The use of photogrammetry in improving quality of workpieces after an injection molding process

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DOI: dx.doi.org/10.14314/polimery.2018.2.7

Abstract: In the paper a possibility of utilization of modern measurement methods in production of plastic parts was presented. This was realized on an example of a bus seat manufactured by injection molding process. Coordinate measuring technique and its application range was briefly discussed. The results of static and dynamic photogrammetry were shown. Thermography was used to investigate cooling process of both: a mold and an object. Material that was used in research and to manufacture seats was also presented with its features and parameters. As it was shown in the research and analysis of results, thanks to utilization of modern measurement and analytic methods accuracy parameters of workpieces manufactured by injection molding process were significantly improved.

Keywords: static photogrammetry, dynamic photogrammetry, injection, polyamide 6, thermovision.

Zastosowanie fotogrametrii do poprawy jakości wyprasek po procesie wtryskiwania

Streszczenie: Przedstawiono możliwość zastosowania nowoczesnych metod pomiarowych do analizy procesu produkcji elementów z tworzyw polimerowych. Omawianą analizę zastosowano do procesu wytwarzania fotela autobusowego metodą wtryskiwania. Na tym przykładzie opisano współrzędnościową technikę pomiarową i jej możliwości aplikacyjne. Pokazano wyniki badań metodą fotogrametrii statycznej i dynamicznej. Do analizy procesu stygnięcia formy i wypraski wykorzystano natomiast badania termowizyjne. Stwierdzono, że zastosowanie nowoczesnych metod pomiarowych i analitycznych umożliwia lepsze poznanie procesów i wprowadzenie zmian pozwalających na istotną poprawę parametrów dokładności wykonania wyprasek metodą wtryskiwania.

Słowa kluczowe: fotogrametria statyczna, fotogrametria dynamiczna, wtryskiwanie, poliamid 6, termowizja.

Modern solutions in design and manufacturing require modern metrology. It is a crucial condition for both: quality control and a closed loop with feedback to improve existing products. This gives an input to design a construction that is modified to fulfill growing needs of customer and technology, where range of deviations can be diminished through better stability of production process and gaining more knowledge about existing systems and machines. Incorporating modern measuring techniques and devices enables for proper traceability of all products and possible problems that may occur. Another requirement from contemporary constructions is – of course apart from aesthetics – to be pro-ecological [1], *i.e.*, to help environment protection by having input to reduce pollution or make fuel consumption smaller. This in turns can be realized by designing lighter machines and structures, still maintaining strength parameters on expected high level. It is particularly obvious when various parts of vehicle equipment are considered, where every reduced kilogram saves fuel and decreases emission of polluting substances to the atmosphere. This tendency is also visible in injection molding industry where plastic products are being consistently re-designed or optimized to meet more and more sophisticated requirements. An example discussed in this paper is a bus seat manufactured by company STER, which is a leading and renowned in the world supplier of that kind of products to many leading bus (for different purposes) and train car manufacturers. As a result of a project, a lighter seat was designed with strength and price on a similar level. Also,

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to obtain this, some elements of manufacturing process were significantly improved.

For the purpose of research and inspection advanced metrology solutions were designed and applied, which aided to visualize and simulate on-going and predicted processes, verify assumptions as well as obtain numerical data with as low measurement uncertainty as possible.

COORDINATE MEASURING TECHNIQUE

Coordinate measuring technique is relatively young (about 50 years) and differs from traditional metrology in many aspects [2, 3]. This technique collects points, calculates features and relations, is very good for automation and becomes more and more popular in both: industry and research labs [4–6]. It is based on digital measurement information converted by a computer using a special transformation algorithm. Coordinates of points are found in *X*, *Y* and *Z* by a contact or non-contact method. A measurement process takes place in Cartesian or polar coordinates. A great advantage of coordinate measuring technique is a possibility of any workpiece location thanks to a workpiece coordinate system, that can be freely translated and rotated. For calculation purposes and machine coordinate system it is realized by uniform transformation equation:

$$p(g) = t(g, l) + R(g, l)\, p(l) \tag{1}$$

where: $p(g)$ – vector coordinates in global system (machine), $p(l)$ – vector coordinates in local system (workpiece), $t(g, l)$ – translation vector, $R(g, l)$ – rotation matrix of local system in relation to global one.

Basing on this equation all six degrees of freedom can be determined. The uniform transformation was shown on Fig. 1.

