application of this method of determining the manufacturing technology on a used car wheel screw (purchased as a replacement part), which fell off the vehicle under normal operating conditions. The examination determined the technology of making that screw.

The pulse infrared thermography method could be employed when it is necessary to quickly replace a defective screw with a new one on a piece of complex military equipment. Namely, in challenging operational conditions of military equipment, it is observed that one of their screws suddenly fails, even though all rigorous climomechanical tests have been passed by the military equipment. Subsequently, it needs to be promptly replaced with a new one, for which the manufacturing method is not known at this time. In this case, this method could potentially facilitate the rapid determination of the screw manufacturing technology, e.g. whether it has been processed by cut or cold-rolled.

2. Methods

The method used in the present research is based on pulsed thermography because an external heat source (flashlight) was used to raise the temperature of the test surface.

2.1. Fundamentals of thermography

Thermal imaging has numerous advantages: contactless, nondestructive, remote, real-time, and two-dimensional measurements, and in the case of the passive method no effect on the heat balance. However, the method also has certain constraints: dependence on the surface properties of the test object (emissions, reflections, transmissivity); only surface temperature is measured; dependence on the distance of the object from the test equipment; and if testing is conducted outdoors, dependence on current weather conditions. For these very reasons, active thermography is currently one of the most widespread methods for nondestructive assessment of the homogeneity of materials (commonly referred to as Nondestructive Testing and Evaluation – NDT&E). In addition to the above method, pulsed transient thermography and lock-in thermography are also frequently used methods [20].

2.2. Threaded fasteners and fabrication technologies

Two or more mechanical parts, connected using threads, constitute a threaded joint. Threaded joints are detachable, such that the connected parts can be separated and re-joined without causing damage. Threaded joints allow accurate positioning of coupled machine elements and their mutual adjustment.

The nature of solid threaded joints is such that they enable load transmission from one machine element to another, load transmission to another machine, or pressure transmission to contact surfaces of various machine parts over a long period of time.

The threaded portion on the outer surface of a cylindrical mechanical component is called the outer (male) thread and that on the inner surface of a cylindrical opening is the inner (female) thread. The threaded portion of a fastener is comprised of a series of spirals of the same shape. The geometry of a threaded (outer) portion is shown in Fig. 1. One turn corresponds to one full revolution of any point on the surface of the thread around its axis. The helical surfaces that restrict the thread are called thread flanks, whereas the cylindrical surfaces that limit the height of the thread are called thread tops and the groove is the depth of the thread. Threads are either “cut” on a lathe or “cold rolled” on special screw threading machines. In both cases, the intermediate product is a rod of a certain (standard) diameter. In the former case, the threads were fabricated by cutting the base material on a lathe with a shaped cutting tool. In the latter case, cold rolling of threads is based on plastic deformation of the base material in a special. The structure of the intermediate product fabricated in either of the two ways is characterized by longitudinally oriented strands along the depth of the material (Fig. 2) [21].

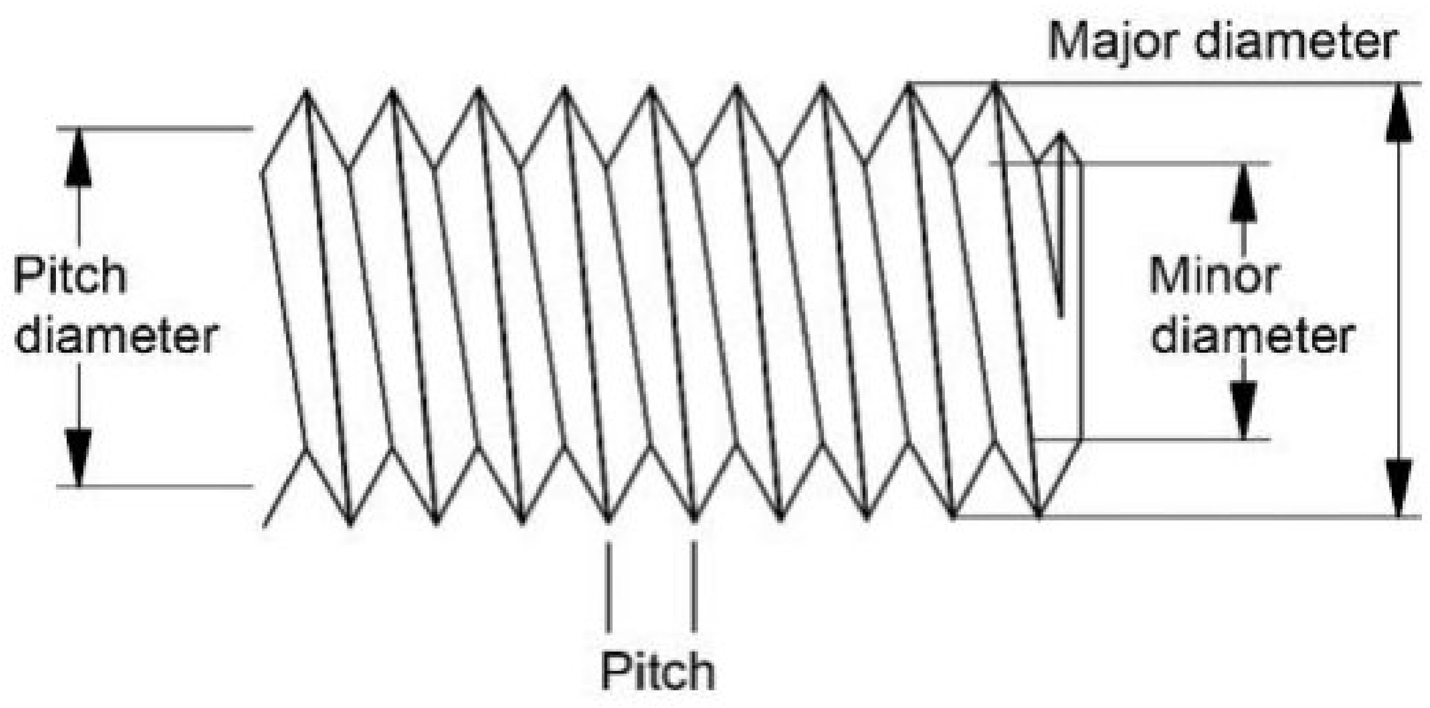

Fig. 1. Geometry of a thread.

