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Direct screw fastening in injection-molded thermosets: Influence of screw-in parameters on fatigue strength

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Abstract

Direct screw fastening in injection-molded thermoset materials is a cost-effective alternative to threaded inserts. However, to prevent damage to the threaded area and to ensure the long-term strength of the joint, reliable process parameterization is required. This study examines the influence of screw-in parameters on the long-term mechanical strength of thermoset components joined by direct screw fastening. For this purpose, four thermoset materials based on phenolic and epoxy resin systems are examined in combination with a DELTA PT DS self-tapping screw. Both the tightening torque and the screw-in speed are varied across three levels. The dynamic long-term strength is evaluated based on incremental load testing. Tube rupture is identified as the dominant failure mode, resulting in failure of the screw-in tube or the surrounding material, while failure of the threaded region is of secondary importance. Within the investigated parameter window, no statistically significant influence of screw-in speed was identified. For the tightening factor, a statistically significant effect was found only for PF 6680. However, no consistent or generally transferable trend was observed. In line with the observed predominance of tube rupture, the assembly parameters can therefore be selected primarily with a view to process robustness and efficiency, enabling shorter cycle times and higher clamping forces.

Keywords: mechanical joining, direct screw fastening, mechanical properties, fatigue strength

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1 Introduction

Thermoset materials are characterized by a permanently cross-linked molecular structure which prevents remelting after curing. In contrast to thermoplastics, this molecular architecture results in high dimensional stability, excellent thermal resistance, and high chemical stability, while simultaneously causing comparatively low ductility and limited capability for plastic stress redistribution under local mechanical loading [1, 2]. Consequently, thermoset components are generally more sensitive to local stress concentrations and notch effects, which may promote crack initiation and brittle failure mechanisms under mechanical loading [3]. Due to this unique combination of properties, thermosets are conventionally used in applications requiring high mechanical, thermal, electrical, and chemical performance, particularly in areas where conventional thermoplastics reach their functional limits [3, 4]. Typical application areas include the automotive industry, aerospace engineering, and electronics [1].

The application of thermoset components in industrial structures generally involves complex multi-step assembly processes. In particular in the automotive sector, high importance is placed on process precision, automation capability, and cost efficiency [5, 6]. Even small reductions in overall cycle time or improvements in process stability can therefore have a significant economic impact [7]. Against this background, injection molding represents a particularly suitable manufacturing process for thermoset components, since it enables highly reproducible and cost-efficient large-scale production while simultaneously allowing the integration of complex geometrical and functional features [2, 8]. In many cases, these functional elements can be directly utilized in subsequent assembly operations, thereby reducing manufacturing effort and assembly complexity [9].

Within injection molding, different approaches exist for generating internal threads. Classical methods include the use of metallic inserts or thread-forming cores [2, 10]. Metallic inserts require additional handling and positioning operations, thereby increasing manufacturing effort and cycle time [2, 11]. Thread-forming cores enable the direct generation of threads during molding, yet substantially increase mold complexity, maintenance requirements, and tooling costs [2, 3]. As a result, direct screw fastening represents a more efficient solution from both an economic and technical perspective [11]. In this approach, the thread is formed directly during assembly by the screw itself, allowing simplified manufacturing and highly automated assembly processes [11]. Consequently, self-tapping screws are commonly applied, whereas the use of thread-forming screws may be limited by the typically brittle behavior of thermosets and the resulting risk of material damage during screw insertion [4]. Furthermore, the local stress state generated during the fastening process strongly depends on the interaction between screw geometry, material behavior, and process parameters such as tightening torque and screw-in speed [1].

Direct screw fastening of thermoplastics has been extensively investigated, leading to established design guidelines such as DVS-Norm 2241-1 and overall design recommendations by Ehrenstein [13]. However, these findings are not directly transferable to thermosets due to their fundamentally different mechanical behavior and reduced capacity for local plastic deformation. Combined with the large body of research on thermoset-specific screw connections, this leads to the design of production and assembly processes being mainly guided by empirical knowledge. Existing studies are restricted to a comparatively small number of investigations. Onasch analyzed deformation mechanisms during direct screw fastening of polyester resins using thread-forming screws [14]. However, the screws considered, namely chipboard and sheet metal screws, do not reflect the current state of the art. Trinter investigated load introduction in sheet molding compounds (SMC) using self-tapping screws and demonstrated that pull-out strength is proportional to thread flank engagement and independent of tightening torque [15]. Significant advancements were achieved through the cooperation between the IKV and the KTP within the research project "Material-optimized design of direct screw fastenings for the cost-efficient joining of injection-molded thermoset components" funded by the Federal Ministry for Economic Affairs and Energy (BMWi). Within this project, the focus was placed on screw-in parameters, molding conditions, and screw-in tube geometries. For the evaluation of the influence of these factors on joint performance, tensile strength was used as the primary quality criterion. The results enabled the formulation of general design recommendations based on short-term mechanical properties [4].