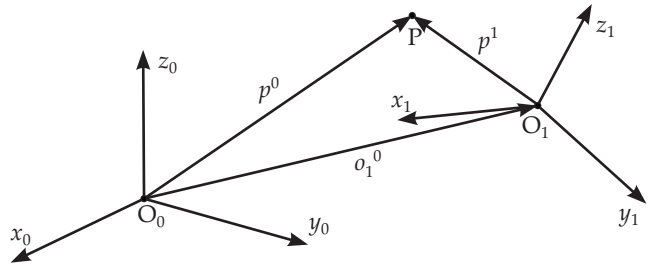

Fig. 1. Uniform transformation

In contact methods geometry of tip plays an important role. It is used in coordinate measuring machines where movable elements change their positions in three perpendicular directions, what is measured by incremental encoders. Coordinate measuring machines (CMM) with a tactile probe can be divided into several groups, depending on construction and moving elements [7]. They vary with accuracy parameters, measuring range in all axes and applications. A typical CMM – apart from construction elements – consists of a probe system, drives to move it in *X*, *Y* and *Z* as well as encoders retrieving a measure unit.

PHOTOGRAMMETRY IN LENGTH AND ANGLE METROLOGY

Measurement methods described above basing upon a physical contact of a probe with a measured object are sometimes not practical or not convenient application wise. Such a situation takes place when measurement pressure from a probe tip is not possible or at least not recommended, *e.g.*, because of deflection of a workpiece. A good example here are all soft elements including car and bus seats made of textiles and plastics. Non-contact methods can be used also for measurement of thin walls, holes (for some techniques only with small depth) and elements susceptible to deflection. Furthermore, most of optical methods are faster and allow to obtain much more measurement points. From the moment in history when power of computers grew in such a way that it is not a problem for calculation primitives from a large set of data and evaluation time got small enough to do it, density of points could be significantly enlarged and accuracy parameters of optical methods could be improved.

A location of a measurement point during non-contact measurement is usually based on triangulation, *i.e.*, a construction of a triangle from which coordinates of an unknown point can be calculated [8, 9]. This can be divided into point methods (where information about the shape of a workpiece is gained from single points) and field ones [where shape is obtained by analysis of a whole image from a charge-coupled device (CCD) camera]. Another criteria of division come from type of registered electromagnetic radiation and the way it is used. Triangulation is then a method of optical measurement of distance, based upon relations in triangle and trigonometrical functions. For this it is necessary to know positions of illumination elements (*e.g.* lasers), *i.e.*, positions from which a workpiece (composed of points) is observed. Such information consist also angles between basic construction and rays reaching a measured point. Such a triangle enables for calculation all the necessary data, this process is repeated for all points of a measured object with required resolution.

For over a hundred years photogrammetry – first as analogue technique and from the end of XX century also as digital one, enables measurements basing on taken pictures – photograms. It became a way of determination mutual location of points and in turns shapes and dimensions. It is enough to have at least two cameras connected to a PC by a frame grabber to register data. Nowadays we mostly use digital cameras or cameras with CCD or complementary metal oxide semiconductor (CMOS) matrices with high resolution. A very important condition for images is their accurate reproduction with central projection. From mathematical point of view this means

creating a line through a given point in space through a central point O to intersection with projection plane, where O′ point is created (Fig. 2).

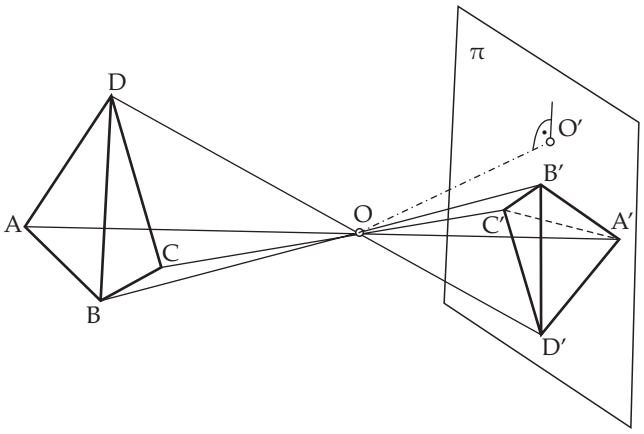

Fig. 2. Central projection of ABCD pyramid

In real life – because of imperfections of instruments – a photographic image is an approximation of central projection, its physical equivalent rather. Lens distortion causes that beams going out of camera do not cover the ones coming back to it. In professional solutions this difference should not exceed 5 μm. Surface of matrix is also not perfectly flat, which is another reason for deformations.

