On the Influence of Parts´ Materials Properties on the Assembly Orientation

doi:10.2478/mape-2020-0036
Date of submission to the Editor: 03/2020
Date of acceptance by the Editor: 06/2020

MAPE 2020, volume 3, issue 1, pp. 422-434

Štefan Václav
ORCID ID: 0000-0003-3266-3645

Daynier Rolando Delgado Sobrino
ORCID ID: 0000-0001-9253-6141
Slovak University of Technology in Bratislava, **Slovak Republic**

Ivan Zajačko
ORCID ID: 0000-0003-3225-0955
University of Žilina, **Slovak Republic**

Peter Pokorný
ORCID ID: 0000-0002-5804-8061
Slovak University of Technology in Bratislava, **Slovak Republic**

INTRODUCTION

Assembly plays a decisive role in global production in terms of its share in the total costs of the products assembled and in terms of the number of people working in the field. In his publication, (Boothroyd 1991) indicates that the percentage of the workers in assembly out of the total number of the workers in manufacturing in the U.S.A. ranged from 26.3% (bicycles) to 45.6% (automobiles), while the cost of the product assembly represented typically more than 50% of the total costs. This whole situation extends to the case of the Slovak industry, where over the last decades there has been a huge increase on the number of assembly-related positions mainly with the automotive industry and its suppliers.

As also stated by the previous author, despite the above-mentioned importance of assembly in industry, this is an issue that have not been paid adequate and abundant attention until recently. This is especially true for the analysis on how the material of a part impacts on the complexity and laboriousness of its assembly process itself.

In this context, the present paper makes a general analysis of commonly used parts´ materials and their characteristics, and this mainly from the perspective on how these influence the assembly process. Most of the emphasis is to be put on solid parts given their broader use in practice, and in the Slovak Industry. In order to achieve this, several key theories and authors will be analyzed within the paper making emphasis on the role of orientation during the assembly process, while also analyzing definitions like Shape and Symmetry. This

Contact address: daynier_sobrino@stuba.sk

theoretical background will help demonstrating, through a particular case study, how to calculate the laboriousness of assembly for a given piece.

BACKGROUND INFORMATION

This section presents a detailed analysis of key concepts and elements such as materials, shape, symmetry and orientation and elaborates on how these influence the same assembly process.

A take on common parts' materials and their properties with respect to the assembly process

In terms of assembly, important are the features of the components related to handling. Solid, fragile or flexible components are handled in different ways. Examples of parts manufactured of various materials are listed in Fig. 1.

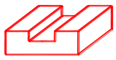
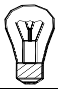
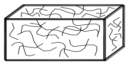
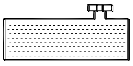
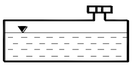
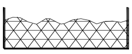
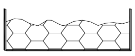
	Material	Example	Efect on assembly
1	**Solid**		**Problem only with orientation**
2	Brittle		Smashing in materials handling
	Abrasive		Abradability in materials handling
	Flexible		Indeterminableness in assembly
3	Gaseous		to ration only
	Liquid		to ration only
	Gelly		to ration only
	Loose		to ration only

Fig. 1 Part as an object of assembly. Classification of material properties of parts: 1 – Solids, 2 – Brittle, abrasive and flexible materials, 3 – Gaseous, liquid, gelly and loose materials

Source: (Václav, 2011)

On the other hand, Free-form components in liquid, pasty, granular or powdery states represent a special group. Their positive feature in terms of assembly is that their assembly handling is simple. Materials are just fed into the assembly cavity or mold. After filling the cavity, the material solidifies, forming a solid component which mostly fills any cavity, regardless of its size and tolerance. Examples include the assembly mounting of semi-conductor elements in epoxy resins in electronics or sealing the glass into the headlight's frames. A special feature of this procedure is that the component is "produced" during assembly, while eliminating the issue of orientation. This includes adhesives, which, after solidification, form a “bonding element” just like a solder and other binders. Adhesives also have remarkable features, such as locking (in screw bonds), insulation or conducting elements (bonding copper wires with carbon brushes for electric motors). Very progressive are multi-material parts made of different materials in different situations. These composite materials are also common in engineering. By varying the structure and density of the filling material (e.g. carbon fiber) in epoxy resins, a light aircraft or a robotic arm can be manufactured with varying strength in different places. The revolution in electrical engineering and assembly in terms of miniaturization was the discovery of the semiconductor effect and its subsequent use in the development of new electronic devices (diode, transistor, photodiode, a semiconductor laser) and circuits (integrated circuits, ICs). The semiconductor effect can be achieved by adding miniature amounts of dotant (e.g. phosphorus) to the base material (e.g. silicon).