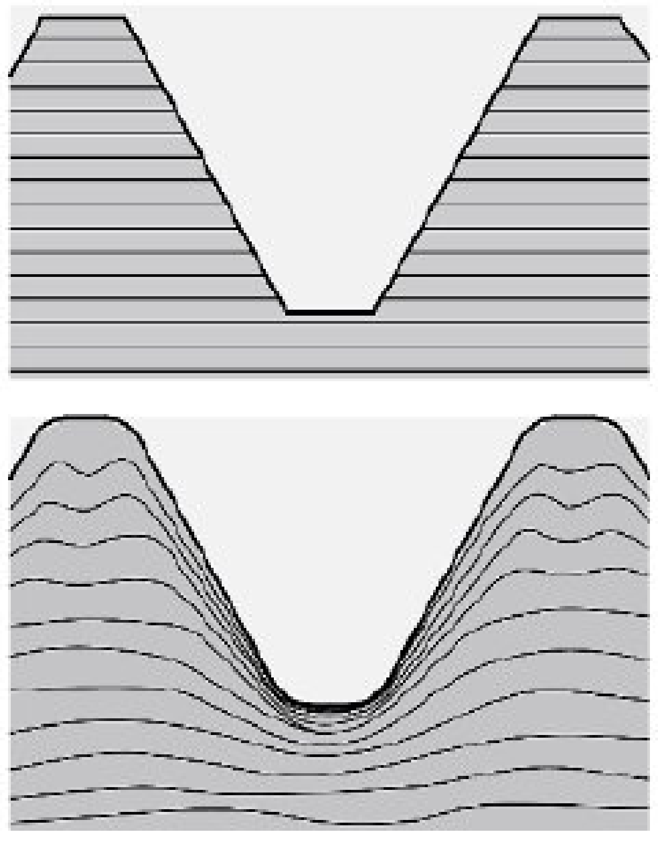

Fig. 2. Strands immediately below the surface of the thread: top–cut thread; bottom–rolled thread.

Compared to cutting, cold rolling offers several advantages: higher productivity in the case of standard threads; longitudinal strands in the base material are not severed as in the case of cutting (Fig. 2); better physical and mechanical properties such as strength, hardness, and resistance to wear and tear; and lower surface roughness (i.e. better quality), as corroborated by electron microscopy.

3. Experimental

The test procedure was as follows: the optical system of the thermal camera was placed near the surface of the test object and then the object's surface was heated in a controlled manner (Fig. 3). The cooling process was sequentially captured by the thermal camera. Suitable software was used to store and process the thermal images.

Four steel threaded fastenings (Fig. 3) were selected for the experiment. The type of steel was 18 × 2H4BA. The geometry of the threaded fastenings was M33 × 2 as defined by the SRPS M.B1.003:1988 standard, which is equivalent to the German DIN 910 standard. The test samples were labeled 1 to 4. Test sample 1 was cut on a lathe and no surface finish was applied. Test sample 2 was cold rolled, with no surface finish. Test sample 3 was cut and the surface with cadmium plated. Test sample 4 was cold rolled and also with cadmium plated. The cadmium-plated samples are light yellow.

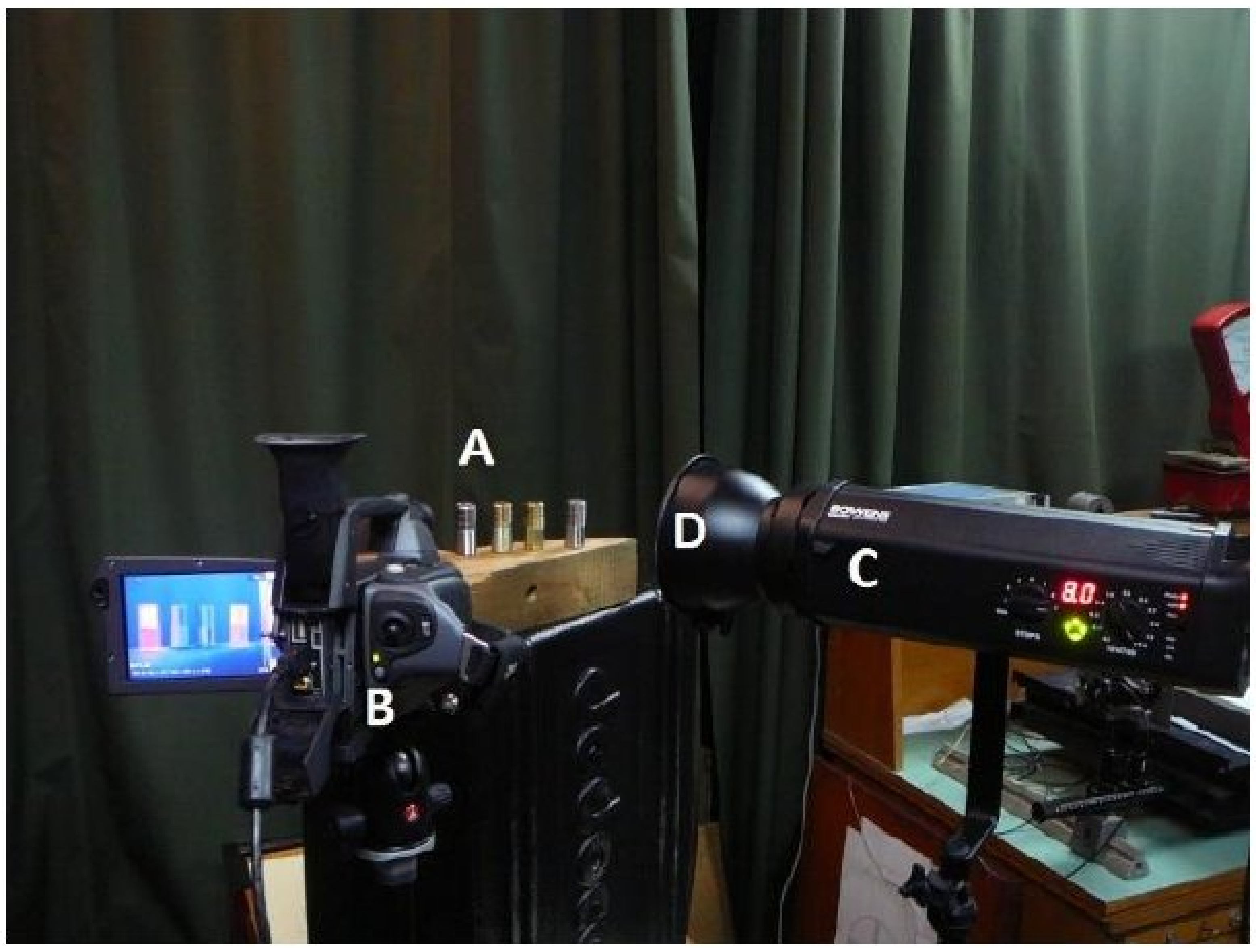

Fig. 3. Experimental setup of the equipment used for testing by pulsed IR thermography: A -Test samples; B - Thermal camera; C - Flashlight; D - Cone on the flashlight.

For better thermal insulation during the test, the samples were placed on a wooden support (Fig. 3). The heat source was a BOWENS BW-3955 flash lamp made by the British company Gemini R & Pro, whose maximum power was 1500 W. The stand of the flash lamp enabled vertical movement. The distance between the flash lamp and the vertical plane in which the threaded fastenings were placed was 30 cm. To better focus the light flux on the test specimens, a spotlight with a cone angle of 65° and an aperture diameter of 20 cm was mounted on the flashlight.

The flash lamp and spotlight were mounted on their stand at an angle of 45° relative to the vertical plane of the test sample. The height of the lamp was the same as that of the wooden support on which the threaded fastenings were placed.

This ensured even heating along both the surface and depth of the threaded fastenings, by controlled light flashes of short duration. A thermal camera FLIR SC620, designed for a 7.5-13 μm wave range, was used to track the surface cooling process of the test samples. Optimal sharpness of the thermal images was achieved by means of a manual zoom.