Photogrammetry allows to obtain points in three dimensions based on flat 2D images [10–12]. To make it happen it is then necessary to make images from minimum two camera positions. Each point is calculated from triangulation from crossing beams. When a number of images grow accuracy parameters get better. For some applications even more than 10 images are collected. To clearly define camera positions coordinates of center of projection are used (X_0, Y_0, Z_0) as well as three camera angles: inclination ω, rotation κ, and yaw φ. They allow to get an orientation of beams in space. To connect data from different camera locations special markers are used (Fig. 3) or orientation in space is given by a special tracking system for a scanner. The examples of devices from both techniques, a laser scanner with markers and a tracked 3D scanner, are shown in Fig. 4.

POLYMERIC MATERIAL AND THE INJECTION MOLDING PROCESS USED IN THE RESEARCH

Polyamide 6 (polycaprolactam) belongs to the group of aliphatic polyamides (PA). This is a high molecular weight compound containing polar amide groups (–CO–NH–) in the main chain, which are separated by nonpolar methylene groups (–CH_2–). The index after the name of PA determines the number of carbon atoms between the nitrogen atoms and determines the method for obtaining the polymer. PA derived from lactams or amino acids have a single digital index (*e.g.* PA 6), while polymers produced from diamines and dicarboxylic acids (or dicarboxylic acid chlorides) have a double digit index (*e.g.* PA 6.6). In the latter case, the first digit is the number of carbon atoms in the diamine molecule and the second is the number of carbon atoms in the dicarboxylic acid molecule or dicarboxylic acid chloride [13–15].

PA belong to polar polymers. The polarity of PA determines the ratio of the number of amide to methylene groups:

$$p = \frac{[-CO-NH-]}{[-CH_2-]} \tag{2}$$

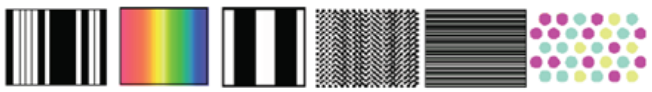

Fig. 3. Special markers to connect images

Fig. 4. A laser scanner requiring markers (HandySCAN) and a tracked 3D scanner MetraSCAN (head and tracking system)

where: p – polarity, [–CO–NH–] – content of polar amide groups, [–CH_2–] – number of nonpolar amide groups.

Polarity of macromolecules is an essential factor determining the properties of PA. Polarity depends on: softening and melting temperature, water absorption capacity, ability for crystallization and crystallographic structure and mechanical properties [14–17].

An important feature of PA is the ability to form intermolecular hydrogen bonds, *i.e.*, strong dipole-dipole interactions, between the hydrogen groups of the amidic bond moieties and the carbonyl groups of the adjacent macromolecule.

These constraints limit the movement of macromolecular segments. Increasing the number of hydrogen bonds causes, among others, growth of crystalline phase melting temperature, glass transition temperature, tensile strength, stiffness, hardness and density, but polymer elasticity decreases [15].

PA are thermoplastic polymers with a strong tendency to crystallize, *i.e.*, to create an ordered structure. The degree of crystallinity of aliphatic PA ranges from 30 to 50 % and depends on, among others, the polarity of the macromolecule and crystallization conditions, mainly cooling rates. The ability to crystallize more polar PA 6 is greater than less polar PA 12. The presence of the crystalline phase in the PA results in their high tensile strength, high modulus of elasticity, hardness, and abrasion resistance. At the same time, the presence of flexible macromolecules in the amorphous regions ensures good impact resistance, polyurethane strength, and considerable elongation at break. PA polymers have high fatigue strength, both for vibration and for multiple shocks [14, 15].

The presence of the crystalline phase also affects the coloration of polyamides. They are mostly milky-cloudy and may be partially translucent or opaque depending on the thickness of the product. The density of PA depends on the content of the crystalline phase, which ranges from 1.12 g/cm^3 for PA 6 to 1.04 g/cm^3 for PA 11.

The configuration of the hydrogen bonds depends on the crystalline structure of PA. The characteristic feature of this structure is the crystallographic polymorphism, *i.e.*, the ability to develop different variants of the spatial network. Depending on the conditions, PA polymers usually crystallize in three crystallographic forms: α, β or γ [16–21]. These forms vary in degree and perfection of macromolecule order. For example, PA 6 crystallizes primarily in the form of a thermodynamically stable, monoclinic form α and less stable, monoclinic or pseudohexagonal form γ [21–24]. Slow cooling and higher crystallization temperatures of melt of PA 6 favor the formation of crystallographic form α, whereas rapid cooling and lower crystallization temperatures favor mold formation γ [21, 23, 24].

