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BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

FACULTY OF MECHANICAL ENGINEERING

Department of Machine and Product Design

Author:

Soós, Enikő
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DEVELOPMENT OF SELF-CUTTING SCREW JOINTS

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Supervisor: Dr. Goda, Tibor

External consultant: Prof. Dr.-Ing. Rainer Renz

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Introduction

Polymer and fiber-reinforced polymer components have been used frequently in various industries in recent decades. Today, plastic and composite materials are preferred to be used not only as materials for cover but as materials for structural components as well due to a broad range of options for processing and utilization. Plastic machine components are gaining importance in the automotive industry as well. One of the reasons for this is that they are much cheaper than metallic materials in many cases; on the other hand, they are extremely lightweight, thereby total vehicle weight is reduced, resulting in improved fuel consumption. Consequently, novel and economical joint types to be applied to plastic components have also appeared, making research thereon important as well. The economy of joints is increasingly coupled with recyclability as a high priority. Self-cutting screw joints are specially suitable in terms of both economy (only a hole needs to be made on the component) and recyclability as no further dismounting operations are required after removing the screw.

The applicability of this joint type is prejudiced by the fact that the pretightening force generated in the joint is changing due to the time- and temperature-dependent behavior of the plastic component and the differences in the thermal expansion of plastics and metals. Physical processes within the screw joint in the course of different operational states can be properly illustrated by simplified models. Various screw manufacturers have made considerable attempts in recent years to provide their clients with as accurate information as possible on producing a screw joint and the screw to be selected. There are supporting softwares based on an experimental database which can forecast pretightening force changes in a given material pair by taking loads in time and temperature into consideration. Nevertheless, constructors still fail to get a picture how a plastic component involved in a joint is deformed, and how its deformation affects the rate and way of changes in the pretightening force. Specialists involved in the production of self-cutting screws have long demanded a numerical model to follow both pretightening force relaxation and the stress and deformation states of the entire construction in the different phases of screw joint operation. In spite of promising attempts, however, no FE model has been developed so far to meet these expectations. One of the major deficiencies of FE models are highly simplified material models. This phenomenon can be mainly explained by the fact that the material properties available – let them be literature data or manufacturer’s specifications – are not accurate and extensive enough to be able to develop a complex FE model. Not to mention that verification of the numerical model itself poses great difficulties.

Yet, speedy developments in digital technology have opened new ways in the testing of plastic components as well. High-resolution cameras can be used for testing components without contact and destruction in dimensions ranging from a millimeter to several meters, at practically arbitrary loads. So in the case of self-cutting screw joints, for instance, not only the impact of the pretightening force can be tested by the methods available but the deformation state of the plastic component as well.

Objectives and main issues examined

This study aims for an experimental and numerical examination of self-cutting screw joints applied to plastic components in order to find answers to the following questions:

- To what extent and how do changes in the pretightening force developed in the joint as a result of mechanical and thermal loads come about, together with changes in the deformation state of the plastic boss?
- What factors and how do they affect changes in the pretightening force and in the deformation state of the plastic boss?
- What is the correlation between pretightening force and boss deformation?
- How is the pretightening force affected by material selection, material non-linearity, fiber orientation in case of short glass fiber reinforced plastic, and the circumstances of installation?
- How is it possible to model the time- and temperature-dependent material behavior of the plastic boss?

The stress and deformation state developed in a self-cutting screw as well as changes in the pretightening force in function of time and temperature can be examined both experimentally and numerically. Processes within the joint during different operational phases such as screw-in, pretightening, heat-up, holding, cool-down, loosening and screw-out can be examined individually as well by numerical simulation. It is somewhat more difficult to analyze these processes and other parameters affecting joint operation by experimental testing. The main aim of FE analyses was to create an FE model to follow the complex material behavior of the plastic boss. In other words, my objective was to develop a modeling technique suitable for examining physical processes in self-cutting screw joints.