An uncooled thermal imaging camera FLIR SC620 with standard optics (Field of View - FOV / minimum focus distance of 24° x 18° / 0.3 m) is utilized in the work. The IC image frequency for the FLIR SC620 camera has a value from 30 Hz to 120 Hz, so the image acquisition time has a value of 33.33 ms to 8.33 ms, respectively. Emissivity is measured using materials of reference emissivity by the thermographic method. Consequently, the measured emissivity had lower values for untreated cadmium samples compared to values for treated ones.

4. Results

Prior to thermal imaging, the surfaces of test samples 1 and 3 were captured by a Scanning electron microscope (SEM) type JEOL JSM-6610LV equipped with energy dispersive spectrometer X-max (Oxford Instruments) [22, 23]. The topographies of the cut and cold-rolled threads are shown in Fig. 4 and Fig. 5, respectively.

The surface roughness of the cut thread (gray color) shown in Fig. 4 is from 0.6 µm to 24 µm and that of the cold-rolled thread (gray color) is from 0.2 µm to 1.6 µm (Fig. 5). In other words, the surface layer of the cold-rolled thread is less rough.

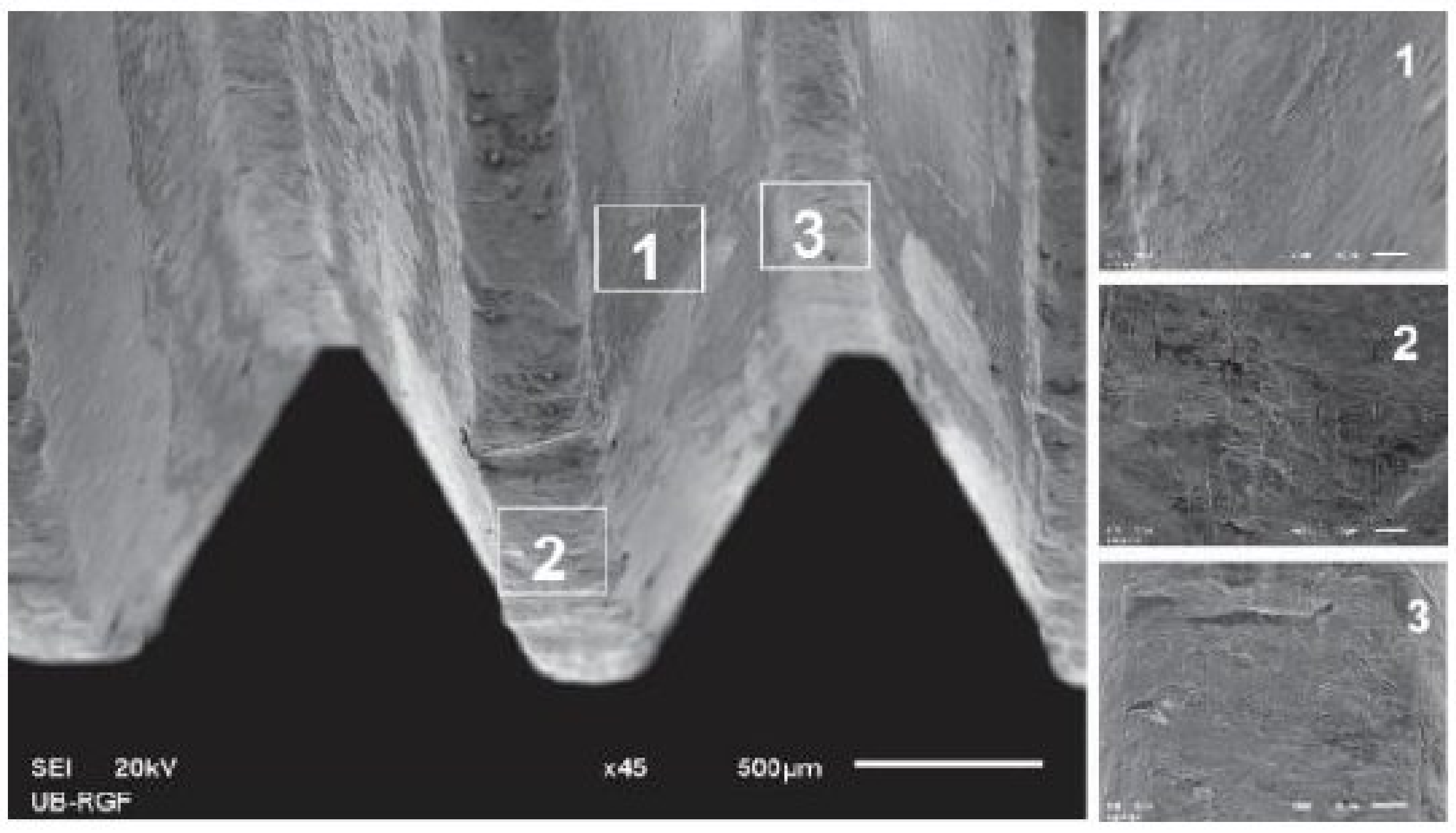

Fig. 4. Electron microscope images: (right) – cut thread; (left) 1 – side, 2 – top, 3 – bottom**.**