The type of crystallographic forms depends on the thermal and mechanical properties of PA. For example, the crystallographic form γ PA 6 is more flexible than α [25–28]. Depending on the manner of crystallization (*e.g.*, from the diluted solution, from the molten phase in the stretching or annealing processes, by the action of iodine or phenol) these molds may pass one to the other [20, 25, 26].

The viscoelastic properties of PA depend on both the number of methylene groups and on the number and distribution of amide groups in the macromolecule [29]. In PA there are at least three relaxation processes called α, β and γ [29, 30]. The area of the highest temperature corresponds to relaxation α [glass transition temperature (T_g)], while the lowest to relaxation rate γ [20, 29]. The height of relaxation peak γ decreases as polymer crystallinity increases, and for long chain PA polymers (*e.g.* PA 12) does not depend on the amount of water absorbed. The intermediate temperature corresponds to the relaxation peak β, which is related to the presence of water forming hydrogen bonds with amide groups in the amorphous PA regions. The relaxation peak β decreases or disappears when PA is dried at elevated temperature under reduced pressure [20].

Differences in the temperature and intensity of relaxation occurring in PA depend on: the number of polar amide groups, transverse bonds and chain entanglement in the amorphous phase, degree of crystallinity, crystallite dimensions, and thermal history of the sample. Low relaxation temperature α is usually accompanied by low melting temperature of PA [20].

An important feature of PA polymers is their ability to absorb water [14, 15]. The cause of the hydrophilic nature of PA is the presence in their macromolecules of polar amide groups. Water molecules are either strongly bound by the interaction with these groups, or micropores in the free water phase [32–35]. The water contained in PA exerts a great influence on the properties of the material and the dimensions of the products, and its effects depend, among others, from temperature [32, 35]. At room temperature and above, water contained in PA acts as a typical plasticizer, *i.e.*, it reduces the forces of intermolecular interactions. At the negative temperature the situation is reversed, the presence of water causes an increase in the stiffness of the polymeric material. The lower the temperature, the greater the rigidity of the polymer [18]. Completely dried PA 6 or PA 6.6 are brittle and have low impact resistance but high tensile strength and tensile modulus. With the increase in water content in PA, their impact strength and elasticity are increased, but they have the strength [14, 15]. The water absorption capacity of PA increases with the increase in the number of amide groups (increase in polarity) in the macromolecule and varies from 2.5 to 11 % depending on the type of PA. The most absorbing water is PA 6 (up to 11 %), lower PA 6.6 (up to 9 %) and least PA 11 and PA 12 (about 2.5 %). The hydroscopic property of PA is not only influenced by their polarity, but also by the order of macromolecule segments (crystalline phase content). The greater the content of the crystalline phase in

the PA, the less water it absorbs and the smaller its impact on the dimensions of the products and their properties [14, 15].

The high hydrophilicity of PA requires careful drying of the granules prior to processing. The moisture in the granulate causes the hydrolytic degradation of the polymer during processing, and thus the deterioration in the performance of the products.

The operating temperature range for PA is between -40 °C and +100 °C. The upper working temperature of continuous PA is limited by their rapid oxidation at temperatures higher than 100 °C. PA polymers are resistant to most organic and inorganic compounds except strong acids, bases and oxidizing compounds [14].

PA are widely used as construction plastics and fiber-forming materials. These parts are made of machines working under difficult conditions such as pump impellers, industrial automation components, and electrotechnical apparatus. More than half of the world's PA production is used for fiber production.

EXPERIMENTAL PART

Materials

In this research PA 6 with 30 % of glass fibers from Zakłady Azotowe Tarnów with trade name Tarnamid T-27GF30 was used. The specification of this material is as follows:

– melt volume rate *MVR* (275 °C/5 kg) = 45 cm^3/10 min;
– density d = 1.35 g/cm^3;
– melting temperature T_m = 221 °C;
– parallel and normal molding shrinkage 0.3 and 0.9 %, respectively.

Preparation of bus seat

Before the injection molding PA was dried in 80 °C for 4 h. The processing parameters were as follows:

– temperatures on plasticizing unit 180/250/270/280 °C;
– injection pressure 110 MPa;
– holding pressure 75 MPa;
– injection speed 110 mm/s;
– screw rotation 90 rpm;
– cooling time 60 s;
– cycle time 75 s;
– mold temperature 90 °C.

