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JUSTIFICATION OF THE APPLICATION OF TIGHTENING ELEMENTS IN THE SHAFT- HUB JOINT

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Today, in the small-series production, a universally adopted way of joining the hubs of driving or driven components with the shaft is by using a key. In addition to the basic requirement to be fulfilled by a joint – a reliable transfer of torque with or without axial and radial force – the joint has to have additional technical features (overload protection by slipping,, changeable rotational direction, axial and radial adjustability, centring accuracy, radial clearance, etc.) and has to meet economic requirements. An increasing number of practical hub-shaft joint applications using friction and tightening elements in particular, prove that the usage of aforementioned method is in expansion. This can be attributed to the development of innovative types of tightening elements with reduced manufacturing cost and production time.

Key words: hub, shaft, frictional joint, tangential joint, tightening element

Opravdanost primjene spoja glavčine s vratilom steznim elementima. Kao univerzalni način spajanja glavčine pogonskih ili gonjenih elemenata s vratilom, danas se najčešće primjenjuje, u pojedinačnoj i maloserijskoj proizvodnji, spoj perom. Pored osnovne funkcije spoja, da opterećenje momentom vrtnje s / bez uzdužne i poprečne sile prenese pouzdano, od spoja se traže i dodatne tehničke (posljedica preopterećenja, promjena smjera vrtnje, uzdužna i kružna podesivost, točnost središtenja, kružna zračnost, deformacije i dr.) i ekonomske značajke. Veliki broj primjera u praksi spoja glavčine i vratila trenjem i to prvenstveno steznim elementima daju spoznaju da je navedeni način u ekspanziji, što je posljedica razvoja novih oblika steznih elementa, nižu cijena spoja u konačnici uz kraći rok isporuke.

Ključne riječi: glavčina, vratilo, spoj trenjem, tangencijalni spoj, stezni element

INTRODUCTION

Standardized methods of power transmission and motion transfer use different elements, such as keys, wedge-shaped shafts, polygonal shafts, and lateral pins to join the hub of driving or driven elements with the shaft, or make use of friction connections (cylindrical tightening connection, conical connection, tightening elements).

Nowadays, the key is accepted as a universal joining method most frequently used in the production of single items and in the small-series production. A machine industry survey has shown that approximately 60% of all hub-shaft joints are based on the keys.

Although the analysis of the hub-shaft joints should be impartial and objective, we cannot avoid the impact of engineering tradition. The choice of the joint type in practice is typically reduced to copying old solutions, adopting someone else's standards, using solutions without a thorough analysis or "ad hoc" solutions which are appropriate to the current technical and economic situation and to the available time. Such choice can be hard to justify because a consequence of such an impulsive approach is the fact that the designer's creativity is reduced, his/her independence is lost, and it may even create a lack of confidence [1-3]. The joints based on keys are often inadequate in meeting increasing demands for higher durability, material savings, energy and labour savings or assembly simplification. The keyway created on both elements of the joint reduces the load-bearing cross-section of the joint and increases the production cost. Its sharp curvatures increase stress due to the cutting effect. Thus, in order to achieve sufficient joint strength, the diameter and the length of both the shaft and the hub have to be increased.

TECHNICAL REQUIREMENTS IMPOSED ON THE JOINT

Besides the transferable torque with or without the axial and the radial force, as one of the fundamental joint requirements, additional technical specifications and economic requirements need to be defined for each individual joint. The information collated for each proposed solution in the form of qualitative and quantitative data and features commonly yields only a subjective assessment of the joint under consideration. There is no con-

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cept of an ideal hub-shaft joint, i.e. the one in which the hub and the shaft form a unit and are manufactured as a single unit. In that case we are talking about the shaft with a transfer element. Additional technical requirements, such as the ability to cope with overload, changes in rotational direction, centring (rotation accuracy) with and without additional elements, axial and radial positioning, radial clearance, etc., are typically analysed in conjunction with economic requirements, such as reduced weight, low production cost, easy assembly and disassembly, replacement possibilities, recyclability, etc. Empirical and/or literature-based information collated in accordance with additional requirements is often insufficient for a comprehensive analysis. In the proposed solutions that have practical applications, certain features must be quantitatively described in the evaluation as “small - medium – large”, “possible - conditional – impossible”, “yes – no”, and similar. In this way, particular joint solutions are graded by quality, thus pointing out the advantage of one solution over other potential options. As that advantage has a crucial influence on decision making, all decisions, need to be based on objective data in order to fulfil the requirements imposed on the joint.