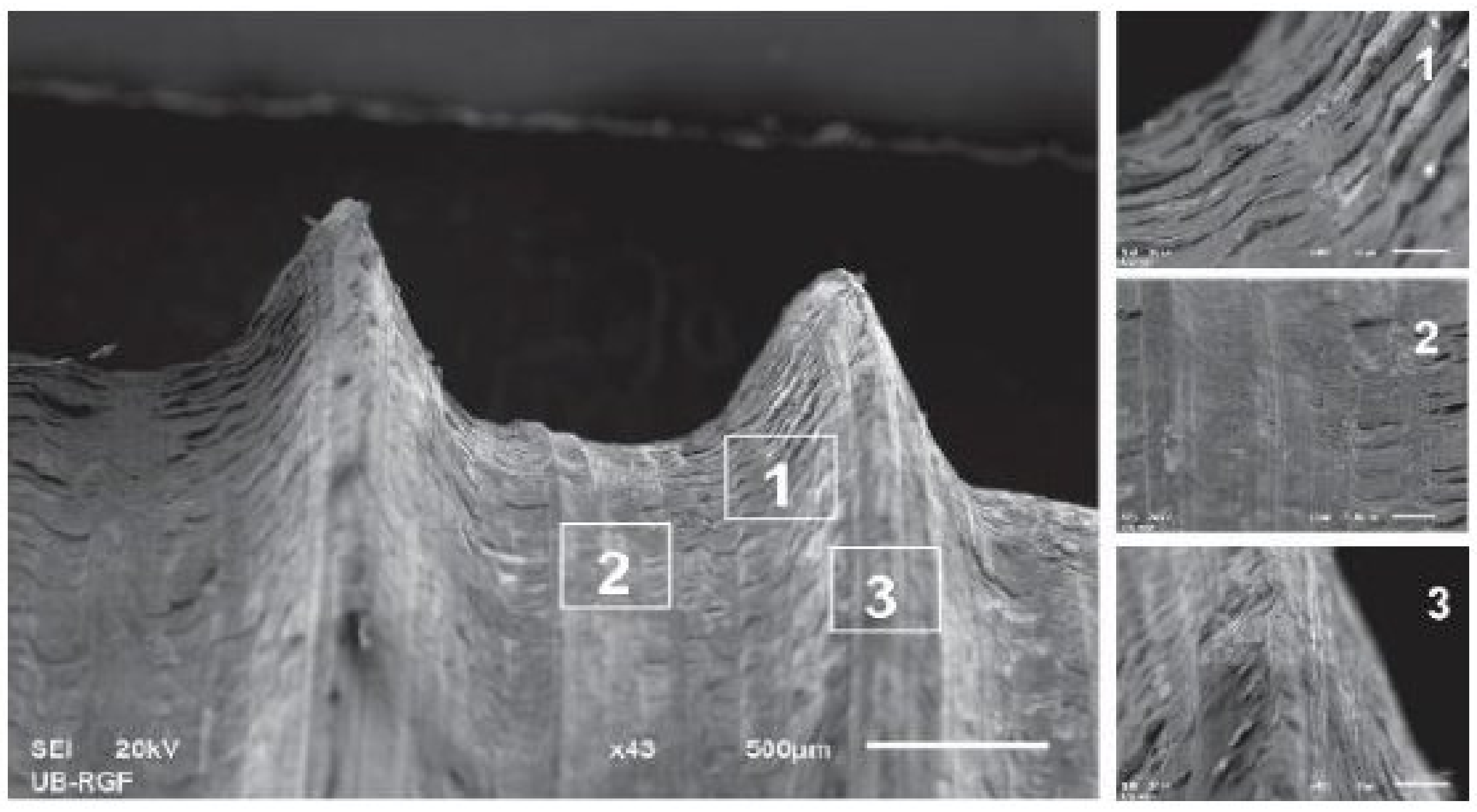

Fig. 5. Electron microscope images: (right) – cold rolled thread; (left) 1 – side, 2 – bottom, 3 – top.

The idea behind using pulsed thermography to determine the way in which threaded fastenings were fabricated is based on comparing thermal images, which are typically expected to reflect the quality of the surface of the test sample. Namely, owing to the difference between the surface layers of the threads made from the same material using standard but different fabrication technologies, it is possible to determine which of the two procedures was followed.

The parameters routinely recorded during the thermal imaging experiment were: ambient temperature estimated by the thermal camera (about 21ºC), distance of the test samples from the camera (30 cm), and relative humidity in the lab (45%). Measurements were conducted under laboratory conditions, where the distance between the test samples and the equipment was relatively small, so that the distance and atmospheric effects, which are significant in thermal imaging, had a negligible impact on the results. A strong heat pulse generated by the flashlight, lasting for 0.71 ms, caused uniform heating of the threaded fastenings (test samples 1, 2, 3, and 4).

As such, the requirement in the case of testing of materials that rapidly conduct heat (such as metals) was met – that the duration of the light pulse be much shorter than that of the generation of a single IR frame. The emitted heat is then evenly diffused through the test sample material. The entire process, from illumination (heating) to cooling, was captured by a thermal camera. The software used in the experiment stored the data (thermal images), which carried test sample surface temperature information.

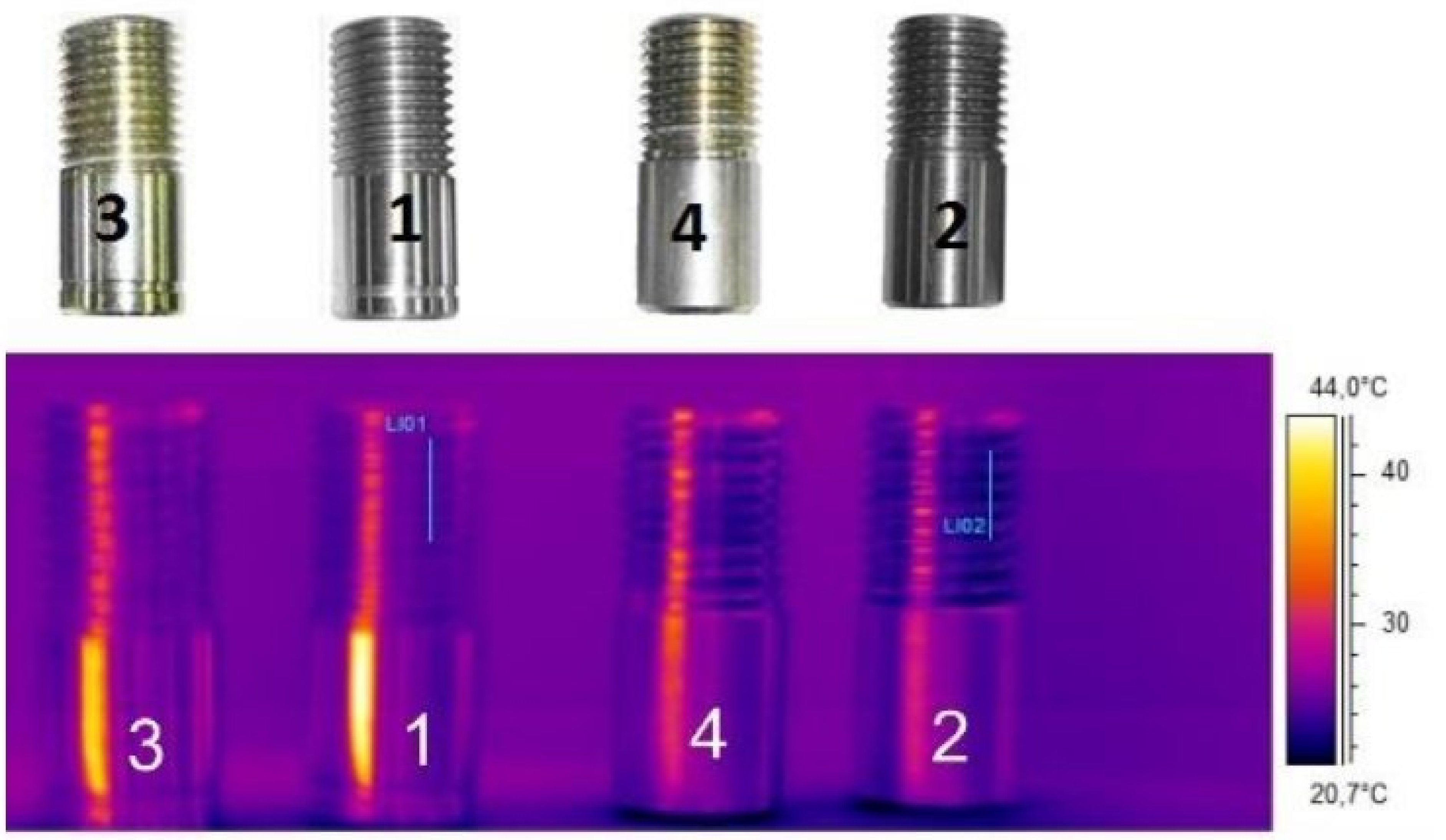

Fig. 6. Photograph and thermal images of threaded fastenings, type M 33 × 2: 1 and 2 have cut and cold-rolled threads with no cadmium finish, and 3 and 4 have cut and cold-rolled threads with cadmium finish.

After capturing, several thermal images were selected. The thermal image shown in Fig. 6 is the 5th frame after the flash was triggered in sequence SEQ. 112, comprised of 30 frames. The four threads are clearly visible.