Methods of testing

Photogrammetry

From practical point of view photogrammetry can be realized either as static or dynamic one. In static version a stationary object is being scanned as a whole or to inspect its particular dimensions. Thus inspection of geometrical features or static deformation is possible (resulting from temperature or forces). These data can be analyzed in three dimensions. In dynamic version an object with markers (points) is moving alongside a trajectory whereas fast cameras record behavior of these markers only. In such a situation displacement, velocity and acceleration in every point (marker) are registered.

In the research static photogrammetry (structured light scanner ATOS) was applied to inspect geometrical deviations of injected bus seats. They were verified in initial situation and after modifications in injection process. Deviations were measured in 22 selected points with statistical analysis performed to show repeatability of production. Distribution of these points is shown on Fig. 5.

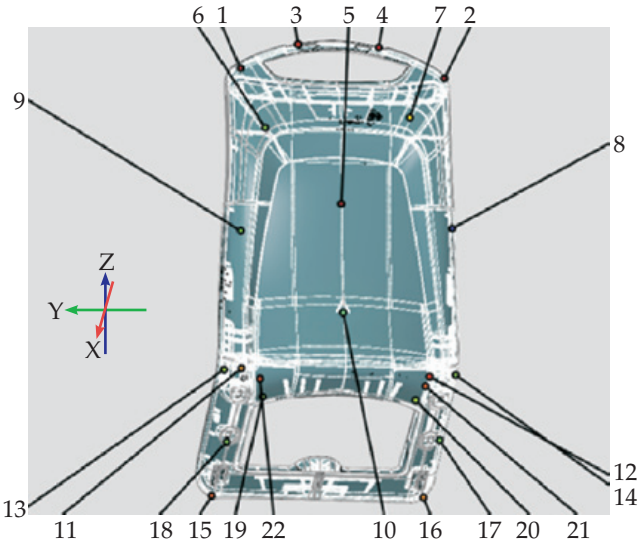

Fig. 5. Distribution of measurement points for static photogrammetry

Thermography

Cooling process was inspected with the use of thermography. That kind of system allows to indirectly measure temperature of an object, by emitted power of infrared radiation. This in turns is transferred by a detecting structure into electric signal that carries information about temperature of a part. A research stand for seat thermal diagnosis was made basing on FLIR thermovision camera.

RESULTS AND DISCUSSION

Using photogrammetry method 30 bus seats were inspected. Deviations were analyzed in initial phase, after first and after second optimization of parameters. Uncertainty was assessed according to a method including dispersion in every point. The results were shown on Fig. 6.

They show that as a result of optimization deviations went down even more than 3 times. Despite a few points located far from center of coordinate system dimensional deviation does not exceed 2 mm regardless cooling process and position.

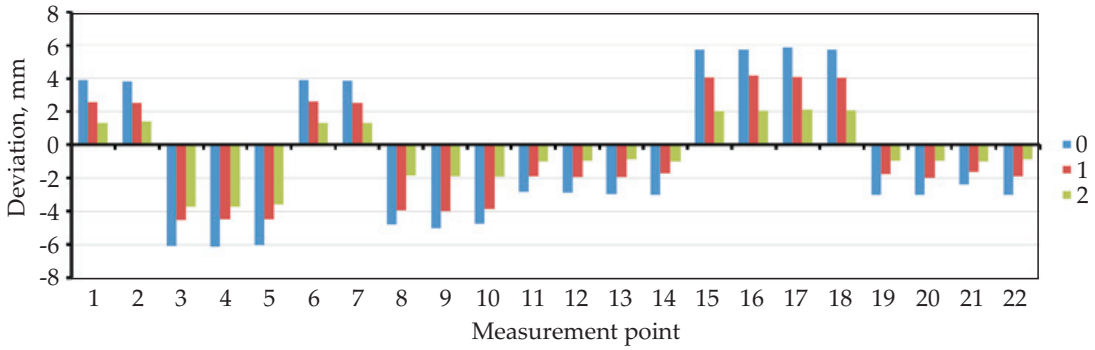

Fig. 6. Deviations in measurement points before optimization (0) and after first (1) and second (2) one

