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ASSESSMENT OF THE CANDIDATE SUPPLIERS' FLUENCY IN ISO GPS STANDARDS ESSENTIAL PRINCIPLES, RULES AND INDICATIONS

Many potential suppliers state that they are ready to produce components according to specified requirements as they are familiar with the ISO GPS system tools for dimensional and geometrical tolerancing. Regrettably, in many instances, this is not true. This paper discusses a survey developed to assess the geometrical dimensioning and tolerancing skills and results derived from this survey executed among 15 potential suppliers. The investigation aims to preselect potential suppliers and evaluate how much support the suppliers will require while also assessing the risks associated with placing an order with a particular supplier. The survey is based on the online test comprised of 27 closed-end questions used to identify strengths, weaknesses, and knowledge of a candidate supplier's personnel. Five different answers are given for each question. The respondent shall indicate one correct answer. The inquiry is practically oriented. Most of the questions include drawings with indicated selected tolerance as well as drawings of the possible actual parts with exaggerated geometrical deviations. The associated question is whether an actual part is made according to the specification. The main conclusion is that most responders disclose a low level of understanding of the ISO GPS system. Urgent education is needed.

1. INTRODUCTION

The ISO GPS system (Geometrical Product Specification system) is the system used to define the geometrical requirements for workpieces in technical-product documentation and the requirements for their verification [1]. This complete system, when used properly, allows for smooth communication between the development, technology, and metrology departments as well as between supplier and customer [2, 3]. Unfortunately, in many cases, serious deficiencies in understanding the ISO GPS system standards by users have been noticed by authors during contacts with potential suppliers or vocational training providers given in the industry.

There are two aims of the paper. The first is the analysis of the current level of competencies in the field of geometrical dimensioning and tolerancing in selected companies in Poland. These competencies should include the expertise and skills for using such knowledge

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efficiently. Analysis can be applied to identify strengths and weaknesses in the use of geometrical dimensioning and tolerancing rules and principles as implemented by various companies and shall be used to select and support potential suppliers. The second aim is a presentation of the general concept of a tool that may be developed and used to assess competencies in the field of geometrical dimensioning and tolerancing, in both educational institutions and industry, with a presentation of the types of questions that shall be included in such a survey.

To perform the diagnosis thoroughly, the authors surveyed 15 Polish industrial companies specialising in subtractive and metal forming manufacturing, aluminium extrusion, and injection moulding, as well as in research and development of new products, including automotive suppliers. The survey is based on an online test comprising 27 close-end questions focused mainly on the practical aspects of correctly understanding geometrical requirements. A total number of 38 answers for the survey have been received. Based on the authors' experience with suppliers, increasing the number of survey takers would not significantly affect the survey results. Thus, the data collected in this study are representative and can be evaluated and discussed.

The survey participants came from various companies located in Poland with widely recognised brands and medium size companies (51–250 employees). This secured a balanced distribution of participants regarding the size of their organisations, responsibilities, work experience, and years of experience within geometrical tolerancing.

The most interesting findings with respect to each issue are discussed and presented in section 3.

2. A BRIEF REVIEW OF THE SURVEYS ON THE ISO GPS SYSTEM KNOWLEDGE AND IMPLEMENTATION

The extent of the ISO GPS system implementation in the industry and the education of technicians and engineers have been recently discussed in several papers. Both factors have a significant impact on product reliability and determine the level of reduced income of the companies as a result of the cost of scraps due to incorrect specifications or interpretations of the geometrical requirements.

The maturity model is used to assess competencies in the ISO GPS system [4]. Reported research analyses the necessities and requirements to implement undoubtedly useful and beneficial standards provided by the ISO GPS system in an agile way, especially in small and medium-sized companies in Germany.

The degree of implementation of the new generation of ISO GPS system standards is given in [5]. The application of particular specifications in drawings of several medium and small enterprises in Bulgaria is shown as a percentage of occurrence in analysed drawings.

The paper [6] is focused on the results of an online survey with the aim of studying the dissemination of the ISO GPS system standards in teaching at technical vocational colleges in North Rhine-Westphalia in Germany. The evaluation of the responses from teachers shows that only 32.8% of them knew of the system. Moreover, 40% of teachers stated that they did not know if the ISO GPS system standards are relevant to their training occupation, which shall be assessed as incomprehensible and demonstrates their unpreparedness to teach for the needs of Industry 4.0.