The task of “how to invent an invention” is the subject of general methods of creativity, e.g. TRIZ method, from the Russian: teoriya resheniya izobretatelskikh zadatch, equivalent of the English acronym TIPS “the theory of inventive problem solving” (Dung, 2003) . The invention may have originated by applying Value Engineering. However, no single method is enough if the investigator does not possess superior knowledge in the given field (e.g. the invention of laser and the “semiconductor effect”). The invention of a new technology (e.g. printed circuit boards, multi-material component) may also and/or will possibly always have a major impact on assembly.

In this regard, Design for Assembly (DFA) methods can be applied only for the inventions “of the second order” (the principle remains, but a better arrangement is preferred), since they entered the scene, when all competitors had already switched to more favorable inventions.

As shown before in Fig. 1, in terms of assembly, products can be usually divided into three basic groups:

- Group 1: Solid (incl. composite) products,
- Group 2: Products with flexible surface,
- Group 3: Free-form products (Fig. 1).

A product made of flexible parts is for example a wiring harness in passenger cars. The flexibility of cables and undefined shape of the product nearly eliminates the automation of assembly. The solution to this problem may be to find a new invention enabling the transfer of energy from the battery and signals from the panel in other than a wired manner.

Another example are the conductors that are difficult to be handled and oriented by a machine. There is a trend to replace them with solid components (PCB, WIRE WRAP technology, sandwich construction, etc.).

On the other hand, brittle and abrasive components cannot be garbled or vibration-oriented (e.g. light bulbs), as this impedes the possibility of easy and inexpensive automation.

Finally, the most frequently used parts in mechanical engineering are solid ones, as already represented in Fig. 1. These do not require specific special treatment (orientation and handling) in the common assembly machines. However, an unfavorable feature of these parts is the specific shape of each, which poses problems with grasping and orientation in particular (Václav, 2012).

Shape, symmetry and orientation as key elements in the assembly process

In order to better understand the topic, it becomes necessary defining what shape, orientation and symmetry are understood for. These are terms which are all properly and technically explained in (Petráčková and Kraus, 1997).

Shape is a unique spatial arrangement of neighboring areas separating the material of the body from the environment. The areas can be defined mathematically (cylinder, cone, polynomial cam surface). Such surfaces smoothly interlock (having common curves) or intersect at the intersections areas. In exceptional cases, shape is a single mathematical surface (sphere, ellipsoid, i.e. mathematically defined shapes). There are also shapes mathematically undefined, with unknown boundaries of areas, e.g., a bust of a human head). Some of these technical surfaces and mathematically-defined shapes will be discussed further on this paper.

On the other hand, orientation in the most complex cases is the sequential or simultaneous rotation of the body around the axes x, y, z, until the body in the system of the axes x, y, z is oriented from the random to the desired angular position. The shape of the body determines if all three rotations are to be performed or if the rotation around each of the axes must be a full revolution.

Similarly, common definitions of symmetry usually differ in a few details (Petráčková and Kraus, 1997), however they agree that planar shapes may be symmetrical with respect to the straight line, and spatial ones with respect to the plane, while the line and the plane represent the “mirror symmetry”.

Symmetry in geometry is a property of shape, where each point A of the body surface on one side of the symmetry plane has its associated point A* lying on the perpendicular line on the opposite side of the symmetry plane. This is at an equal distance from the plane of symmetry as point A, see Fig. 2a. The definition also applies to space, and in space, a plane is the “mirror symmetry”. On the other hand, in the case of a prism, see Fig. 2c, this is symmetrical with respect to the planes ρ_1, ρ_2, ρ_3, the cylinder with respect to the volume of planes intersecting the axis of symmetry o1, see Fig. 2d, and the ball has three such axes o_1, o_2, o_3, see Fig. 2e. In the specific case of a circle, the symmetry with respect to the axis means that, for a given body, there is an infinitely large volume of symmetry planes passing through the axis of symmetry, see Fig. 2b.

On the other hand, according to various encyclopedia and dictionaries, the word symmetry has different meanings in cosmology, biology, medicine, etc. If the body is symmetrical with respect to the horizontal plane in any orientation, two positions are acceptable: the upper side or the lower side of the body are above the plane of symmetry. This is specially important in terms of the assembly.