Critical review of literature

Having examined the literature in the subject, it can be stated that a number of studies discuss the analysis and optimization of the tightening torque. Several theoretical models have been created, examining tightening torque in function of screw displacement ([1]). These analytic models are based on major simplifications not only in terms of geometry but also in regard to material behavior and physical processes occurring. Theoretical models on the simulation of tightening torque have been verified by experiments as well; however, behavior following the tightening of the joint cannot be examined by these models any longer.

In [2] an axial symmetric FE model is used to model screw-in and pretightening. As regards the material properties used, it should be mentioned that neither the time and temperature dependence of mechanical material properties nor the temperature dependence of thermal properties are taken into consideration by the author. In view of the real behavior of plastics, the applied elastic-plastic material model independent of time and temperature can be considered as a significant simplification of real behavior.

In [3] the threads of the screw are also modeled by concentric rings, but the radial and axial position of rings can be controlled separately. The mechanical and thermal characteristics used in their FE model are basically temperature-dependent, but the dependence on time of material behavior is not taken into consideration in the elastic-plastic material model used. The impact of time is only taken into consideration for yield stress, so this material model can model the time-dependent behavior of plastics only approximatively.

[4] proposes a 1/8 FE model instead of the axial symmetric approach to model screw-in process, which, however, does not allow for the investigation of thermal phenomena due to considerable calculation demands. The elastic-plastic material model applied is not suitable in this case, either, for modeling temperature-dependent material behavior [5].

My work was assisted by further important studies ([6], [7], [8]), primarily imparting measurement results on the actual behavior of self-cutting screw joints. They are mainly characterized by the fact that they examined screw joints assembled with bosses made of various materials at different load levels and drew valuable conclusions on pretightening force relaxation.

In summary, it can be established that none of the FE models in the literature on self-cutting screw joints take into consideration the simultaneous time- and temperature-dependent material behavior of plastics, therefore they are not suitable for investigating time-dependent phenomena (relaxation, creep, elastic-plastic behavior depending on deformation speed).

As regards the experimental testing of self-cutting screw joints, it can be established that studies available in the literature only discuss the measurement of pretightening force reduction, the failure modes, and the impact analysis of simple thermo-mechanical loads. They do not include investigations on the impact of complex thermo-mechanical stress- and deformation-states of the plastic boss.

Therefore this PhD thesis focuses on the following two main areas:

- A series of systematic experiments to better understand real behavior.
- Development of an elastic-plastic (viscoplastic) material model suitable for modeling time- and temperature-dependent material behavior and integration thereof into a finite element environment.

Testing methods

In the course of my work, I traced pretightening force changes in the joint and deformation states along the surface of the plastic boss in different operational phases (screw-in, pretightening, heat-up, holding, cool-down, loosening, and screw-out) at various temperatures. The former was performed by a load-cell, and the latter by a new type of optical deformation analysis, the optical grating method. In order to better understand and separate physical processes, the screw joint was examined in three different test arrangements. The first scenario included a real arrangement of the self-cutting screw joint. The second one included an arrangement where the head of the screw is not seated on the end face of the boss, so boss compression can be avoided and only the tightening impact of threads and thermal expansion prevail. In the third case, the impact of threads was excluded by a bolted joint (here only boss compression had to be taken into account). Heat-up to various temperatures, cool-down and relaxation processes were also examined separately. Joints in the different arrangements were subjected to cyclic thermal loads. It was a special challenge to design the test arrangement and to find the optimal placement of add-on equipment (e.g. furnace, screwdriver) in order to be able to perform optical measurements as effectively as possible. Although there was some information on earlier, rudimentary measurement arrangements, it was not taken into consideration in respect thereof that results should be used later on for FE calculations; therefore the joint had to be practically designed under boundary conditions to be accurately reproduced in modeling as well.

In addition to cyclic thermal loads, the simple process of heat-up / holding / cool-down was also examined in the various test arrangements. The impact of boss material on the pretightening force produced in the joint was also investigated as measurements were performed on a matrix material (PA6) in addition to a PA6GF30 material.