However, thermoset components are predominantly employed in high-performance applications associated with long product life cycles and demanding service conditions [11]. While short-term tensile strength provides an important first assessment of joint performance, it does not adequately represent the loading conditions encountered during practical operation. Thermoset assemblies are frequently exposed to cyclic mechanical loading, long-term static preload, and varying environmental conditions during service life. These loading scenarios may promote progressive damage accumulation, local microcrack initiation, preload reduction, and ultimately fatigue-related failure of the joint. Consequently, the investigation of long-term mechanical behavior is essential for the robust and reliable design of directly screw-fastened thermoset structures.

The present study therefore aims to close this gap by systematically investigating the influence of key process parameters on the long-term mechanical performance of directly screw-fastened thermosets. In particular, the effects of tightening torque and screw-in speed are analyzed with respect to fatigue performance and long-term mechanical stability as the primary quality criteria. The objective is to identify relevant process-property

107 relationships and thereby contribute to the development of reliable design recommendations for durable thermoset
108 fastening systems in industrial applications.

2 Materials and Methods

For the investigations, a total of four thermosetting molding compounds were used. These include two epoxy resins, namely Epoxidur EP 3685 and Epoxidur EP 3681 from Raschig GmbH, Ludwigshafen, Germany, and two phenolic resins, namely Bakelite PF 1110 and Bakelite PF 6680 from Bakelite GmbH, Iserlohn, Germany. The investigated materials are listed in Table 1. The materials were selected based on their industrial relevance. In addition, the materials were chosen to represent different application profiles of thermosetting compounds. The phenolic resins are characterized by excellent mechanical properties and are therefore commonly used in automotive applications. The epoxy resins, in contrast, exhibit exceptional flowability, making them particularly suitable for encapsulation of sensitive electronic components. All four materials are highly filled compounds with filler contents ranging from 60 wt. % to 80 wt. %. The corresponding filler compositions are summarized in Table 1.

Table 1 Selected resins and respective composition

Commercial name	Abbreviation	Filling degree [wt.%]	Filler composition	Manufacturer
Epoxidur EP 3685	EP 3685	75	Glass fibers and inorganic fillers	Raschig GmbH
Epoxidur EP 3681	EP 3681	70	Glass fibers and glass beads	Raschig GmbH
Bakelite PF 1110	PF 1110	80	Glass fibers and glass beads	Bakelite GmbH
Bakelite PF 6680	PF 6680	60	Glass fibers and glass beads	Bakelite GmbH

The materials were used to produce screw-in tubes, as shown in Fig. 1 (right). The corresponding injection mold was developed within a predecessor project and is illustrated in Fig. 1 (left) [4]. It comprises nine cavities, enabling the production of screw-in tubes with different geometries within a single molding cycle. To ensure comparability, a reference geometry was selected for all investigations. The dimensions of the reference specimens are also shown in Fig. 1. The injection molding experiments were carried out using an Arburg Allrounder 370 A from Arburg GmbH + Co. KG, Loßburg, Germany. The test specimens were produced under material-specific and constant injection molding parameters. These parameters were determined via preliminary studies and are listed in Table 2 for the four materials.