The results of the survey covering engineering education of the Geometrical Production Specification and Verification in China are given in [7]. The results show that: there is a significant gap between textbook teaching and the latest ISO GPS standards; the frequency of the latest ISO GPS usage is relatively low, and the current delivery methods cannot address the requirements of end-users soundly.

Research reported in [8] shows that only a minority of German companies systematically and reliably introduce statistical tolerance analyses to existing development processes. The complexity of the ISO GPS system standards is indicated as one of the reasons. The presented research also demonstrated that the ISO GPS system standards are met with great reluctance and scepticism due to their immense scope and complexity. The grounds are that engineers lack the time, support, motivation, and interest to get involved in such a comprehensive set of standards [8].

The conclusion from the analysed literature is that the ISO GPS system standards implementation in industry and education is not fully successful in several countries. It faces many challenges and obstacles. The plus/minus tolerancing is definitely ambiguous; lack of geometrical tolerances or their misinterpretation generates a risk for companies, but on the other hand, the production must go on. The market requires products, and companies expect profits. The information above stimulated the authors to develop the online survey that shall help to select suppliers, thereby reducing the risk of misplacement of an order.

3. ANALYSIS OF SURVEY RESPONSES

3.1. GENERAL INFORMATION ON THE TEST AND THE FORMAT OF QUESTIONS

The developed test contains 27 questions covering the following areas: size, form, orientation, position, run-out, maximum material requirement, datum systems and measurement uncertainty [9]. The balance has been maintained between the number of questions, more of which could discourage responders from participating in the survey, and the desire to get to know respondents in depth. The number of questions is not spread evenly for each topic. Five different answers are given for each question, and only one of them is correct. The size, position, datums, and maximum material requirement have been considered essential practical knowledge for tolerance application in industry. Therefore, the number of questions related to those subjects is higher compared to the others. Despite that, every topic listed above contains at least two questions, and one of them is designed to be significantly easier to find if a responder has elementary knowledge of dimensioning and tolerancing according to the ISO GPS system.

In the subsections below, the respondent answers are analysed and discussed for selected questions from the test. Each question is related to a figure; therefore, questions are shown in the paper in the particular figure captions. The black lines are used to show the nominal geometry of parts, as it is usually depicted on the technical drawings. Each question shall be answered taking into account only the specifications given in the drawing. For every question, only selected tolerances and datums are specified to avoid overcomplicated fully-dimensioned drawings. The actual products with exaggerated geometrical deviations are shown in blue. The sets of 5 answers for each question are not given to keep the paper concise. The answers selected by the majority of respondents are shown, and the discussion points out whether the answer is correct or incorrect.

3.2. LINEAR SIZE – DIAMETER INTERPRETATION

One of the most common tasks in engineers' everyday life is the verification of compliance of manufactured shafts with specifications regarding size. This was one of the questions (Fig. 1) with the highest number of correct answers. 84% of survey participants solved it correctly. All five examples given in the figure below comply with the requirements presented in the drawing. This is in line with the independency principle [10], which states that by default, every GPS specification for a feature or relation between features shall be fulfilled independently of other specifications.