In the first part of the test, marker lines were drawn on the selected thermal image, through interesting areas of test samples 1 and 2. The markers were parallel to the centerline of the threads and slightly longer than five turns. Marker line LI01 ran through the cut thread with no cadmium finish (test sample 1), and marker line LI02 through the cold-rolled thread with no cadmium finish (test sample 2). The temperatures were read out from the marker lines, to examine the effect of the fabrication technology on temperature distribution.

Fig. 7 and Fig. 8 are magnified photographs of test sample 1 and test sample 2, respectively, showing areas I through V of marker line LI01 and LI02 (the threaded portion of the fastening), along with the temperature distribution plot. The temperatures were read out at characteristic points: bottom, side, and top of the thread.

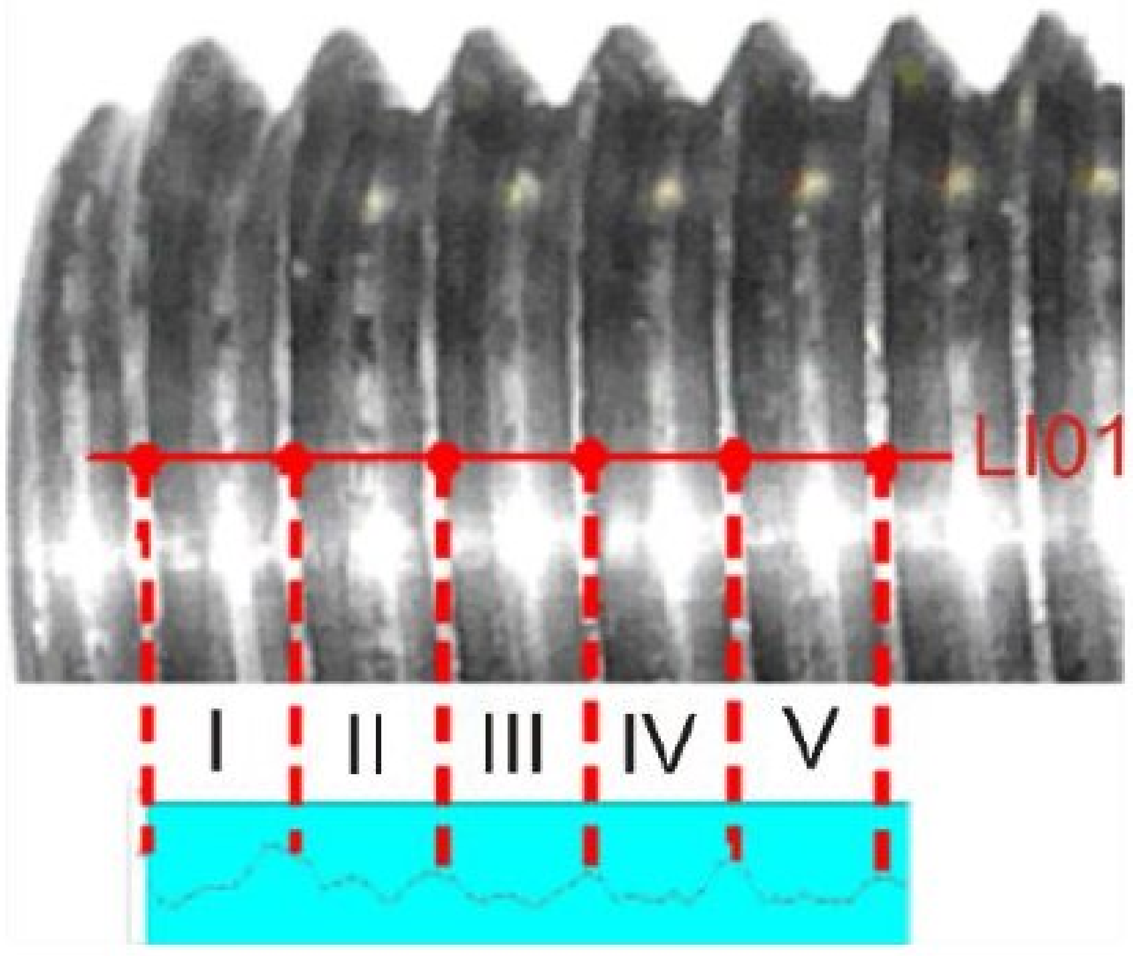

Fig. 7. Photograph of cut thread (test sample 1) with no cadmium finish and surface temperature distribution plot.

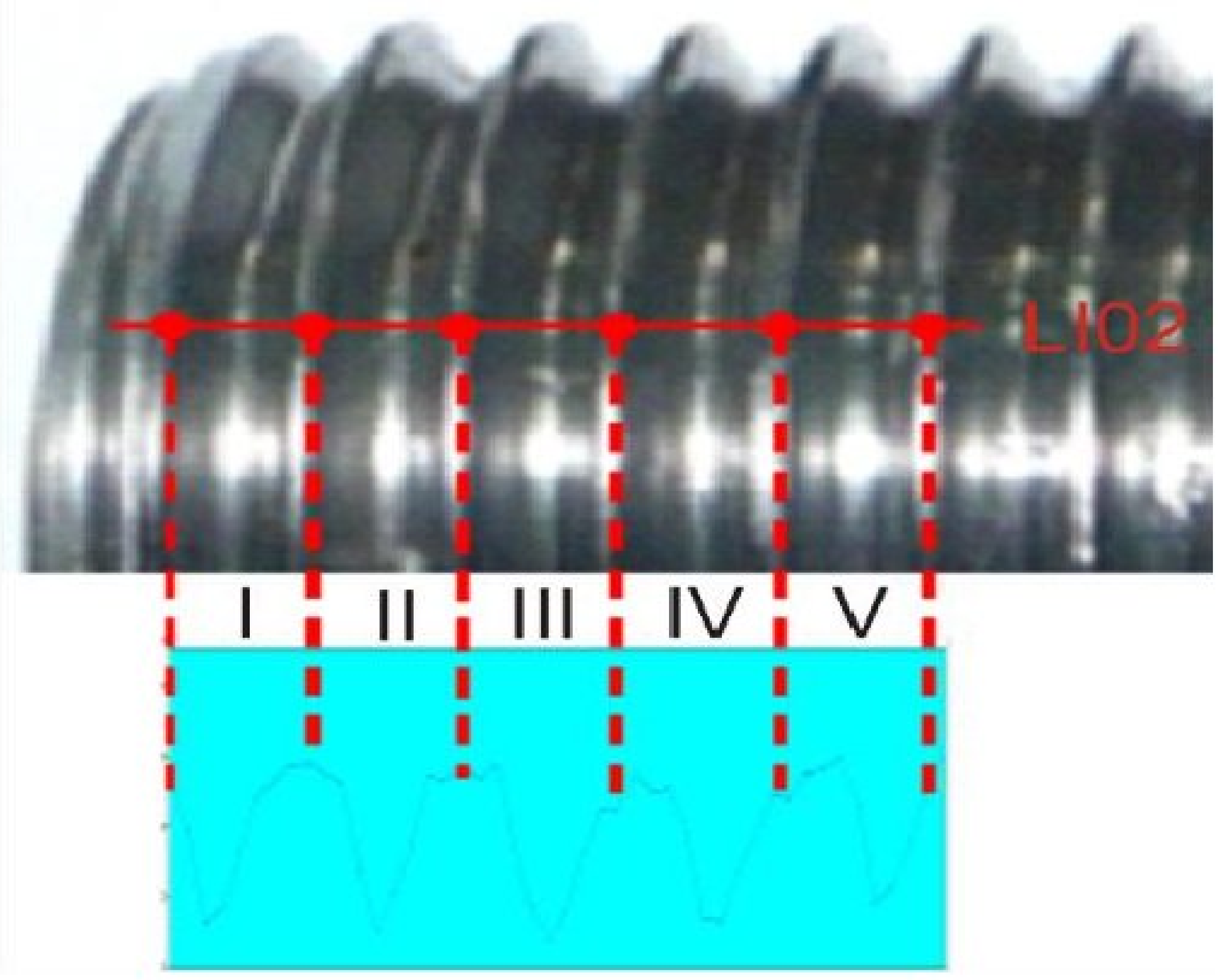

Fig. 8. Photograph of cold-rolled thread with no cadmium (test sample 2) finish and surface temperature distribution plot.