ECONOMIC REQUIREMENTS IMPOSED ON THE JOINT

A large number of practical decisions are based on economic factors, or in other words, on how to meet the basic requirements at a minimum cost, or how to achieve the best performance with the available means. The economic evaluation is reduced to the cost analysis as an accepted criterion [1]. The cost analysis is performed by the evaluation of manufacturing costs, the costs of joint materials and the costs of assembly / disassembly.

Material costs of joint components

The joint component parts are the main contributors to the overall cost. They include the shaft and the hub, and the transfer elements (in the case of indirect power transmission and motion transfer) as well as auxiliary structural elements (nuts, bolts, flanges, etc.). The analysis of a comparison of dimensions of the joint using the key and those of other types of joints [4-6] can show the cost of a particular material used in the joint and can help estimate potential savings.. For joints with tightening elements [6], an increase in the shaft diameter increases material savings (Figure 1). Using the same principle, hub material savings are evident. However, quantitative data can only be obtained by analysing specific cases. For shaft diameters ≤ 25 mm, the joints using the key can have smaller hub dimensions, and therefore reduced mass, due to the auxiliary component inserted into the hub.

The specific torque c_T (Nm/kg) is used in the assessment of the joint performance vs. material. Clearly, the best ratio is achieved for joints that can transfer maximum torque with the minimum mass of joint components. Hub-shaft joints using the key have c_T = 400 - 700 Nm/kg, whilst joints with two keys – 2 x 120 ^{0} have c_T = 800 - 900 Nm/kg. For the joints using standardized tightening elements, the value of specific torque is c_T = 1500 - 3500 Nm/kg, depending on the number and type of embedded components.