In order to facilitate numerical simulations, experiments were also completed to determine composite material properties. As the boss is predominantly compressed in the joint, material properties were determined by compression tests. It should be mentioned here that measurements at various temperatures were not performed on standard specimens but on form specimens made of the plastic boss I used in screw joint tests. Thereby differences in the geometry and fiber orientation of specimens used in experimental tests and of actual structural components can be eliminated. Besides, composite fiber orientation was also studied using cross-sections and scanning electron microscopic images of the boss.

In the course of FE modeling, both the viscoelastic and elastic-plastic behavior of the composite were taken into consideration. A 40-term generalized Maxwell model was used for modeling viscoelastic behavior and viscoplastic behavior was modeled by FE simulation based on an ”overlay” technique.

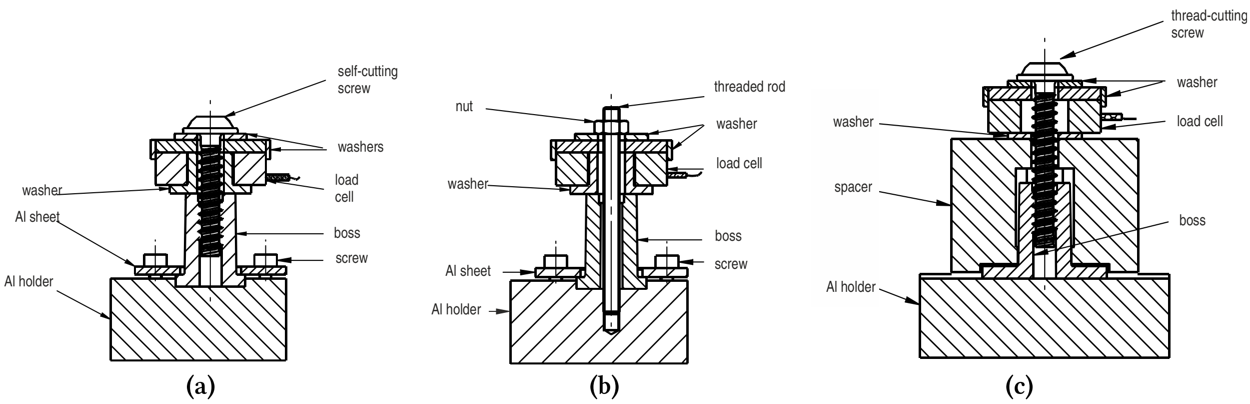

Figure 1. Test arrangements examined: (a) self-cutting screw joint, (b) bolted joint, (c) self-cutting screw joint (without boss compression)