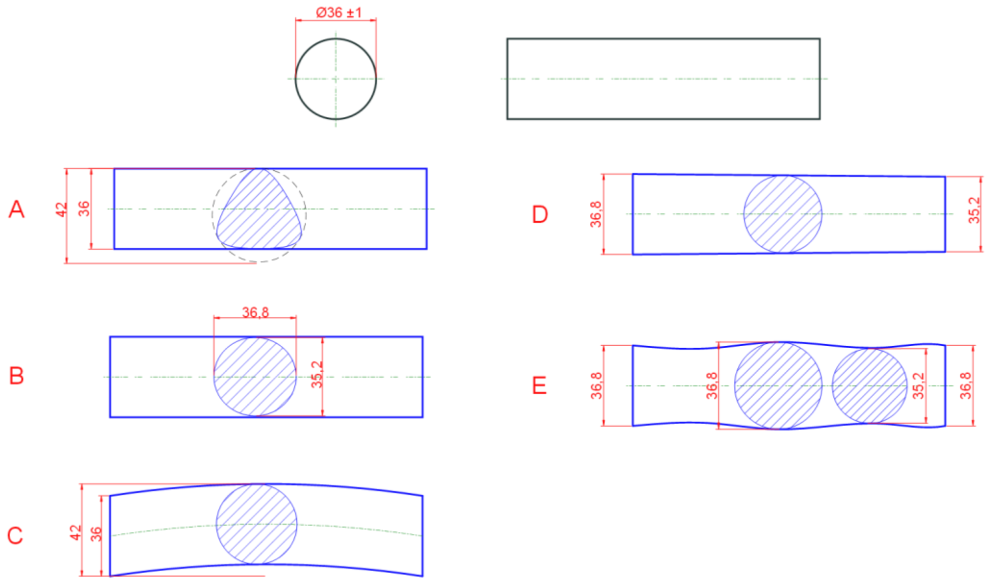

Fig. 1. After processing, a significant form deviation was observed. Which of the following products comply with the specification?

However, it turned out to be an unexpected surprise that question about whether the shaft may be smoothly inserted into the hole (Fig. 2) was correctly solved only by 24% of the survey takers. Moreover, 25% of respondents who provided a correct answer to the question shown in Fig. 1 incorrectly solved the related task on the possibility of assembly. This leads to the conclusion that responders do not fully understand the term "size", and they do not know how to apply this concept in practice. The most dominant incorrect answer states that it is possible to insert the shaft inside the hole because the specified lower limit deviation of the hole and the upper limit deviation of the shaft provide a minimum clearance of 0.1 mm. Concerning ISO standards, this was true until 2010, when ISO 286:1998 was replaced by ISO 286-1:2010 [11].

On the other hand, the assembly is possible without any obstacles according to American Standard ASME Y14.5-2018 [12], which, according to Rule #1, requires that when the shaft/hole is at maximum material size, its form must be perfect. It was clearly stated that the survey is addressed to the ISO GPS system indications and interpretations. Another survey may be aimed at disclosing whether engineers in companies in Poland understand and identify differences between the ISO GPS system standards and the ASME standard. Due to globalisation, both tolerancing systems are used in Poland, sometimes simultaneously within the same company.

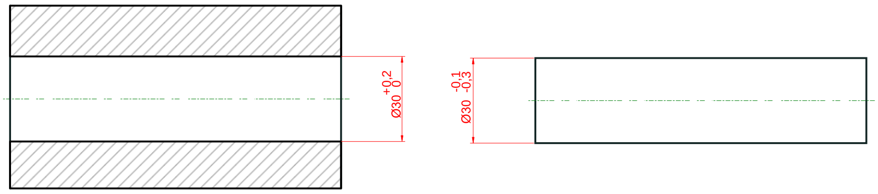

Fig. 2. Does the following specification allow for smooth insertion of the shaft into the hole?

3.3. FORM TOLERANCES

The form tolerance states how far an actual surface can vary from the desired theoretically exact geometrical form. This includes straightness, flatness, roundness, and cylindricity [13]. Regarding flatness (Fig. 3), it was found, that more than half of the respondents are incorrectly using and understanding the terms flatness and parallelism, which is the orientation tolerance. Form tolerance can never be greater than the corresponding orientation tolerance. It seems that a significant part of the respondents, 32% of them, were incorrectly looking for a datum (reference), without considering that form tolerances do not require datums to be specified. The datum indicator on the bottom surface is intentionally left included in Fig. 3 because this drawing is an excerpt from the drawing that contains more geometrical specifications.

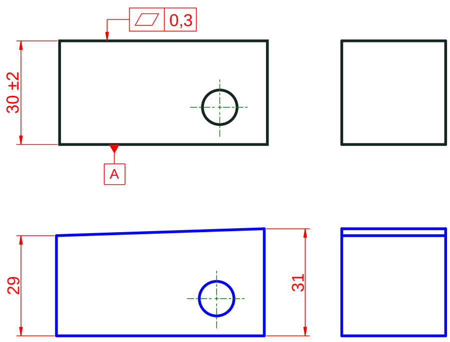

Fig. 3. After processing, the tilted top surface was observed. Does the product comply with the specification?