The temperatures along marker line LI01 in Fig. 7 and marker line LI02 in Fig. 8 are numerically represented in Table I. The temperatures on the bottom of the cut thread are in the range from 24.3°C to 24.6°C (average 24.46°C). The temperatures on the side of the cut thread are from 24.5°C to 24.6°C (average 24.54°C) and on the top of the cut thread from 24.6°C to 25.1°C (average 24.82°C). The temperatures on the bottom of the cold-rolled thread were in the range from 21.4°C to 21.6°C (average 24.48°C). The temperatures on the side of the cold-rolled thread were from 22.5°C to 23.0°C (average 22.70°C), and on the top of the cold-rolled thread from 23.8°C to 24.0°C (average 23.92°C).

Tab. I Temperatures at characteristic points of cut threads (test sample 1) with no cadmium plating with marker line LI01 and cold-rolled thread (test sample 2) with no cadmium plating marker line LI02.

Area	**Temperature on the bottom of the thread (°C)**		**Temperature on the side of the thread (°C)**		**Temperature on the top of the thread (°C)**	
	cut	cold-rolled	cut	cold-rolled	cut	cold-rolled
Area I	24.5	21.6	24.6	22.5	25.1	23.9
Area II	24.5	21.5	24.6	22.5	24.6	23.8
Area III	24.6	21.4	24.5	22.8	24.7	23.9
Area IV	24.4	21.4	24.5	22.7	24.8	24.0
Area V	24.3	21.5	24.5	23.0	24.9	24.0
Average	24.46	21.48	24.54	22.70	24.82	23.92

Fig. 9 shows in parallel the temperature distribution plots along marker lines LI01 and LI02 (i.e., the cut and cold-rolled threads with no cadmium finish, respectively). The shapes of the curves and the differences in temperature between the bottom and top of the threads make it possible to associate and geometric positions of the points on the threaded fastenings.

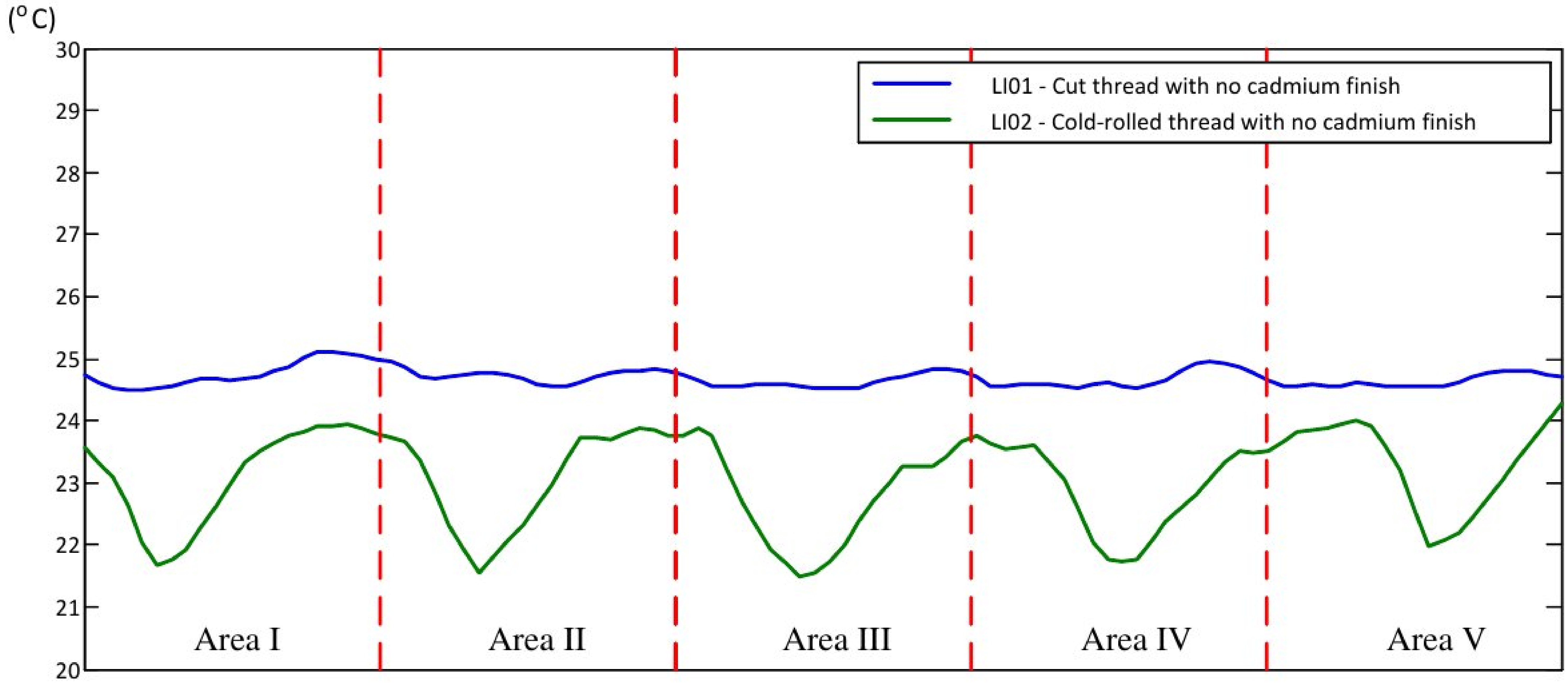

Fig. 9. Parallel temperature distribution plots along marker lines LI01 and LI02 – cut and cold-rolled threads with no cadmium finish, respectively**.**

4.1. Checking the effect of cadmium plating on temperature distribution

In the second part of the experiment, the objective was to check the effect of the cadmium surface finish on the appearance of the thermal images or, in other words, the temperature distributions at characteristic points of the threads. To that end, thermal images were captured of "pairs" of threaded fastenings: cut and cold-rolled with no cadmium finish and cut and cold-rolled with cadmium finish (test samples 1, 2, 3, and 4, respectively).

Fig. 10. Photograph of thermal camera display of thermal image during testing of the effect of cadmium plating on the temperature distributions of the threads

A typical thermal image, displayed on the thermal camera in cases such as this, is shown in Fig. 10. It is the 5th thermal image out of the 30 captured in sequence SEQ. 120. Marker lines were drawn in the same way as in the first part of the experiment and denoted by L201, L202, L203, and L204.