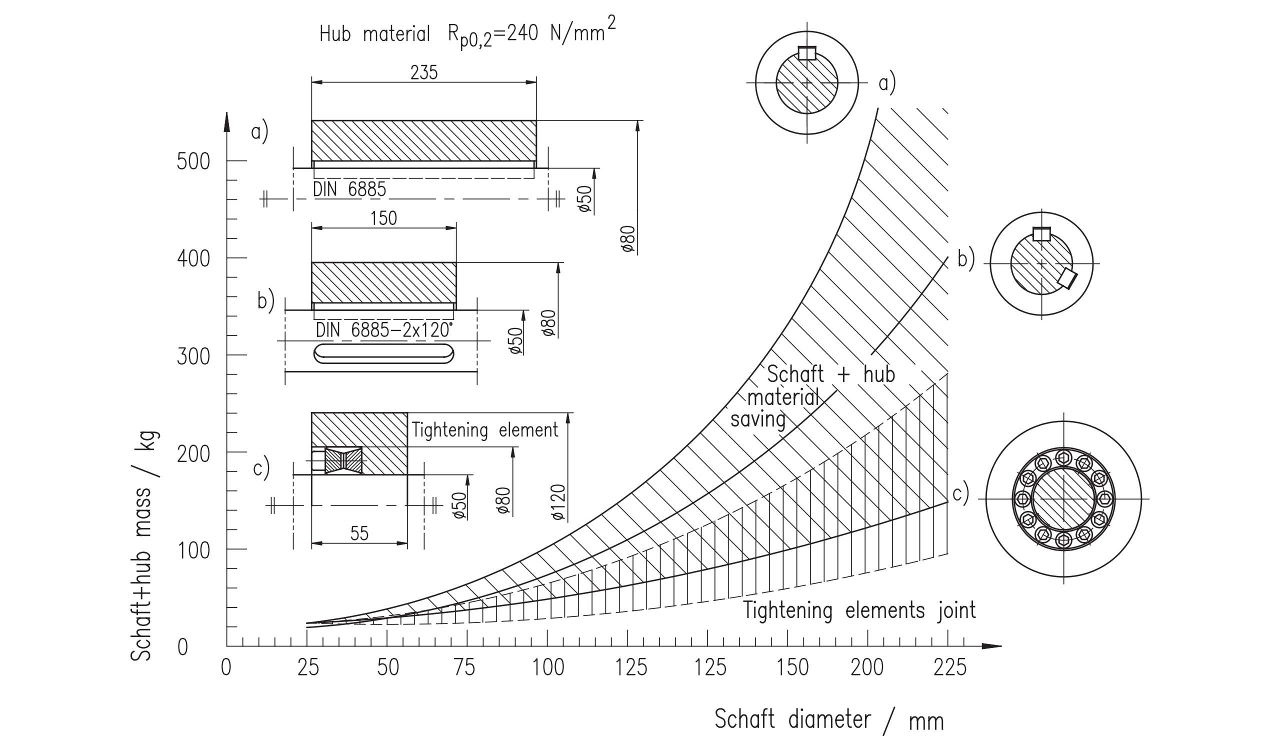

Figure 1 Hub and shaft material savings for different joint types

As the hub-shaft joint, with or without intermediate components, is always a part of a structure, the analysis of that particular structure can identify the areas where material savings in the shaft-hub joint manufacture can be achieved.

Quality of the material of joint components

In addition to the analysis of the quantity of the materials used for the manufacture of the joint, it is inevitable to include the analysis of the quality of the materials. The quality of the material used for joint components (R_m, $R_{e(p0,2)}$) has a direct impact on the joint mass reduction, and, as a result, this reduces or sometimes increases (as in the case of using unsuitable or expensive materials) the cost of the joint manufacture. Figure 2 shows relative joint material costs [7]. It can be observed that using steel alloys, such as 42CrMo4 (Č4732) and 34Cr4 (Č4130), or cementing steels, such as 16MnCr5 (Č4320) and 15CrNi6 (Č5420), results in considerably lower relative costs per unit strength compared to the construction steels, such as S235J (Č0361) and E295 (Č0545), and to carbon-based steels, such as C22E (Č1330), C30E (Č1530), etc. As a direct consequence of using better quality materials, the mass of the hub-shaft joint component is reduced, resulting in lower overall cost.

Manufacturing costs of joint components

The cost of manufacturing is determined by the technical requirements which determine the technology of production [8] and control, the number of parts to be produced in a series, as well as the ancillary expenses incurred in the product development and design, in the transport, maintenance, and depreciation of the machinery, etc. The criterion of efficient manufacturing includes the cost of material in the first place, but also the manufacturing costs of component parts, which have to be reduced within the limitations posed by the available machines and the available manufacturing capacity or by design processes (new designs or adapted designs). Expenses related to assembly and disassembly, reproducibility and recycling of the joint can only be determined indirectly from its features or from suitable analogies [9, 10]. The choice of implemented production technology is directly related to the number of parts to be produced, whilst the ancillary costs are constant irrespective of the number of parts in the series. Production of a single item is the most expensive, hence it is rarely studied. Within small-series production, manufacturing costs can be significantly reduced using standardized, readily available joint components. Prices of tightening elements have been on the decrease in the past 10 years, in some cases by as much as 50 % due to the mass production and large-series production (for the standard shaft diameters of the order R20, according to DIN 748). Cylindrical tightening elements, due to their low manufacturing costs and their automated installation, have made standard tightening elements redundant in mass production (e.g. automotive industry).