Parallelism (orientation) controls flatness (form) deviation, but not vice-versa. It shall be noticed that the part height variation is an independent (and fulfilled in the presented case) requirement [10], but 16% of respondents claim that the flatness deviation is equal to 2 mm. So, to sum up, 48% of respondents rely on intuition that assessment of the flatness deviation requires a datum. This is an astonishing and frightening lack of competence! The definitions of form tolerances [13] seem to be quite simple and obvious.

3.4. ORIENTATION TOLERANCES

Orientation tolerance is a geometrical tolerance that determines the orientation of a geometrical feature with respect to a datum or datum system [17]. Despite the relatively simple requirement, only 34% of respondents answered the question correctly (Fig. 4), confirming the conformance of the manufactured part with the specification. This question was expected by the authors to be answered correctly by more than 70% of survey takers. In the analysed case, the specification does not limit surface perpendicularity to any other surfaces (datums) than the indicated datum A. Therefore, the product is correctly manufactured according to the specification. Despite the clear guidelines that all questions shall be answered based only on the tolerances and datums specified on the particular drawing, the number of incorrect answers to this question is puzzling. It is also worth adding that in the next question devoted to angularity requirement, for which perpendicularity and parallelism may be considered as special cases, 39% of respondents were not aware that millimetres are the only units used for the tolerance values in the geometrical tolerance indicator.

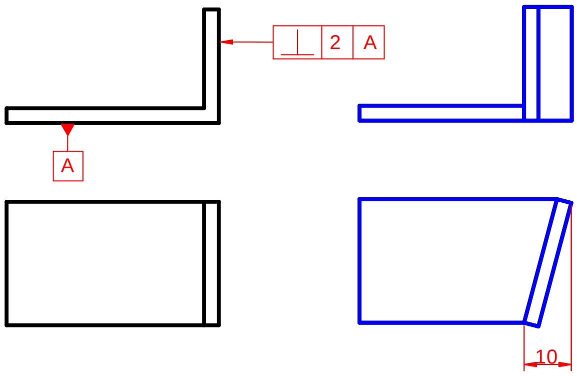

Fig. 4. After processing, the tilted top surface was observed. Does the product comply with the specification?

3.5. LOCATION TOLERANCES

The group of location tolerances covers position tolerance, as well as coaxiality and symmetry tolerances [13]. The position tolerance is one of the most versatile, and it may be applied to control the position of a single feature, such as the axis of the hole or shaft as well as the plane. Moreover, the position tolerance may be used to control a pattern of features [14]. Daily contact with suppliers in the industry has shown that a correct understanding of position indication causes problems even when a single geometrical feature is controlled. Therefore, in the survey, the reversed question is intentionally used twice. One case is shown in Fig. 5. Unfortunately, 79% of respondents replied that the specification in Fig. 5 locates the hole in the plate without any ambiguities, which is not a true statement. Engineers still strongly believe in the correctness of +/– tolerancing for features other than that of the size, which was already definitively criticised as an ambiguous practice in the year 2011 in the previous edition of the standard [15]. The test includes more questions with drawings featuring tolerance indicators that contain the position tolerance symbol, but they are more focused on investigating the correct datum (datum system) indication and interpretation. The survey also contains one question verifying the understanding of the coaxiality tolerance.

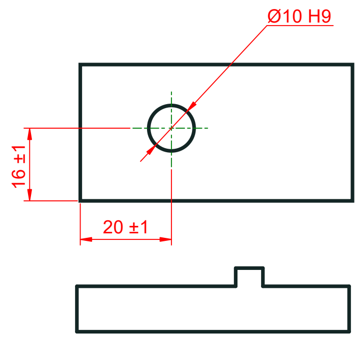

Fig. 5. Is the following specification correct?

The presence of the form and orientation deviations on all real workpieces makes tolerancing with the usage of limit-deviations ambiguous for dimensions other than linear or angular sizes unclear, i.e. results in a specification ambiguity. The dimension 20 ±0,1 seems to be univocally defined in Fig. 6a, but during an attempt at its verification on a fabricated workpiece, several values (x1, ……, x8 and more) could be associated with such ambiguous specifications. Plus/minus tolerancing does not provide a precise specification for verification of the hole location in the plate (Fig. 6b, Fig. 6c).