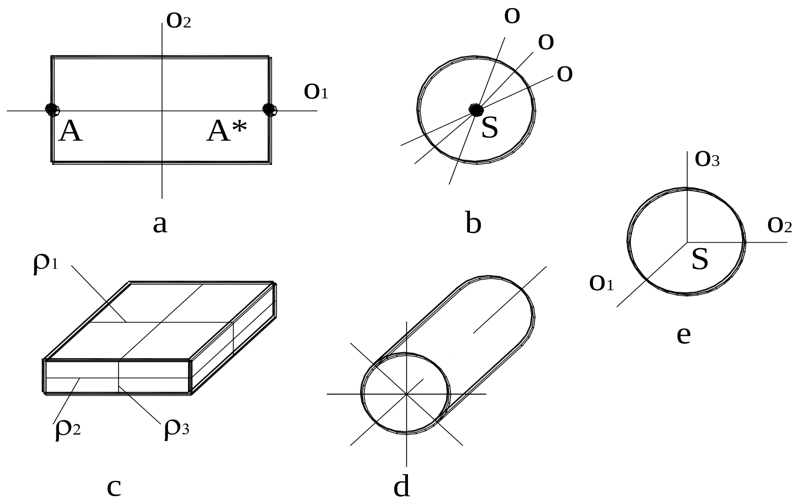


Fig. 2 Part as an object of assembly. Symmetry – basic concepts
a – rectangle; b – circle; c – prism; d – cylinder; e – sphere

If, in addition, the body is symmetrical with respect to another vertical plane, two more positions are acceptable in assembly: when the “front” or the “rear” of the body is on the left of the plane of symmetry. Symmetry reduces the number and size of standard movements. Apart from symmetry, important for assembly are the various relationships between the contour width, thickness and length of the body – slenderness ratios, affecting the percentage of the components falling on a plane and placed on the surface X, surface Y, and surface Z etc.

Key facts about the theory behind the orientation in the assembly process

Unfortunately, the parts from production are usually supplied for assembly in a disordered and disoriented manner. This is the reason why the research papers studying the orientation of components mainly deal with automatic orientation (Bässler and Schumaus, 1988; Boothroyd and Dewhurst, 1983; Boothroyd and Dewhurst,1990; Boothroyd et al. 1982). The first theoretical contributions focused on explanation the shape classifiers and sample solutions of automatic orientation and reported a catalogue of successful solutions (Łunarski, 1991; Johansson, 1989).

However, only some of the papers have tried to arrange the parts according to the degree of symmetry, which is something the present paper makes emphasis on and demonstrate using a practical example based on well-known theories found in the state of the art and practice. As slightly already mentioned before, along with the shape and size of the components assembled, the orientation is also crucial for the performance and assembly costs (Senderská, 2007). Professor Boothroyd was the first researcher to deal with the issue of the component’s orientation and the systemization of the procedure (Boothroyd et al., 2002).

Boothroyd theory

Authors like (Boothroyd et al., 1982) and (Boothroyd and Redford, 1968) concentrated only on the orientation of slender parts of a cylindrical shape. He found the prevalence of two types of symmetry, or asymmetry, so called “α symmetry” and “β symmetry” (imbalance) (Fig. 3). These values are considered as a criterion of assembly complexity.