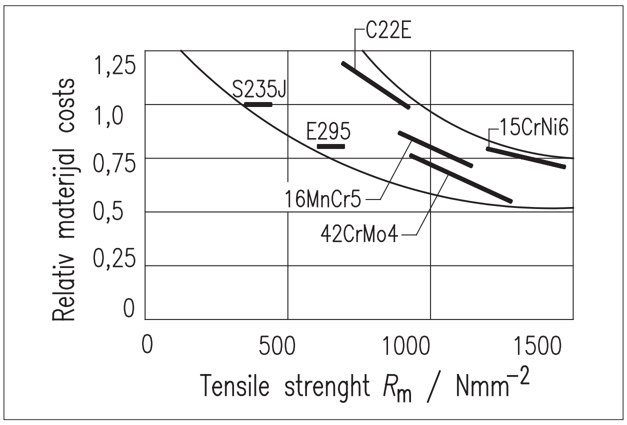

Figure 2 Impact of material strength R_m on the relative joint material cost

Impact of dimension tolerances

The inner hub bore and the shaft are usually cylindrical rotating members which establish a friction joint due to the action of frictional force and/or provide the centring of joint components relative to each other. It is very expensive to produce joint components with very precise dimensions, so every designer knows that meeting close tolerances for shaft and hub bore is costly. As a result, the design process has to be reduced to the motto "as little as necessary". Research into the relation between the manufacturing costs of the hub bore and the shaft [11, 12] and the achieved tolerances shows that the manufacturing costs (Figure 3) are increased by two times to 15 times (tolerance IT4) when compared to the IT11 ISO standard tolerance achieved by drilling. It is

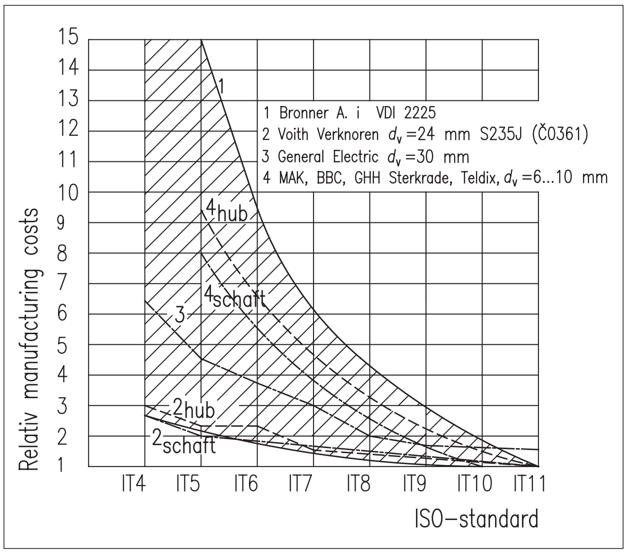

Figure 3 Relative manufacturing costs of the hub bore and the shaft in accordance with ISO standard [7]

therefore necessary to analyses each individual manufacturing cost, especially in the large-series production and mass-production.

The cost of tighter tolerances, as a fraction of overall manufacturing costs of a joint, increases with the diameter. The tolerance demanded by the designer dictates the production process, hence directly influences the overall manufacturing costs of the shaft and hub bore. For each technological process there is a limit of achievable tolerances and surface roughness. Therefore, industry standards provide guidelines on achievable tolerances for each production line and on a set of machine tools to be used.

Impact of surface roughness

Even though there is a close link between the surface roughness and IT quality for a certain range of tolerances, the designer often stipulates unnecessarily low surface roughness or, due to his/her lack of knowledge on the final functionality, unacceptably high surface roughness. The cost of achieving a specific surface roughness is affected by the same factors as the dimension tolerance, i.e. small roughness (smoother finish) is analogous to the tight tolerance, yielding the increased manufacturing cost [13]. The finer surface finish with surface roughness of R_Z = 3,2 – 12,5 μm achieved by turning is related to a much lower manufacturing cost of joint components, whilst parts with $R_Z \leq 25\ \mu$m have a lower relative price of machining which is ≥ 1 (Figure 4). The surface roughness of parts with large dimensions does not dominate their overall cost. However, if the designer demands a specific surface treatment (e.g. glass-surfacing, shot peening or polishing), the additional cost thus incurred has to be considered, irrespective of the part dimensions.