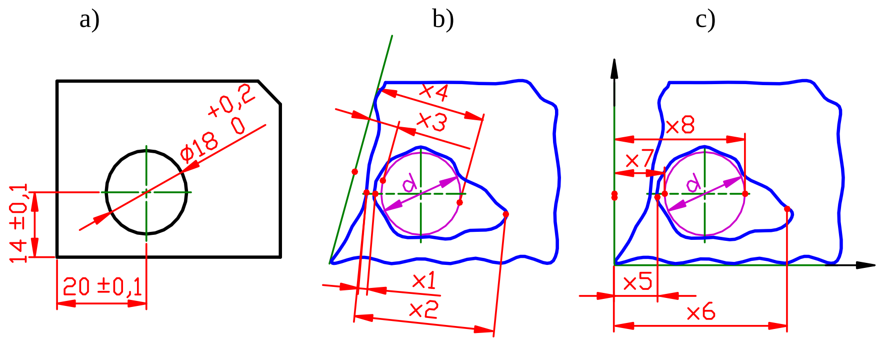

Fig. 6. a) Specification with +/– tolerancing; b), c). The ambiguity of specification with +/– tolerancing for an actual workpiece

3.6. RUN-OUT TOLERANCES

Total and circular run-out tolerances (radial and axial) may be distinguished [13]. The most popular are radial run-out tolerances. Therefore, two questions in the survey deal with circular radial run-out. Circular radial run-out tolerance controls roundness as well as concentricity in any cross-section of the cylindrical surface. We have seen many drawings with the error that occurs in Fig. 7 as it is not specified univocally which datum axis is the reference (is it an axis of diameter 30 ±0,2; 45 h7; 22 m6; or common axis). Only 32% of respondents have replied that the drawing below is ambiguous, although such an indication is shown as deprecated in annexes to the subsequent three editions of ISO 1011, based on the 2004 edition. This result can thus be used to predict that the designers cannot specify their intention correctly (or that they are not even aware that such geometrical deviation exists because the datum is incorrectly indicated) or that quality control can proceed correctly with fixing the product for verification in this incorrect specification case of the 3-step shaft.

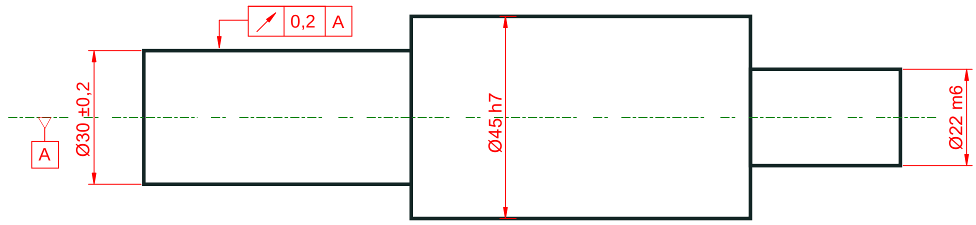

Fig. 7. Is the following specification correct?

3.7. MAXIMUM MATERIAL REQUIREMENT

Maximum material requirement (MMR) [16] seems to be one of the most powerful tools in the ISO GPS system. It is the condition for a feature which contains the maximum amount of material, i.e., the smallest hole or largest pin within the stated limits of size. This tool can provide several advantages for assembly design, such as reducing the cost and complexity of manufacturing and inspection, as parts can have more variations without impacting the functional requirements. This also improves the possibility and reliability of the assembly, as parts can have more clearance or interference to accommodate misalignment, deformation, or thermal expansion. Additionally, this enhances the flexibility and versatility of the design, as parts can be interchangeable or compatible with different mating features or components. It is frequently used, and currently, almost every drawing in the automotive industry contains specifications with MMR. On the other hand, we know that the full understanding of the MMR modifier meaning is scarcely available among the majority of engineers, also because its symbol is not as intuitive as graphical symbols for fourteen geometrical tolerances [13]. Therefore, the simple introductory question (Fig. 8) is formulated in the survey. The ability to correctly indicate the value of the maximum material size (MMS) for the hole/shaft is the condition sine qua non to understand and apply MMR. 66% of respondents indicated MMS = 15.9 mm properly, but it also means that one in three respondents could not identify the correct answer. Unfortunately, only 39% of responders successfully went further and were able to correctly calculate the diameter of the cylindrical plug gauge (Fig. 9). To summarise, only 60% of respondents that properly calculated the maximum material size were able to successfully apply analytical skills regarding the practical usage of the maximum material size. Such a result may be rooted in a lack of proper, concise education in the maximum material size concept. It is puzzling, considering how frequently MMR is specified in the drawings.