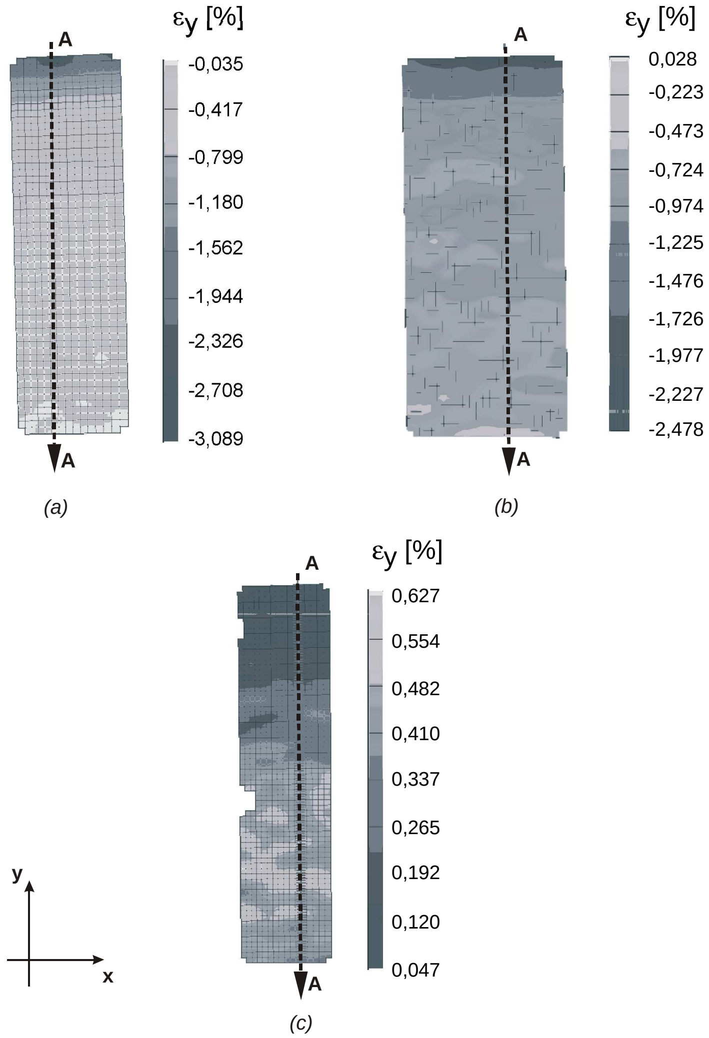

Figure 2. Axial deformations on the boss surface (a) self-cutting screw joint, (b) bolted joint, (c) self-cutting screw joint (without boss compression)

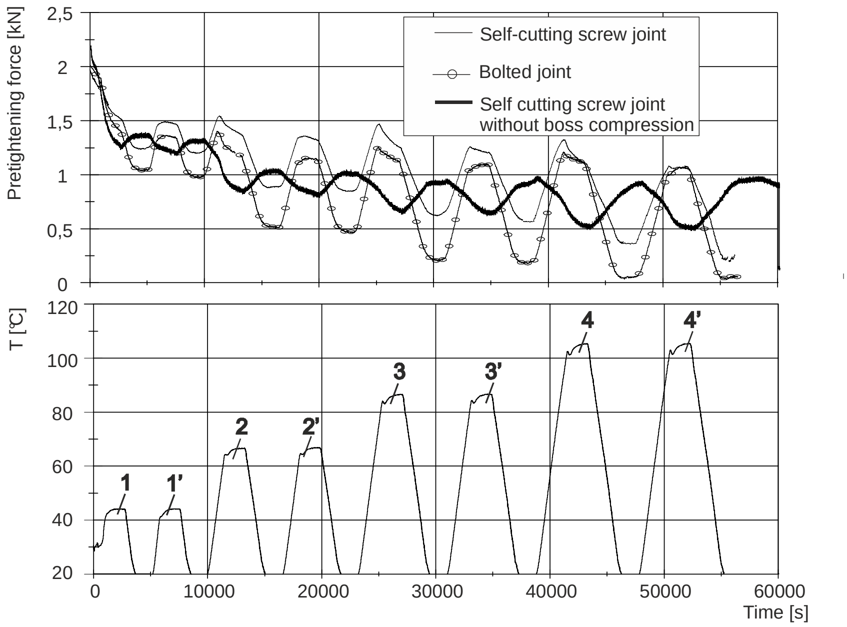

Figure 3. Changes in the temperature profile applied and the pretightening force in function of time in the three different test arrangements

Theses

1. The experimental conclusion on self-cutting screw joints (in the case of PA6GF30 boss) was also demonstrated for bolted screw joints and self-cutting screw joints without boss compression, namely that a predominant part of pretightening force relaxation occurs, in respect of repeated heat-up and cool-down, during heat-up to a temperature higher than the first temperature previously experienced by the screw joint and ensuing cool-down. In case of a second heat-up to the same temperature, no further considerable force reduction occurs: the pretightening force changes reversibly in accordance with thermal expansion / contraction. In case of heat-up to a temperature higher than the previous temperature, however, the pretightening force is considerably reduced again. [S10]

2. Based on experiments performed on self-cutting screw joints, it was concluded that the 30 mass per cent of glass fiber reinforcement applied in polyamid 6 bosses not only abates pretightening force reduction during the first heat-up and the ensuing cool-down, but it also modifies the ratio of force reduction during heat-up and cool-down as compared to each other from three and a half in the case without reinforcement to about one [S2], [S5], [S12].