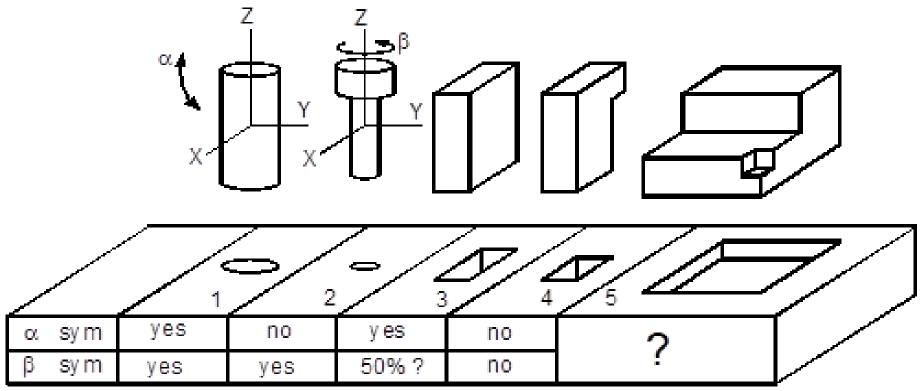
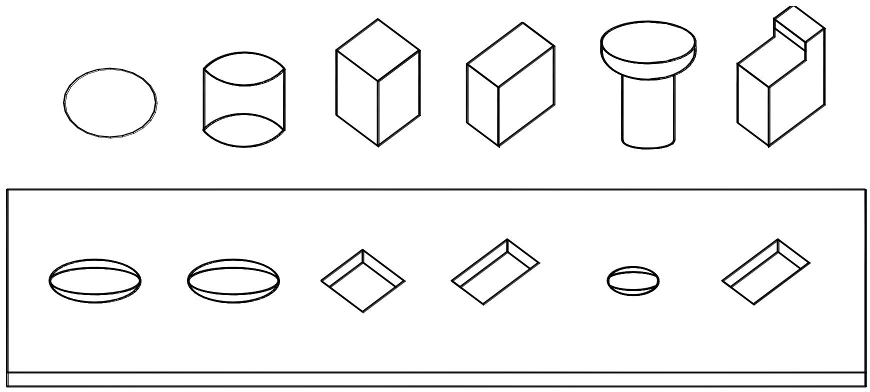


Fig. 3 Boothroyd theory of orientation
Source: (Boothroyd, 1991)

Alpha (α) Symmetry – the symmetry plane perpendicular to the longitudinal axis of the part. Beta (β) Symmetry-the symmetry with respect to rotation of the part around the longitudinal axis. Later, he quantified the “α and β symmetries” (Boothroyd and Dewhurst, 1983) with respect to the required rotation angles in degrees, see Fig. 4.



α	0°	180°	180°	90°	360°	360°
β	0°	0°	90°	180°	0°	360°

Fig. 4 Component as an object of assembly. Boothroyd theory of orientation
Source: (Boothroyd, 1991)

The cylinder in Fig. 3 is “α and β symmetric” and can be nested to the opening by its upper or lower side. When orientating a cylindrical part which has been nested from one side, it is already “α asymmetric” and can be inserted into the opening only by one side. Similarly, other displayed components were assessed; however, the last oriented component could not be measured by the author.

In his work, Boothroyd stated that it was only the beginning of this theory, as it does not apply to the components which are not axially symmetric but are quite general in form. Before the assessment, the same author in another publication (Boothroyd and Dewhurst, 1983) pre-oriented the component so that its longitudinal axis was in the direction of axis "z", see Fig. 4. The component was thus rotated by "gamma symmetry"; its value was not assessed, however. On the other hand, this same author focused on the above-mentioned theory by resolving the orientation of components that are not axially symmetric; i.e. he solved the orientation theory of components of any shape.

Valentovič theory

The work of (Valentovič, 1996, 2000) found that, regarding the three-dimensionality of space, three symmetries should be distinguished for each shape (whether it is slender or not). Each of them can be measured by the number of revolutions (or fractions of a revolution). This author developed a theory applicable for all possible shapes of parts. For example, Fig. 5a demonstrates this for "flat" components. As it can be seen, e.g. a circle does not have to be oriented into a circular hole; it can simply be put into the hole (Václav, 2012).

If it is necessary to insert a square into a square hole, in the worst case a quarter revolution can be taken; if it is necessary to insert a hexagon into a regular hexagonal hole, in the worst case, a sixth of a revolution can be taken. If the shape is quite general, the full revolution is needed in the worst case.

The author of the theory developed the principle for all three views and concluded that in order to assess the complexity and laboriousness of orientation, it was necessary to carry out the operation three times: in a draft view, side view and plan view of the part, see Fig. 5b. The orientation of a sphere in all three views does not need any revolutions, which means that laboriousness is equal to zero. However, when orienting a cylinder, see Fig. 5b, half a revolution in the draft view is needed, half a revolution in the side view and 0 revolutions in the plan view. When orienting a cylinder embedded from one side, 1 full revolution in the draft view is needed, 1 full revolution in the side view and 0 revolutions in the plan view. The Figure similarly explains the orientation of other shapes, even the most complex ones. To orientate the latter components, 1 revolution was needed in draft view, 1 revolution in side view and 1 revolution in plain view.