Cost of joint assembly/disassembly

The direct cost incurred by assembling and disassembling a joint with a small number of parts, with low or medium complexity of the process, can amount to as much as 20 % of overall joint manufacturing cost. For the assembly of systems with a large number of parts and/or high complexity this share increases up to 40 % of the manufacturing cost. Joints made by using a small number of parts with similar or identical assembly requirements can be substantially automated in the large-scale and the mass production, indirectly affecting the choice of standard joint type (e.g. standardized tightening joint in automotive industry). Subsequent and additional processing and tucking in of incomplete parts, unsuitable dimension tolerances and errors in shaping and positioning account for up to 43 % of all assembly activities (Figure 5) [9, 10]. The design requirement „tuck in on assembly“ is in principle very expensive in

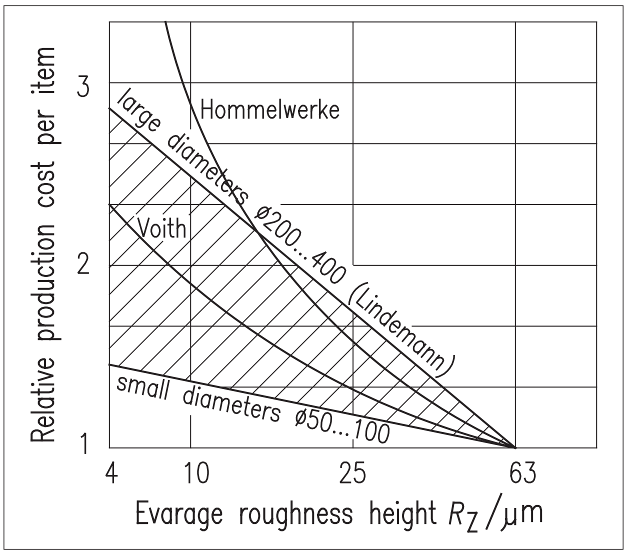

Figure 4 Impact of surface roughness on relative manufacturing cost by turning

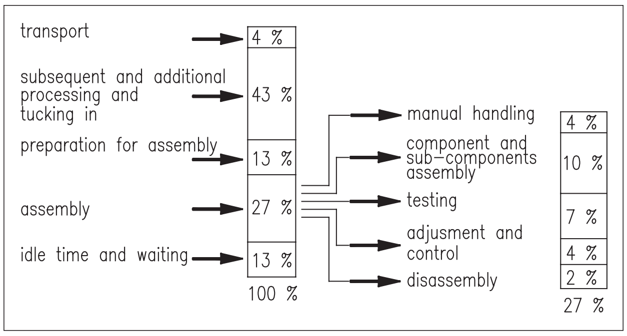

Figure 5 Assembly activity structure in the single-item and the small-series production

practice, and results from unsuitable tolerances of the components in the assembly sequences. The actual process of assembling components into u unit accounts only for 10 % of overall cost of the assembly.

Therefore, the designer in collaboration with the foreman (production line manager), has to analyse and produce a detailed plan for the sequences of the part, component and sub-component assembly, has to specify the standard and special tools, machinery, measuring and control equipment to be used, and the final testing methodology in order to minimize the assembly costs.

CONCLUSION

In addition to the quantity of materials used to manufacture the shaft and the hub, the cost analysis has to include also the quality of materials used. The quality of component materials has a direct impact on the joint mass reduction and on the manufacturing cost which can be decreased or increased in some cases as in the case of using expensive and unsuitable materials.

The joint manufacturing cost is also determined by technical requirements which affect the choice of manufacturing technology, assembly process, and quality control, by the number of parts in a series as well as by ancillary production costs.

It has to be emphasised that due to their simplicity, cost-effectiveness and the ability to transfer larger torque (i.e. larger torque per unit mass of finished product Nm/kg) tightening elements are increasingly more often used in the single-item and the small-series production than the conventional shaft-hub joints. The decision on which joint type is to be used for each individual product rests with the designer, but economic factors (material savings, manufacturing costs, assembly and disassembly time) have to be considered. Cost reduction of up to 60 % in the manufacture of friction joints using tightening elements compared to joints established on the basis of shape is not an unrealistic prediction since the decisions on about 60 – 75 % of overall production costs are made during the design phase.

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