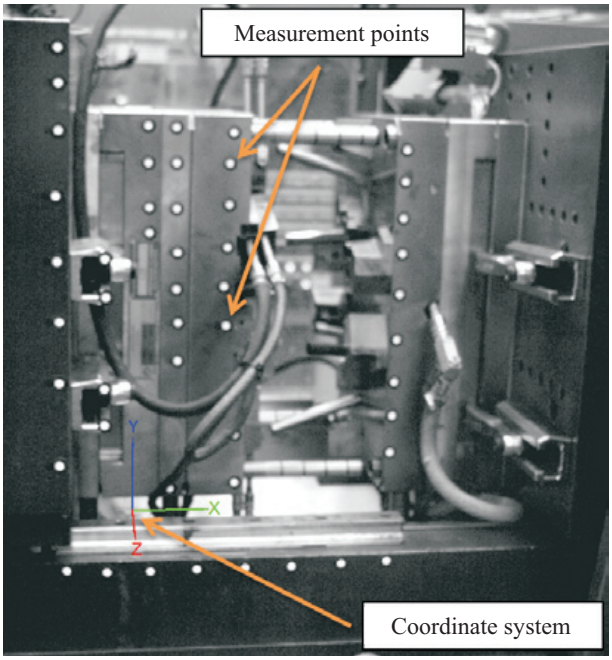

Fig. 7. A mold on injection molding machine

Analysis of injection molding machine

An analysis of stiffness of injection machine was an example of dynamic photogrammetry application (using PONTOS measurement system). This task is very important from workpiece repeatability as well as machine durability point of view. It was thought to find out all possible movements of a mold when it is being closed. For the test a setup with four seats was used. A mold on the machine is shown on Fig. 7. The measurement system had a measurement volume slightly over 0.5 x 0.5 x 0.5 m, while frequency of collecting images was set to 20 Hz.

The research was done with different closing forces, starting from 500 kN and ending with 1200 kN. The measurements were taken in 100 kN interval, so for 500, 600, 700, 800, 900, 1000, 1100 as well as 1200 kN. For all measurements identical procedures were kept and coordinate system was defined exactly the same way. Points were analyzed in *X* direction, *i.e.*, in the direction of closing the mold. To show the differences measurement results for two extreme situations are presented: the lowest force 500 kN and the highest 1200 kN.

After an investigation and discussion four measurement points on the plot were chosen for further analysis: two extreme on left side of a mold (points 1 and 2) as well as two extreme ones on right side (points 3 and 4). To picture a behavior of both sides of the mold an analysis of deviations of points was performed. Deformation of four points mentioned above is depicted in Figs. 8 and 9. Behavior of points on the whole length of left and right side of a mold is shown in Figs. 10 and 11.

Plots from Figs. 8 and 9 show movement of both parts of the mold in *X* axis. Displacement in upper part is slightly bigger what can be clearly seen also on images with vectors (red color for upper part, blue for lower). Furthermore Figs. 10 and 11 show that right (closing) part of the mold during injection is also pushed above in *Y* axis. Comparing results for two extreme forces (500 and 1200 kN) it can be seen that bigger displacements appear for bigger forces.