The above-mentioned theories of orientation consider both big and small parts, and yet the size makes the difference. It is therefore recommended that the given laboriousness is not calculated only by using rotations (Po), but also taking into account the rotary trajectories to be carried out (Ps). When turning a large part, trajectories are greater than when turning a small component.

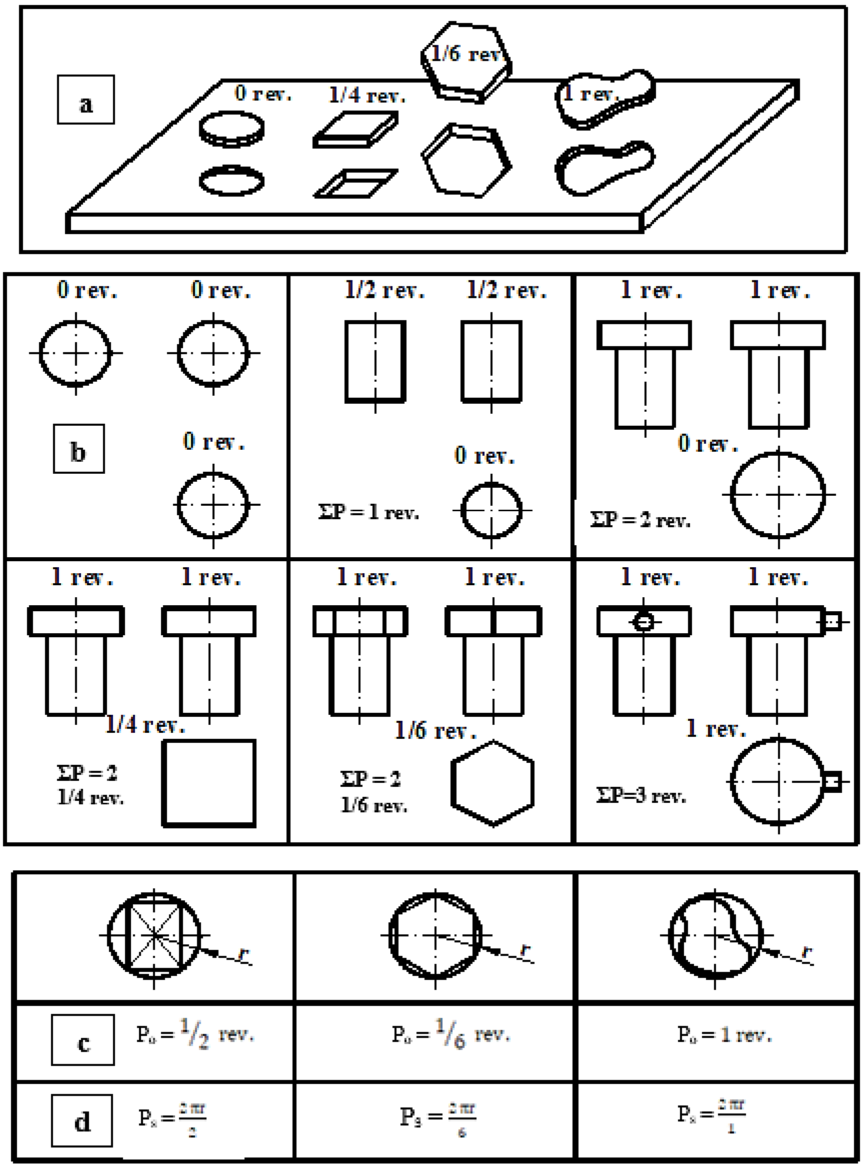


Fig. 5 Laboriousness of orientation and assembly:
a – Orientation in plane measured in revolutions, b – Orientation in space measured in revolutions (P_o), c, d – Laboriousness of orientation (P_o) and trajectory laboriousness (P_S).

The above-mentioned indicates that the laboriousness of orientation (P_O) is the sum of the orientation trajectories of the draft view, side view and plan view as shown in Fig. 5c. This means that according to Valentovič theory, the laboriousness of rotating a rectangle is half a turn. The author recommends that the laboriousness means a semi-circle (Fig. 5d), i.e. it is a path described by a semi-circle. The same applies for other shapes. In this way, the sum of the pathways determines the laboriousness of the given component orientations.

Similarly, Fig. 5d shows how to consider both the orientation and handling dimensions of a component when investigating laboriousness (trajectory laboriousness of orientation – P_S).