Fig. 11 shows in parallel the temperature distribution plots along marker lines L201, L203, L202, and L204 – cut threads without and with cadmium plating and cold-rolled threads, without and with cadmium plating, respectively.

Table II shows the temperature distributions at characteristic points of marker lines L201, L203, L202, and L204 – cut threads without and with cadmium plating and cold-rolled threads, without and with cadmium plating, respectively.

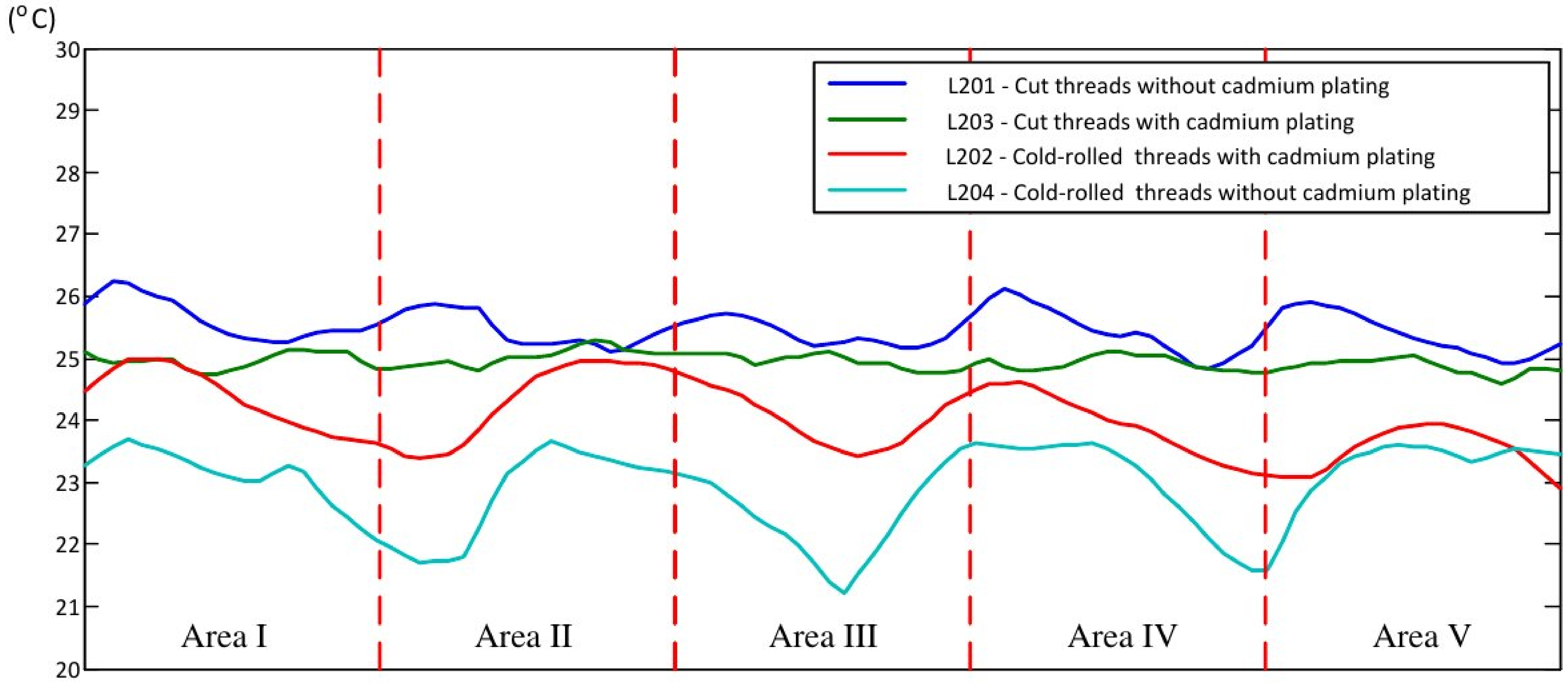

Fig. 11. Parallel representation of temperature distribution plots along marker lines: L201 – test sample 1, cut thread with no cadmium plating; L203 – test sample 3, cut threads with cadmium plating; L202 – test sample 2, cold-rolled thread with no cadmium plating; L204 – test sample 4, cold-rolled threads with cadmium plating.

Tab. II Temperatures at characteristic points of cut and cold-rolled thread without or with cadmium plating.

Area	Temperature on the bottom of the thread (°C)	Temperature on the side of the thread (°C)	Temperature on the top of the thread (°C)

	cut	cut + cadmium	cold-rolled	cold-rolled + cadmium	cut	cut + cadmium	cold-rolled	cold-rolled + cadmium	cut	cut + cadmium	cold-rolled	cold-rolled + cadmium
Area I	25.2	24.8	23.5	21.9	25.6	24.9	24.0	23.0	26.4	25.1	25.0	23.6
Area II	25.0	24.8	23.2	21.4	25.4	24.9	24.5	23.0	26.0	25.1	25.0	23.6
Area III	25.1	24.9	23.6	21.4	25.2	25.0	24.0	22.9	26.0	25.2	24.9	23.6
Area IV	24.9	24.9	23.5	21.5	25.3	25.0	24.0	23.0	26.1	25.0	24.9	23.5
Area V	24.5	24.9	23.5	21.2	24.4	25.0	24.5	22.9	24.9	25.0	25.0	23.4
Average	24.94	24.86	23.46	21.48	25.18	24.96	24.20	22.96	25.88	25.08	24.96	23.54

Fig. 12 shows in parallel the temperature distribution plots along marker lines LI01 and LI02 (i.e., the cut and cold-rolled threads with no cadmium finish, respectively), as in Fig. 9. Consequently, the red line in Fig. 12 represents the temperature profile of the used defective thread of an unknown manufacturing method. Based on Fig. 12, it is demonstrated that by applying the pulsed thermography method to a thread of an unknown manufacturing method, through a comparison of curve shapes and temperature differences between the lower and upper parts of the thread, it can be determined whether the thread has been cut or cold-rolled. In addition, it has been observed that the curve shape of the defective thread corresponds to the curve shape of a thread manufactured by cold-rolled technology. In this way, the production and rapid replacement of the screw in military equipment are facilitated.