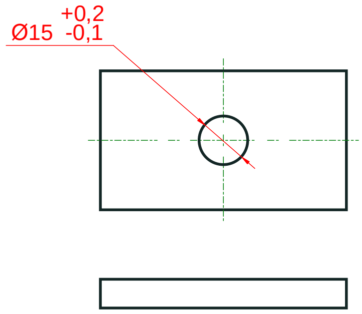

Fig. 8. Maximum material size for the hole is equal: ….

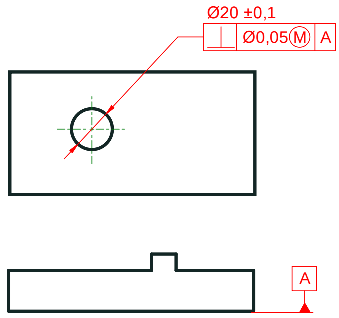

Fig. 9. The diameter of the full-form cylindrical plug gauge shall be as follows: ….

3.8. DATUMS AND DATUM SYSTEMS

The terminology, rules, and methodology for the indication and understanding of datums and datum systems in technical product documentation are given in [17]. Before analysing the results, the difference between datums and datum features is worth mentioning. Functionally, the datum feature is the real (non-ideal) integral feature (real plane, hole etc.) that contacts the counterpart feature during assembly. During measurement, the datum feature is a part feature that contacts a datum. The datum is a theoretically exact feature (plane, axis or centre plane) with respect to which measurements should be made. The datum features shall be selected based on the functional relationship of the tolerance feature to the datum features and, thus, the functional requirements of the design.

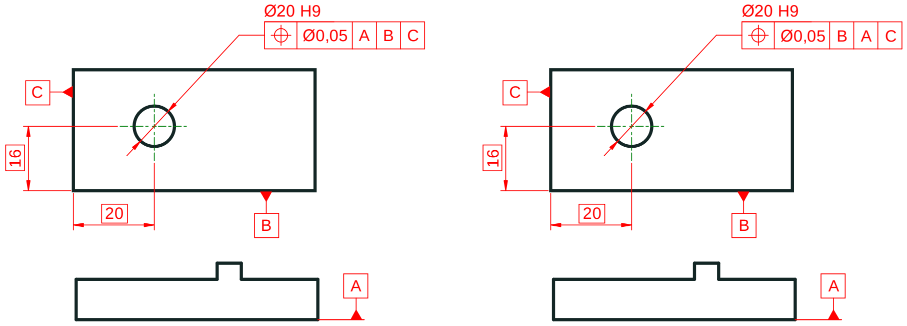

Fig. 10. Are these two specifications equivalent?

To ensure proper assembly, corresponding interfacing surfaces of mating parts should be selected as datum features. An extremely important point, which is frequently omitted, is the understanding of datum sequencing. The order in which datums are specified determines how a part is to be positioned during assembly, which shall be reflected during inspection because, in the real world, parts are not perfect (Fig. 6). Various assembling sequences will end up with different results. The absence of knowledge about datum sequencing among respondents has been identified (Fig. 10). Only 45% of respondents detected that the following specifications are not functionally equivalent and may lead to different results in measurement.

3.9. MEASUREMENT UNCERTAINTY

The issues of geometrical tolerancing are the core of the inquiry. However, bypassing the subject of measurement uncertainty, which is also covered by the GPS matrix model [18], would make the test incomplete. Moreover, it is a topic worthy of a separate study. Measurement uncertainty can be defined as a parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measured length [19].