RESULTS AND DISCUSSION BASED ON A PRACTICAL EXEMPLIFICATION

The following Fig. 6 illustrates a practical example of the above-mentioned theory, i.e. the Calculation of laboriousness of assembly. The prism is fastened in a clamp, there is a screw to be screwed into the top of the prism, and a pin to be inserted at the side. To calculate the laboriousness of the whole orientation, the laboriousness of all orientation movements will be examined (all movements in terms of orientation) performed within the process of assembly. First, the prism is to be oriented, see Fig. 6, position 1, by ¼ of a revolution before being inserted into the clamp. Closely above the opening, the screw has to be oriented, see Fig. 6, position 2; the orientation can be calculated as described above (2 1/6 revolutions).

The future product must be then turned by 90 degrees, in order to insert the pin from the top, and then the orientation necessary for the pin (1 revolution, Fig.6, position 3) can be calculated again. From the process of calculating the orientation, it is easy to derive:

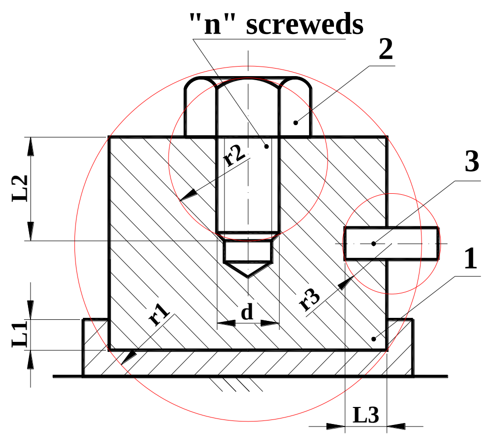


Fig. 6 Laboriousness of assembly, 1 – prism, 2 – screw, 3 – pin

Trajectory laboriousness P_s:

prism: $(\frac{1}{4}2\pi r_1 + \frac{1}{4}2\pi r_1 + \frac{1}{4}2\pi r_1),$ (1)

screw: $(2\pi r_2 + 2\pi r_2 + \frac{1}{6}2\pi r_2),$ (2)

pin: $(\frac{1}{2}2\pi r_3 + \frac{1}{2}2\pi r_3 + 0).$ (3)

Assembly laboriousness P_m:

- prism: L_1 (clamping),
- screw: $L_2 + \pi dn$ (screwing or feed and rotation),
- pin: L_3 (turning the hole for the pin into the vertical position): $\frac{1}{4}2\pi r_1$.

Total trajectory assembly laboriousness P_{cs}:

$$Pcs = Ps + Pm \quad (4)$$

where:

P_{cs} – total trajectory and assembly laboriousness [mm],

P_s – trajectory laboriousness [mm],
P_m – assembly laboriousness [mm].
The above-mentioned suggests that the orientation is a phenomenon typical for assembly and represents up to 50% of the amount of work performed in the process of assembly. It happens in part because the parts are generally supplied for assembly in a disoriented position. On the other hand, when designing a product, it is not necessary to add partial laboriousness; it is enough just to minimize those variables that increase the overall laboriousness.

A few general rules:
1. The shorter the trajectory laboriousness, the better the product design.
2. The total trajectory and assembly laboriousness can be decreased by choosing suitable forms and dimensions.
During manufacturing, the parts are oriented; however, they are frequently just fed into the boxes where they are disoriented again. The following Fig. 7 and the subsequent equation show an example of assessing laboriousness (P) by using graphical methods.