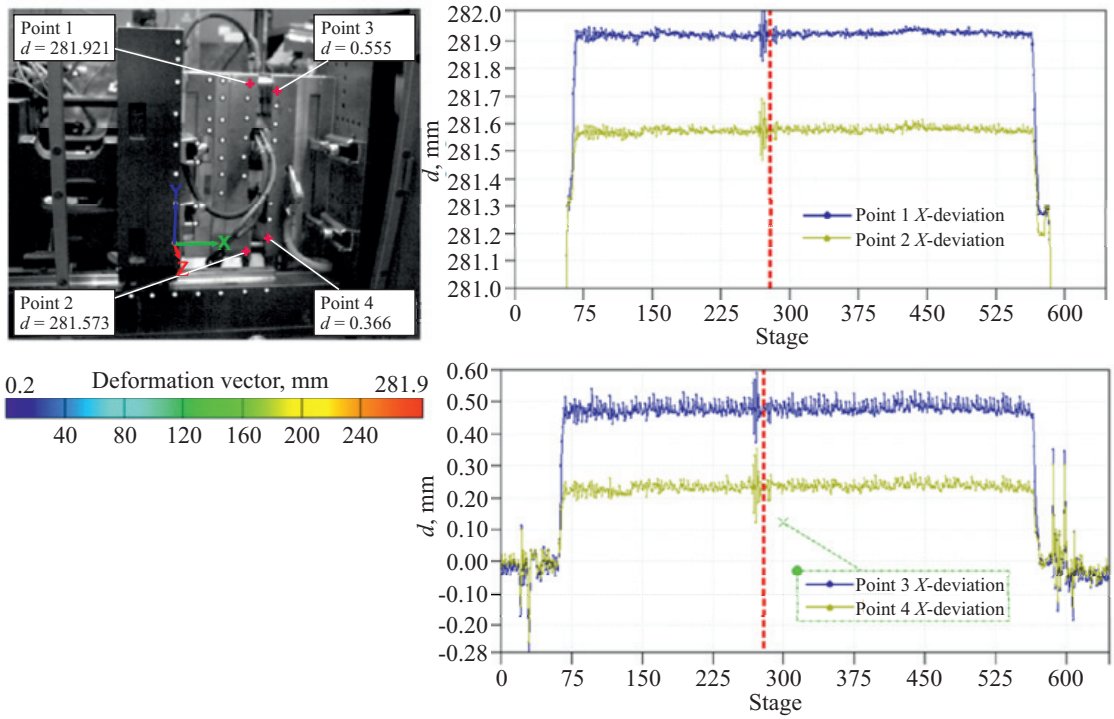

Fig. 8. Measurement report for 500 kN force in *X* axis

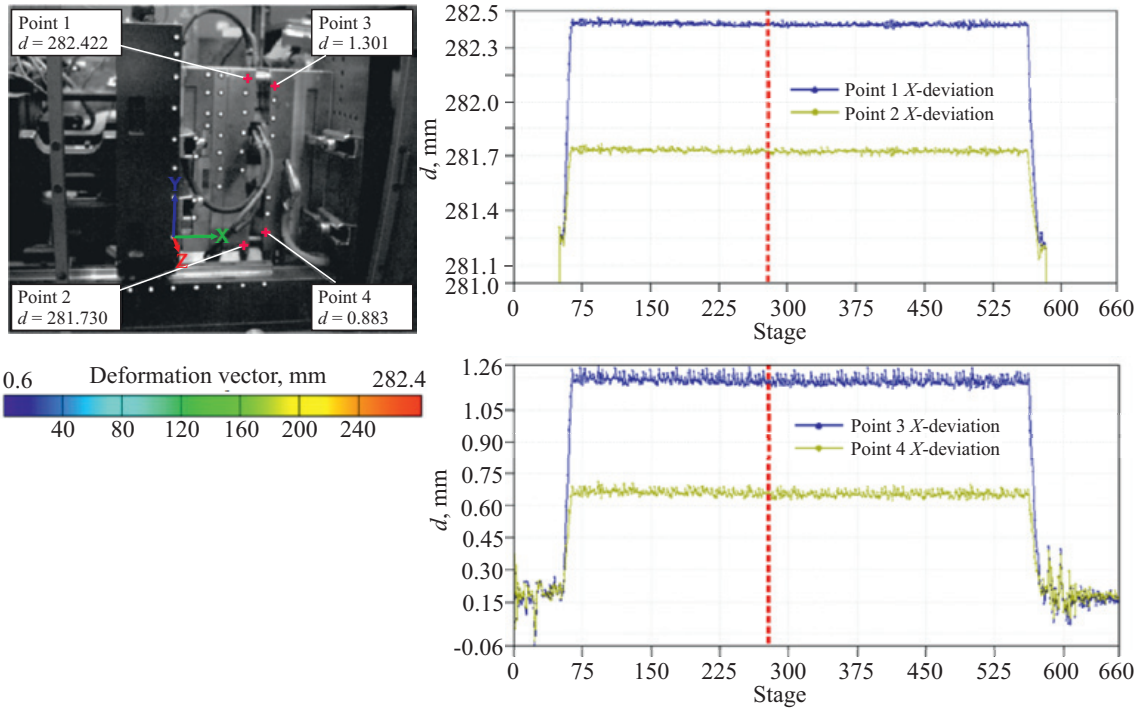

Fig. 9. Measurement report for 1200 kN force in *X* axis