3. Having compared experimental results on self-cutting screw joints and bolted joints, it was concluded that under identical experimental conditions and cyclic thermal load, the pretightening force reduces much more intensively in case of the bolted joint than in case of the self-cutting joint. The pretightening force at the end of the cycle in the case of self-cutting screw joint is five times larger than in the case of bolted joint [S3], [S10].

4. The viscoelastic / viscoplastic behavior of bosses made of polyamid 6 reinforced by 30 mass per cent of glass fiber (PA6GF30) can be modeled by a 40-term generalized Maxwell model, based on the ”overlay” technique developed and taking viscoplastic behavior into account as well [S9], [S11].

5. It was established that the part with different fiber orientation at the top of the boss has practically no influence on the global behavior of the self-cutting screw joint and on pretightening force reduction. In other words, removal of the headpiece of the boss does not actually affect the mechanical behavior of the self-cutting screw joint. Furthermore, it was established that the extent of axial deformations measured at the beginning and at the end of the first cycle of heat-up / holding / cool-down is different. Deformations to be measured after cool-down are larger than the ones to be measured before heat-up [S3], [S5].

6. In case of a PA6GF30 boss applied in a bolted joint, it was demonstrated experimentally that in case of repeated pretightening / heat-up / cool-down / loosening, pretightening force relaxation is gradually reduced. After 12 hours of rest, pretightening force reduction slows down even more. Furthermore, it was established that in case of repeated heat-up / holding / cool-down as applied to pretightened screw joints, the extent of axial deformations measured at the first and at the second cycle of heat-up / holding / cool-down is different. Changes in the deformation state during the second repeated cycle of heat-up / holding / cool-down are reversible, meaning that deformations to be measured before heat-up and after cool-down are practically identical. In contrast, deformation gradually increases in the course of the first cycle, therefore the deformations to be measured before heat-up and after cool-down are different from each other. In other words, axial deformation changes in the first cycle are irreversible [S9].

Utilization of results

The viscoplastic ”overlay” modeling procedure developed by myself can be used for modeling processes within self-cutting screw joints, also to be verified by the experiments shown. As a second step following verification, screw joints can be optimized. Such a model can be used for further specifying forecasts on joint behavior, and the number of experiments related to the phase of screw development can also be reduced.

In addition to fastenings in the automotive industry and in covers for household appliances and other machinery, self-cutting screw joints are also present in medical technology (e.g. implant fastenings or entire screw implants). Accordingly, it can be extremely useful for design engineers to have a tool to estimate, with appropriate accuracy, the behavior of self-cutting screw joints of various designs and material pairs in an early phase of design.

References

[1] Seneviratne, L. D.; Ngemoh, F. A.; Earles, S. W. E.; Althoefer, K. A.: Theoretical modelling of the self-tapping screw fastening process, Proc. Instn. Mech. Engrs, Vol. 215 (C), pp: 135-154 (2001)

[2] Erdős-Sélley, Cs.: FE modelling of the mounting process of metal screw and composite part, Periodica Polytechnica, Vol. 48, No2, pp: 133-143 (2004)

[3] Ellwood, K. R. J.; Fesko, D.; Bauer, D. R.: An axisymmetric model for thread forming in polycarbonate and polypropylene screw and boss fasteners, Polymer Engineering and Science, Vol. 44, No. 8, pp: 1498-1508 (2004)

[4] Mathurin, F.; Guillot, J.; Stéphan, P.; Daidié, A.: 3D finite element modeling of an assembly process with thread froming screw, Journal of Manufacturing Science and Engineering, Vol. 131, No 4 pp: 151-158 (2009)

[5] Launay, A.; Maitournam, M.H.; Marco, Y.; Raoult, I.; Szmytka, F.: Cyclic behaviour of short glass fibre reinforced polyamide: Experimental study and constitutive equations, International Journal of Plasticity, Vol. 27, pp. 1267-1293 (2011)