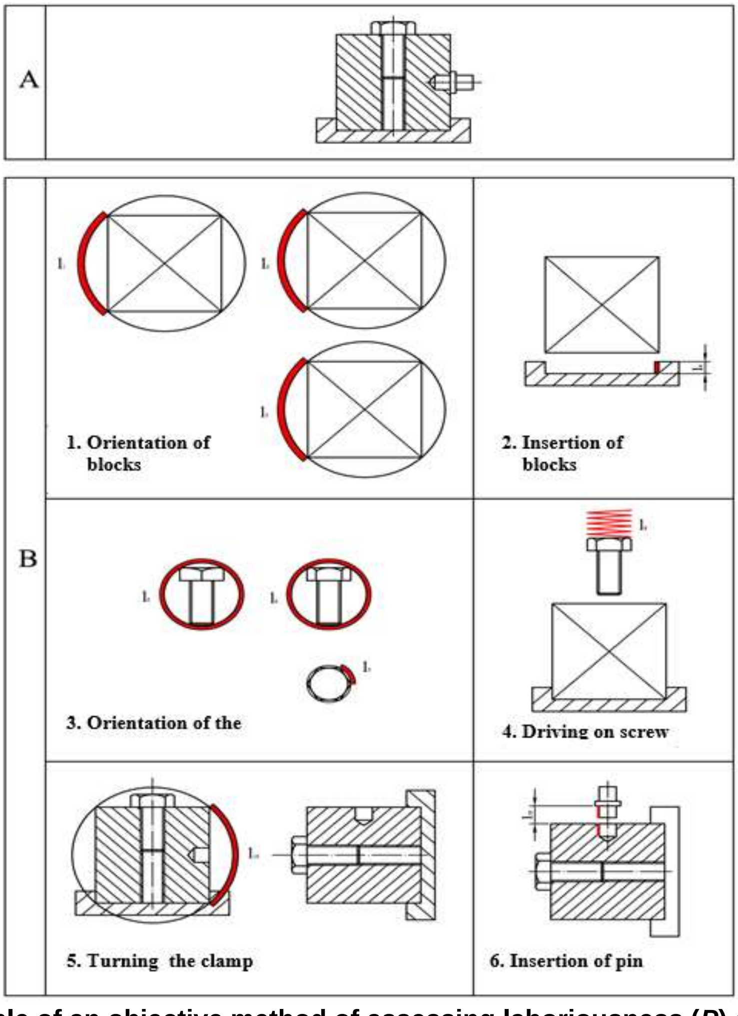


Fig. 7 Example of an objective method of assessing laboriousness (*P*) of assembly A – assembly role, B – examining laboriousness (*P*),

The device shown in Fig. 8a cuts out washers. When using common machines, the washers fall down freely into the hopper. In the machines of the future, the components will not be allowed to fall, instead, they will be oriented in the process of manufacturing and placed in a carrier (palette).

$$P = l1 + l2 + l3 + l4 + l5 + l6 + l7 + l8 + l9 + l10 \qquad (5)$$

where:

P: Total laboriousness [mm], *l*1…10: individual lengths in mm the laboriousness is measured for.

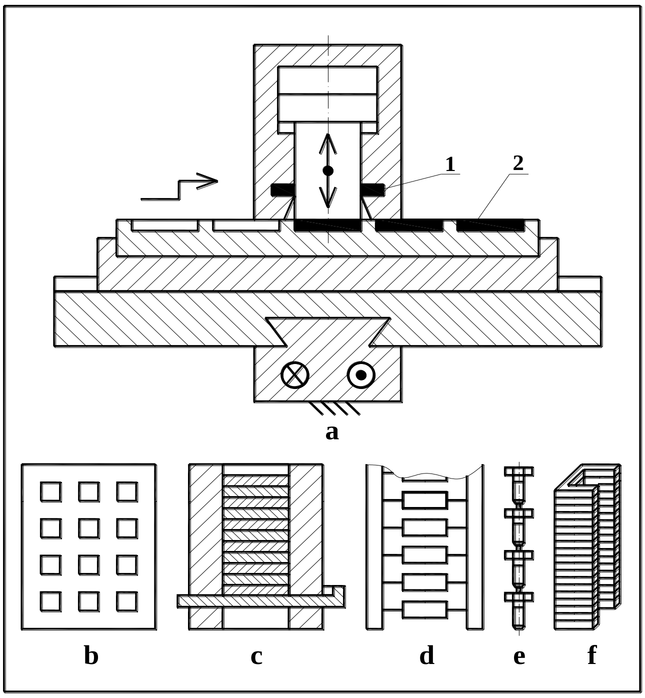


Fig. 8 Manufacturing – assembly system which does not require orientation of parts a – cutting machine cuts out the washers from the tape (position 1) and automatically puts them on a palette (position 2), b – flat palette, c – stack of cassettes, d – tapes with stuck parts, e – screw rod, f – glued clips

In the near future, it is expected that an increasing number of such production machines will be able to supply components aligned to the oriented state e.g. on pallets (Fig. 8b), cassettes (Fig. 8c), tapes (Fig. 8d), screw rods (Fig. 8e) etc. The advantage in the case of screw rods is that the screws are oriented, while their "necks" are screwed off (Fig. 8f), which simultaneously checks the torque.