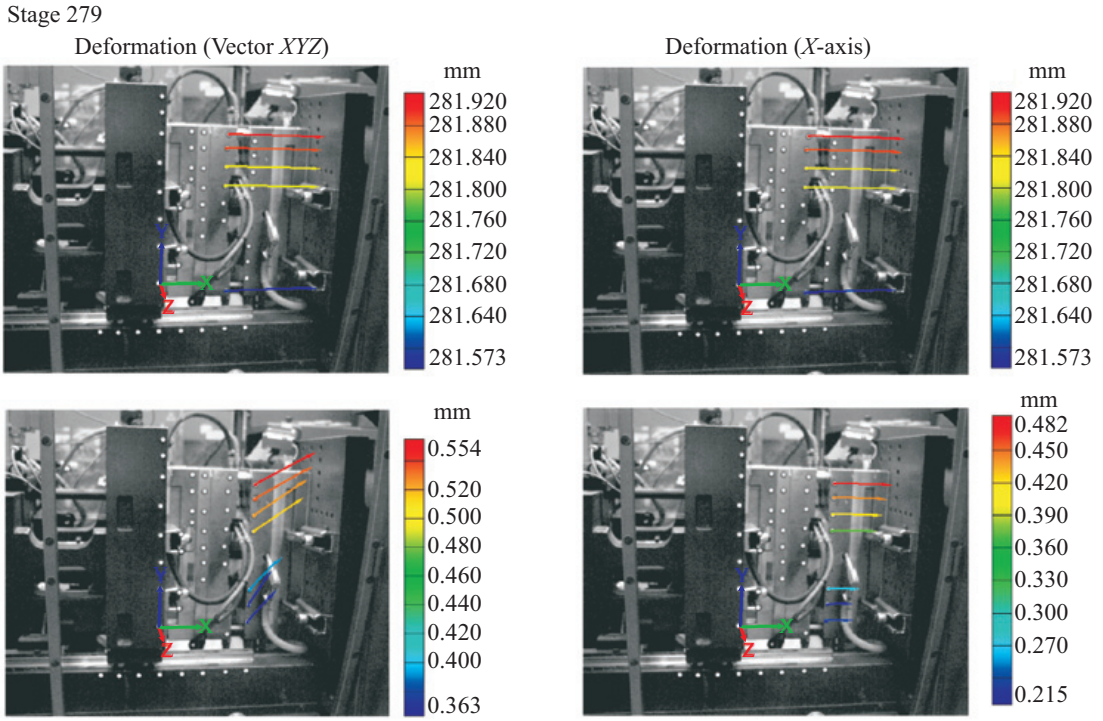

Fig. 10. Measurement reports deformations for 500 kN force

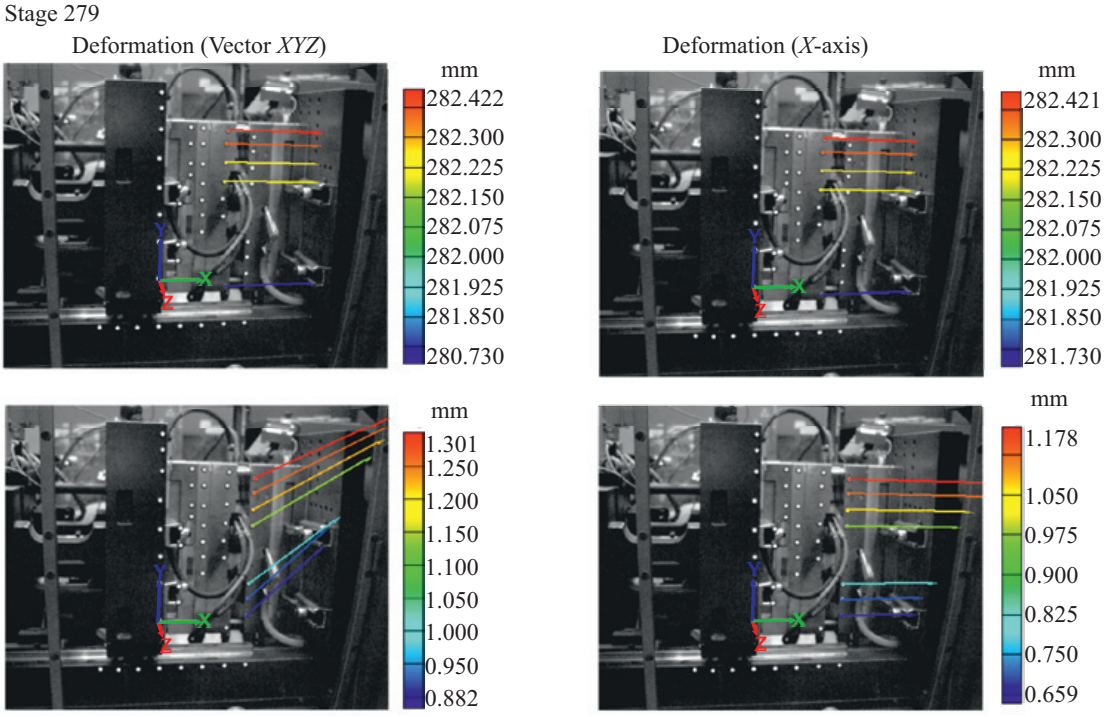

Fig. 11. Measurement reports deformations for 1200 kN force