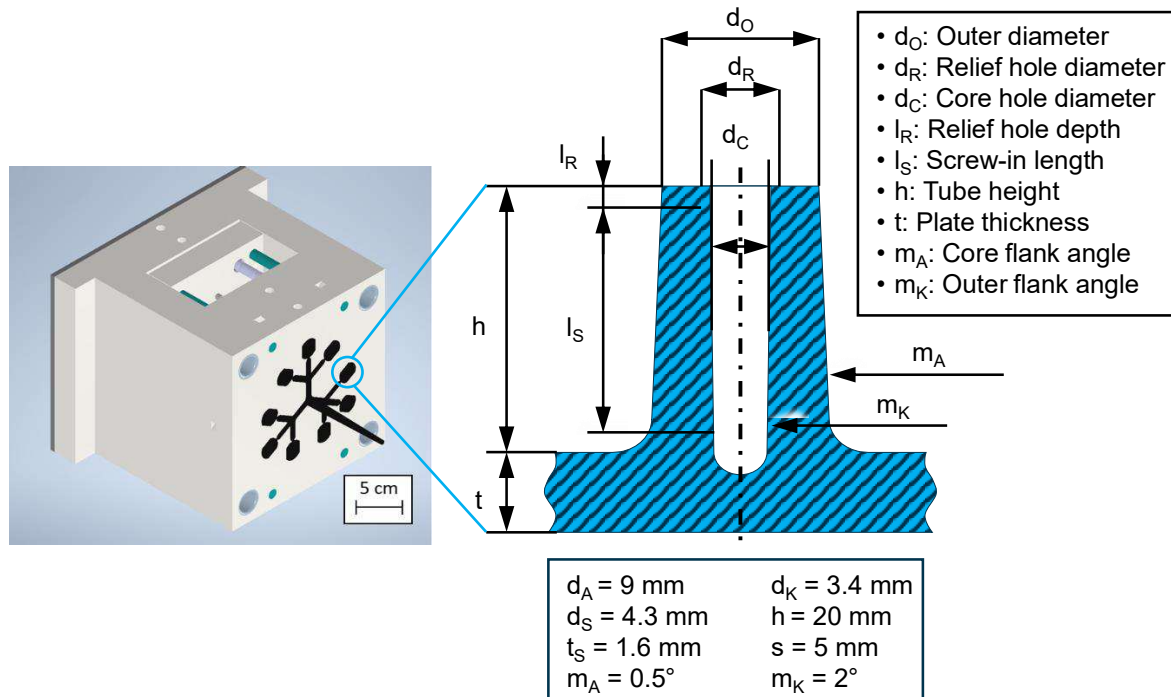


Fig. 1 Injection mold (left) used for the production of the screw-in tubes (right)

Table 2 Material specific injection molding parameters

Material	Mold temperature [°C]	Injection flow rate [cm ³ /s]	Holding pressure [bar]	Holding time [s]	Curing time [s]
EP 3685	175	5	500	12.5	80
EP 3681	185	25	550	20.0	80
PF 1110	175	60	800	10.0	80
PF 6680	170	10	900	14.5	80

The investigations were conducted in a two-step process. First, the screw-in process was performed. For this purpose, a screw-connection test bench from Desoutter GmbH, Seligenstadt, Germany, was used. The screws employed were DELTA PT DS screws with a nominal diameter of 4 mm from EJOT SE & Co. KG, Bad Berleburg, Germany. The screws are electro-galvanized self-tapping screws. The joining partner for the screw fastening process was a steel block. The thickness of the block can be varied to achieve different screw-in lengths, whereby the screw-in length used in this study was 8 mm. The experimental setup is schematically shown in Fig. 2. The screw-in process consists of two phases, as illustrated in Fig. 3. In the first phase, up to the contact of the screw head with the screw-in tube (snug point), thread formation occurs. This phase is performed at higher rotational speeds as shown in Table 3. After reaching the snug point, the screw-in speed is reduced to 50 rpm. The transition between both phases is determined using the torque-gradient method. In this approach, the derivative of the torque with respect to the rotation angle is analyzed. During thread formation, this value oscillates around zero. Once the screw head contacts the screw-in tube, a distinct increase in the gradient is observed, which is used to identify the switching point. In the second phase, the tightening torque is applied to generate the preload force, which represents a key quality parameter in screw fastening processes. Excessive tightening torque (over-torque) may lead to damage of the screw-in tube.