The measuring of shaft diameters using a callipers is provided solely as an example. The question aims to identify if the responders know how the verification of a shaft diameter, as specified in Fig. 11, shall be performed and what factors shall be taken into account in deciding whether the particular measuring instrument may be applied. Only 29% of participants were aware that it is not possible to determine if the part was or was not produced according to the specification without taking into account the maximum permissible error (MPE) of the measuring device. It is worth underlining that the industry co-author has, in his engineering career, never seen a report where measurement uncertainty was provided. The other co-author has observed measurement uncertainty statements only in reports delivered by accredited laboratories. The need to consider measurement uncertainty is shown in ISO 14253-1:2017 [20], which is also a part of the ISO GPS system and establishes the rules for verifying conformity or nonconformity with a given tolerance. It must also be mentioned that the uncertainty budget contains many components, and to simplify answers to the question in the inquiry, only MPE is listed. Such simplification is intentionally utilized for this inquiry, and it is only valid in relation to measurements made using very simple instruments [21].

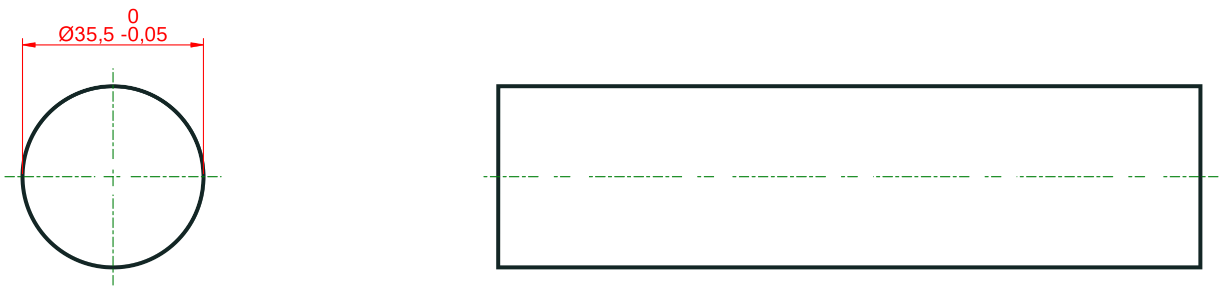

Fig. 11. A digital calliper 0-150 mm with a resolution of 0.01 mm was used for the diameter measurement of the shaft shown in the figure above. The result was 35.48 mm. Does the product comply with the specification?

It shall be underlined that the only universal measurement technique that allows for measurement of both dimensions and geometric deviations is the coordinate-measuring technique, i.e. the use of coordinate-measuring machines [22]. The problem of determining the uncertainty of coordinate measurements is a challenging task. However, attempts are being made to develop a simplified method [23, 24]. The assessment of the capability to estimate measurement uncertainty for coordinate measurements in the industry requires a separate inquiry.

4. CONCLUSIONS

4.1. DETAILED RESULTS OF THE SURVEY

The findings of the survey of practical, applicable knowledge and skills in the usage of the ISO GPS system geometrical tolerancing standards are presented in the paper. Responses given online by 38 surveyors are analysed. The participants were asked how long they have been aware of geometrical tolerances – the average is six years. Only 6% of respondents declared that they have below two years of experience with geometrical tolerances. On the other hand, 21% of respondents claimed they have over ten years of experience with geometrical tolerancing usage.

The test is focused on discovering if responders could identify the limits for the actual geometry of the produced parts set by particular tolerance indicators. Some questions in the survey may seem trivial and very basic for those who are familiar with the ISO GPS system. However, the statistical assessment of the survey results is not optimistic.

The average score of the correct answers calculated for all responders is 45%, with the standard deviation being 16%. The percentage of correct answers calculated for the best four respondents (top 10% of participants), who came from different companies, is 72%, with a standard deviation of 4%. The participants that achieved the best results have mostly seven years of experience with the usage of geometrical tolerancing. The percentage of the correct answers calculated for the worst four respondents (10% bottom line) is 18%, with the standard deviation being 6%.

An interesting fact: years of experience with the usage of the ISO GPS system standards does not evidently go hand-in-hand with good results. This might mean that a significant number of the responders are self-asserted and think their knowledge is better due to their years of experience, which was revealed not to be the case. On the other hand, authors have noticed respondents with relatively better results compared to experienced engineers, considering that they have just started their careers. However, this conclusion can apply to any other competency survey but cannot be treated as a stereotype [21].

The score of correct answers for the question that was easiest for all responders is 87%. The score of correct answers for the question that was most difficult for all responders is 16%. These values confirm that the difficulty of the questions in the inquiry was chosen correctly.