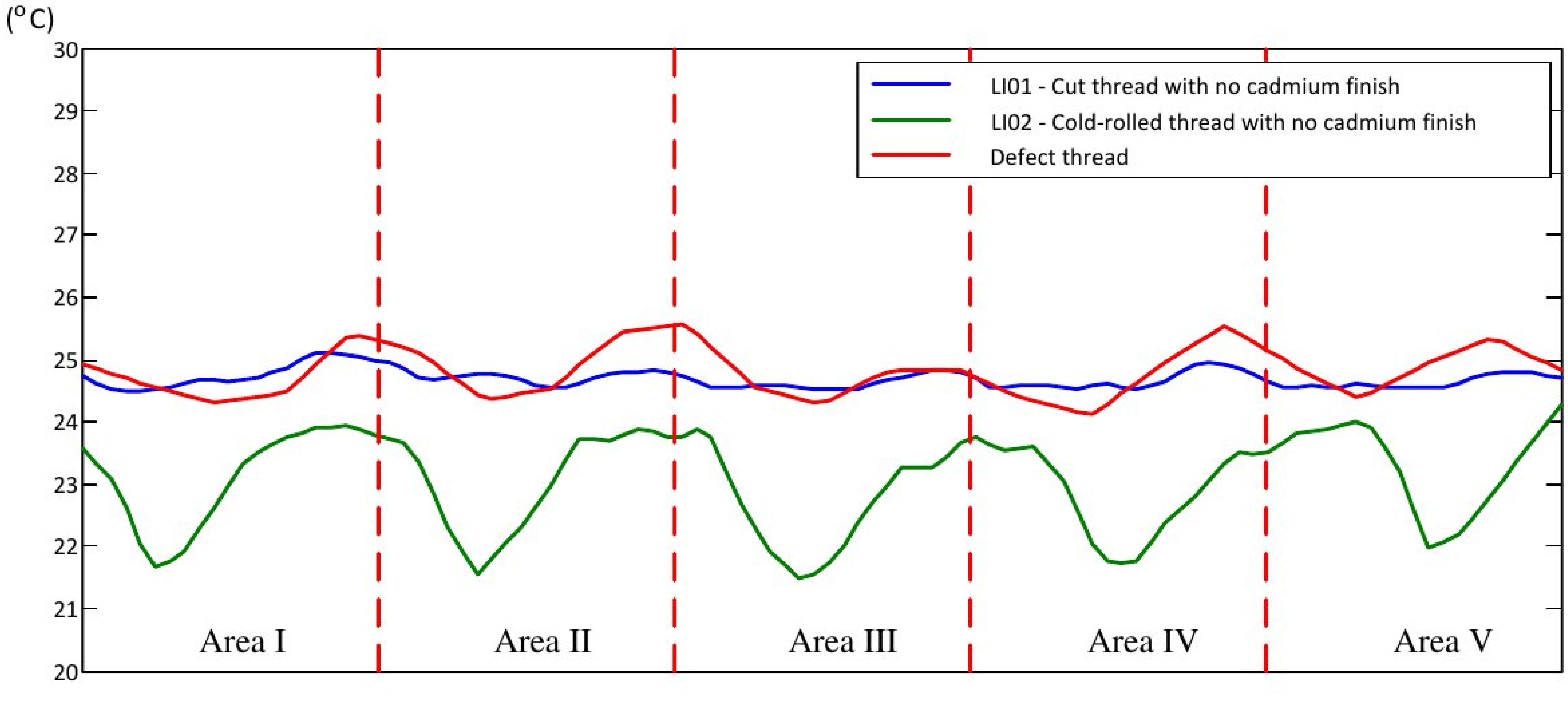

Fig. 12. Parallel temperature distribution plots along marker lines LI01 and LI02 – cut and cold-rolled threads with no cadmium finish. The red line represents the temperature profile of the used defective thread of an unknown manufacturing method.

5. Discussion

The four samples of threaded fasteners were all made from the same type of steel and their geometries were identical. There was no visible difference in the surface roughness, which depends on the fabrication technology. Differences could only be detected by electron microscopy. However, differences in the surface finish (with or without cadmium plating) were clearly visible to the naked eye.

Thermal imaging was conducted under identical ambient conditions and the differences in the distances between the test sample and the test equipment were negligible. The emissivity of the rougher surface of the cut threads was lower (i.e., the reflexivity was higher) because it was a poorer absorber of heat from the light pulse. The differences in surface emissivity and reflexivity were taken into account in the experiment.

Temperatures were read out from marker lines LI01 and LI02, which were drawn parallel to the longitudinal axes of the threads. The thread lengths were approximately five complete turns, as shown in Figs. 7 and 8. Temperature differences were noted at characteristic points of the thread: bottom, side, and top. Apart from temperature variations, the curves that defined the temperature distributions along marker lines LI01 and LI02 also differed (Fig. 9).

The curve that represented the temperature distribution along the cold-rolled threads was spikier than that of the cut threads (which was smoother), as a result of the different surface roughness of the threads fabricated using different technologies. Under identical experimental conditions, the surface of the cold-rolled threads was warmer than that of the cut threads because of the different surface quality (cut threads were poorer heat absorbers).

Given that the test samples were made from the same material and that the experimental conditions were identical, the different surface temperature distributions during the cooling process (after active heating) could only be attributed to different surfaces (i.e., fabrication technologies).

Temperatures were read out along “pairs” of test samples, with and without cadmium plating, from marker lines L201 and L203, and L202 and L204, respectively. The temperature distribution plots showed that the temperatures remained different at characteristic points, like in the first part of the experiment.

The temperatures differed at characteristic points of the threads, along the marker lines. These differences indicated that the surfaces of the non-plated samples were warmer than those that were cadmium-plated, which was as expected because a pure metal surface is a better heat conductor.

The shapes of the temperature distribution curves remained the same (plots in Figs. 11 and 12), meaning that they depended solely on the fabrication technology of the threads. The values of surface temperature indicated a dependency on the presence (or absence) of cadmium plating.

6. Conclusion

The results of the experiment, during which the surface temperature of threaded fasteners was measured by pulsed thermography, as presented in the paper, corroborate existing knowledge that the surface quality of the sample (i.e., the surface structure/roughness of the material), as well as properties such as surface emissivity and reflexivity, affect the degree of warming and thus the appearance of the thermal image.

Based on the shapes of the temperature distribution plots derived from the thermal images, it was possible to determine which fabrication technology, cutting or cold-rolling, was applied to manufacture the threaded fastenings.

This conclusion makes it possible to avoid costly or destructive test methods, as well as subjective judgment, which have been common during post-overhaul inspection of the mechanical components of machinery. Using pulsed infrared thermography, it is possible to determine the fabrication technology of threaded fasteners quickly, reliably, and on the spot. Electron microscopy showed that the quality of the cold-rolled threads was superior.

The experiment confirmed that it is possible to apply pulsed infrared thermography to detect differences in the physical properties of materials used to fabricate mechanical components whose geometries are the same. This fact is potentially significant in cases where spare parts of unknown origin (manufacturer) are installed. The equipment used during the experiment has recently become more affordable, so the research showed how its applicability can be broadened to include the determination of technologies used to fabricate mechanical components.

Pulse infrared thermography is one of the contactless methods that are simple to be applied when it is necessary to quickly determine the manufacturing technology (cold-rolled or cut), for example, a screw that is intended to be replaced by a new one on a piece of complex military equipment (aircraft, helicopter, or tank), or a piece of commercial equipment (excavators, conveyor belt, etc.).

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Сажетак: *Методе испитивања без разарања, укључујући пулсну инфрацрвену термографију, постале су прилично честе у процени материјала. Метода је погодна за проверу квалитета површинске обраде структуре материјала до одређене дубине, а све више се примењује у областима одржавања система и процене стања машинских елемената. Дакле, код уградње резервних делова (завртњева) за војне потребе, нпр. у авионе, хеликоптере, тенкове или оклопна возила, као и за комерцијалне сврхе, нпр. багере или друге машине, потребно је те делове додатно прегледати како би били сигурни у њихов квалитет. У раду се разматра примењивост пулсне инфрацрвене термографије у контроли квалитета завртњева, кроз одређивање технологије израде стандардних навојних спојева (ваљањем или сечењем), као и технологије завршне површинске обраде завртњева слојем кадмијума.*

***Кључне речи**: Пулсна IC термографија; Навој завртња; Испитивање и евалуација без разарања.*