CONCLUSIONS

This paper made a general analysis of the parts' materials and their characteristics, and the way they influence the assembly process. Emphasis was made on solid parts given their broader use in practice and in the Slovak industry. Several theories and authors dealing with the theory of assembly were analyzed. Emphasis was made on key definitions influencing the assembly process as it is the case of shape, symmetry and specially orientation. A simple case study was used for demonstrating how to calculate the laboriousness of assembly in the concrete case of a given assembly piece. The results of this paper allowed verifying the assumption that the orientation was a specially challenging phenomenon typical for assembly and it represented up to 50% of the amount of work performed in this process, it was also verified the main problem of assembly that states that: the best orientation is no orientation.

ACKNOWLEDGEMENTS

This publication has been written thanks to the support of the research project VEGA 1/0019/20 "Accurate calculations, modeling and simulation of new surfaces based on physical causes of machined surfaces and additive technology surfaces in machinery and robotical machining conditions".

REFERENCES

Bässler, R. and Schumaus, T. (1988). Procedure for assembly – oriented product design. In: International Conference on assembly automation. London: March.

Boothroyd G. and Dewhurst, P. (1983). Design for assembly handbook. Department of Mechanical Engineering, University of Mass. Amherst, Ma, USA.

Boothroyd, G. (1991). Assembly automation and product design. CRC Press, 1st Ed., pp. 2-6. New York: Basel. ISBN 0-8247-8547-9.

Boothroyd, G. and Redford, A.H. (1968). Mechanized Assembly. London: Mc. Graw – Hill.

Boothroyd, G., Dewhurst, P. (1990) Product Design for Assembly, Boothroyd Dewhurst, Inc., Wakefield, RI, USA, (First Edition 1983).

Boothroyd, G., Dewhurst, P. and Knight, W.A. (2002). Product design for manufacture and assembly, New York: M. Dekker.

Boothroyd, G., Poli, C. and Murch, L.E. (1982). Automatic Assembly. New York: Marcel Dekker Inc. 1982.

Dung, P. (2003). Enlarging TRIZ and Teaching Enlarged TRIZ for the Large Public. In: International Conference TRIZCON 2001. [online] California, USA, March 25-27. Available at: http://www.hcmuns.edu.vn/CSTC/home-v.html.

Johansson, M.I. (1989). Product Design and Materials Handling in Mixed – Model Assembly. PhD. Chalmers University of Technology. Göteborg, Sweden. pp. 6-24

Łunarski, J. (1991). Technologiczność konstrukcji maszyn montowanych automatycznie. (Technology od constructions of machines in automated assembly). TEKOMA. Warsaw, Poland.

Petráčková, V. and Kraus J. (1997). Slovník cudzích slov (Dictionary of foreign words). Media Trade s.r.o., p. 863. SPN Bratislava 1997.

Senderská, K. (2007). Automatická orientácia a prívod súčiastok v automatizovanej montáži. (Automated orientation and parts supply in automated assembly), Košice, Slovakia: TUKE Transfer inovácií (Transfer of innovations).

Václav, Š. (2011). Objective method for assembly. Hochschule Anhalt, 1st Ed., 102 p. Germany. ISBN 978-3-86011-044-7.

Václav, Š. (2012). Vybrané state z teórie montáže. (Selected chapters form the theory of assembly) Habilitation thesis. Slovak University of Technology in Bratislava.

Valentovič, E. (1996). Knowing your orientation. Assembly Automation, 2, pp. 31-33. ISSN 0144-5154.

Valentovič, E. (2000). Geometric and static conditions of assembly. Assembly Automation, 3, pp. 233-236. ISSN 0144-5154.

Abstract: The material of a part or component has a decisive impact on the complexity and laboriousness of assembly process. Thus, solid, fragile and flexible parts and components are all handled in a different way. The present paper classifies some of the most common types of materials parts are usually made of, while also analyzing their impact on the assembly process. In mechanical engineering, solid parts are most often used, given that these do not require special measures in known assembly orientation and handling techniques. However, such solid materials pose several challenges as well, and this mainly due to their several specific shapes, which means a specific problem in gripping and especially in their orientation during the assembly process. In this regard, the paper also addresses with one of the most important and assembly-troublesome properties of these solid parts, which the degree of symmetry. The degree of symmetry of solid parts has a direct impact on the complexity and laboriousness of their orientation in assembly. The last part of the paper focuses on the theoretical basis for the calculation of complexity and laboriousness in the assembly of parts.

Keywords: Assembly orientation, Materials of parts and components, degree of symmetry, complexity, laboriousness