[6] Renz, R.; Wendtland, T.; Kasper, F.-J.: Recyclinggerechte Befestigungstechnik bei Bauteilen aus thermoplastischen Kunststoffen. Abschlussbericht zum FKM-Forschungsvorhaben Nr. 216 (1998)

[7] Tome, A.; Ehrenstein, G. W.; Drahtschmidt, F.: Joint Performance of Mechanical Fasteners under Dynamic Load – Self-Tapping Screw in Comparison with Threaded Inserts in Brass and Plastic, In: Moalli, J. (Editor): Plastic Failure Analysis and Prevention, William Andrew Inc., New York (2001) ISBN 1-884207-92-8

[8] Drahtschmidt, F.; Ehrenstein, G. W.: Threaded Joints in Glass Fiber Reinforced Polyamide, Polymer Engineering and Science, Vol. 37, No 4, pp: 744-755 (1997)

Publications of the author

[S1] Rick, T., Soós E.: CATIA verzió, GÉP LI. Évfolyam, 2000/10, pp: 64-66 (2000)

[S2] Soós, E., Renz, R.: Experimental and Numerical Investigations of a Thread–Cutting Screw Joint. In: Penninger A, Ziaja Gy, Vörös G (szerk.) GÉPÉSZET 2002: Proceedings of the Third Conference on Mechanical Engineering. Budapest, Hungary, 2002.05.30-2002.05.31. (BME) Budapest: Springer Hungarica Kiadó, pp: 674-678. ISBN: 963 699 1650

[S3] Soós, E., Renz, R.: Experimental Investigation of a Thread - Cutting Screw Joint Subjected to Cyclic - Thermal Loading. In: Penninger A, Kullmann L, Vörös G (szerk.) GÉPÉSZET 2004: Proceedings of the Fourth Conference on Mechanical Engineering. Budapest, Hungary, 2004.05.27-2004.05.28. Budapest: Budapest University of Technology and Economics, pp: 597-601. ISBN: 963 214 7480

[S4] Schmachtenberg, E., Brandt, M., Mennig, G., Roth, S., Renz, R., Soós, E., Küster, B., Sura, H.: Faserverstärkung richtig simulieren. KUNSTSTOFFE-PLAST EUROPE, Vol. 5, pp: 94-99. (2004) IF: 0.119

[S5] Soós E.: Műanyag alkatrészeken alkalmazott önmetsző csavarkötések kísérleti vizsgálata. GÉP LV:(10-11) pp: 149-152. (2004)

[S6] Soós E.: Acél érdességcsúcs és elasztomer sík lap csúszó-érintkezésének vizsgálata. In: XIII. Nemzetközi Gépész Találkozó (OGÉT 2005). Szatmárnémeti, Románia, 2005.04.28-2005.05.01. pp: 302-305.

[S7] Goda T., Soós E.: Acél érdességcsúcs és gumi sík lap csúszó-érintkezésének numerikus vizsgálata. In: OGÉT 2006: XIV. Nemzetközi Gépész Találkozó. Marosvásárhely, Románia, 2006.04.27-2006.04.30. Kolozsvár: pp: 146-149. ISBN: 973-7840-10-0

[S8] Goda T., Soós E.: Gumi próbatestek dinamikus mechanikai analízisének (DMA) hőtani vonatkozásai. MŰSZAKI SZEMLE 38: pp: 123-126. (2007)

[S9] Soós, E., Goda, T.: Numerical Analysis of Sliding Friction Behavior of Rubber. MATERIALS SCIENCE FORUM, Vol. 537-538, pp: 615-621. (2007)

[S10] Soós E.: Önmetsző csavarkötések kísérleti vizsgálata ciklikus hőterhelés esetén. GÉP LX:(10-11) pp: 84-87. (2009)

[S11] Soós, E., Goda, T.: Mechanical behavior of glass fiber-reinforced bosses: experiments and FE simulations, Vol. 55 (1), pp: 1-12. (2011) ISSN 0324-6051

[S12] Soós, E., Goda, T.: Experimental analysis of self-cutting screw joints: effects of the boss material, 2012 (benyújtott, Gépészet 2012)