The average result of 45% correct answers, which is the measure of the geometrical tolerancing application proficiency, is relatively low compared to the declaration that 53% of responders have more than five years of experience with geometrical tolerancing. This indicates a weak level of familiarity with the ISO GPS system in the industry. It is important to emphasise that a relatively large value of standard deviation (16%) demonstrates that some individuals know the provisions given in the ISO GPS system standards. On the other hand, there is also a group of people for whom the ISO GPS standards are terra incognita, although taking into account the range of their responsibilities, they should be familiar with the ISO GPS system. There is a significant dispersion of knowledge among the responders.

Generally, the study has shown a low level of understanding of basic concepts related to product geometry-tolerancing set in the ISO GPS system standards. Survey participants too often rely on intuition. It is clearly visible on questions related to the form tolerances and orientation tolerances: inclined surfaces were treated as non-flat surfaces and vice-versa - when answering questions about the form deviations, respondents were incorrectly looking for a reference to a datum. Unlike the humanities, engineering is always based on mathematics and strict rules; therefore, there is no place for intuition here.

The respondents incorrectly understood the terms datums or datum features. The term “dimensioning” is on par with the term “tolerancing”, and some responders see them as synonymous. The incorrect answers to the questions related to compliance with certain specifications are especially glaring. Some wrong answers may likely be attributed to knowledge transferred from older generations of engineers that is not necessarily correct. Nowadays, a belief in the effectiveness of tolerancing with the usage of dimensions complemented by limit deviations still lingers within technical departments. Moreover, the absence of unification between the ISO GPS system standards and the other standards (e.g. extruded profiles [22]) does not make the issue any easier.

4.2. GENERAL CONCLUSIONS FROM THE CONDUCTED RESEARCH

What are the roots that caused these poor results? Is it a complexity of the ISO GPS system or a lack of proper education – both in technical universities and internal vocational training? In Poland, only a few technical universities have geometrical tolerancing courses in their curricula. The content, quality and effectiveness of some in-house vocational training, as well as companies’ internal training materials, are not sufficient.

It is worth mentioning that the authors have also started to investigate the knowledge of engineers outside Poland, mainly in Western Europe and the Asia-Pacific area. “Exit polls” show no significant difference between these regions and Poland, but we still have to wait for full results and lessons learned.

Despite mediocre or even weak survey results, it is worth noting that industrial production is being carried on very satisfactorily across the globe. With new products still appearing on the market, the provocative question may be asked: is the ISO GPS system therefore necessary?

In the same way, the questions and the answers concerning APQP (Advanced Product Quality Planning) may be given. Both, the ISO GPS system and APQP, were developed a long time after the first aircraft took to the air or the first cars hit the roads. However, we do not have access to the production-scrap rate in the early years of the 20th century. Furthermore, the first definition of size was officially published in 1949 in US Military Standard (Mil-Std. 8 1949), after World War II, during which planes, tanks and millions of other military equipment were used successfully.

The point is, that behind growing industrial production hundreds of hours are spent between supplier and customer technical departments discussing unclear drawing requirements (or simply a lack of good drawings), clarifying the geometry of critical function features etc. After reaching a deceptive consensus, the same issues reappear when it comes to determining the procedure of product verification. Those hundreds of wasted hours and funds are caused by the absence of a proper understanding of the ISO GPS language. In extreme cases in the automotive industry, it triggers recalling actions. About 323.4 million vehicle recalls were issued between 2010 and the third quarter of 2019, an 81.8% jump from the previous decade [23]. In many instances, suppliers who do not understand requirements try to achieve a nominal geometry of a product that is unnecessary – excessive additional costs are generated. There still exists the firm conviction that the ISO GPS system standards are needed only for high-tech products.

The survey has also shown positives – in almost half of the companies, one person usually had a significantly higher score than other participants. This person should be identified within the company and given a leadership role in implementing the ISO GPS system geometrical tolerancing standards. Currently, it is challenging to be a design engineer and product definition engineer simultaneously, as progress in each discipline is increasing with every decade. It may be a good approach to follow the idea of a design team that is separate from the product definition and establish a product definition team which specialises only in the proper definition of acceptable geometry variations.

Managers need to understand that the overall production costs can significantly decrease through an improved level of education concerning geometrical tolerancing, which in turn will result in the enhanced use of ISO GPS system standards.

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