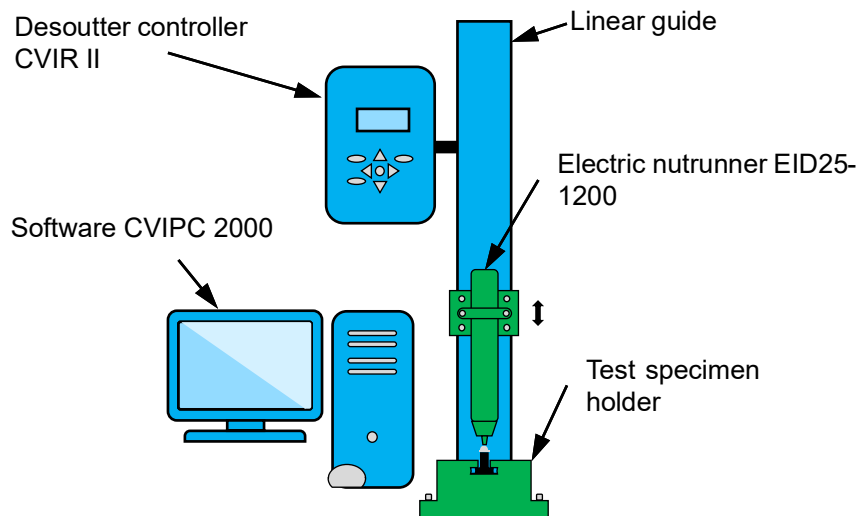


Fig. 2 Screw connection test bench

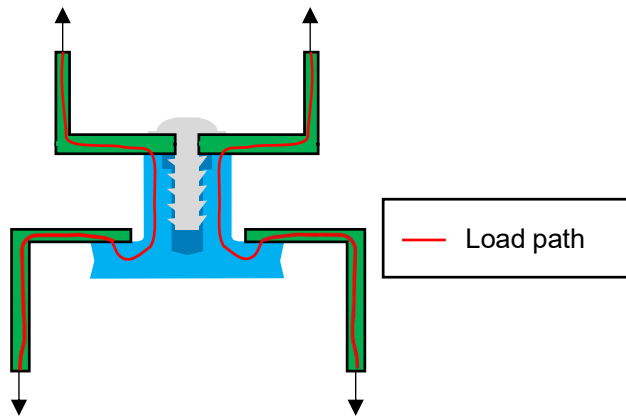


Fig. 4 Clamping setup and respective load path for the mechanical tests

Statistical analysis was performed to support the interpretation of the experimental results. The distribution of the data was assessed using Q–Q plots and the Shapiro–Wilk test. Based on this assessment, one-way analysis of variance was applied separately for each material and process parameter. The investigated factors were screw-in speed and tightening factor X_M . Since eight individual ANOVA tests were performed, the significance level was adjusted using the Bonferroni correction, resulting in $\alpha_{adj}=0.00625$. For each material and each parameter level of screw-in speed and tightening torque, five specimens were tested. The results obtained from this study will be presented and discussed in the following chapters.

3 Results and Discussion

3.1 Initial Condition of the Screw Joint

Before evaluating the influence of the screw-in parameters on the long-term mechanical performance, the initial condition of the screw joints must be considered. In particular, assembly-induced damage and manufacturing-related imperfections may influence the subsequent fatigue behavior and therefore have to be distinguished from damage that develops during cyclic loading.

The tightening torque for each material was determined based on the corresponding driving torque T_D and over-torque T_O . The driving torque represents the torque required for thread formation, whereas the over-torque corresponds to the torque at which damage of the screw joint occurs during installation. Both values were experimentally determined by over-torque tests. Based on these characteristic values, the investigated tightening torques were calculated using Equation 1. The experimentally determined values are summarized in Table 4.

Table 4 Experimental results for Driving torque and Over-torque

Material	Driving torque T_D	Over-torque T_O
	[Nm]	[Nm]
PF 1110	0.80	5.50
PF 6680	0.80	3.97
EP 3681	0.73	2.97
EP 3685	1.03	3.40

The results demonstrate that all investigated material systems exhibit a sufficiently large assembly window between the driving torque and the over-torque. During the screw-in experiments, no assembly-induced failures such as screw fracture or tube bursting were observed. Consequently, the selected core hole diameter and screw-in length can be regarded as suitable for all investigated material-screw combinations. This confirms that the joints were assembled under technically appropriate conditions and that no macroscopic damage was introduced during installation. Therefore, the failure mechanisms observed during the subsequent fatigue tests can primarily be attributed to damage accumulation under cyclic loading rather than to unsuitable joint geometry. Furthermore, varying the screw-in speed and the tightening factor did not result in an immediate failure of the joint during the fastening process. Such an immediate failure would have indicated a direct and pronounced influence of the selected screw-in parameters on the joint.

Besides the assembly process itself, manufacturing-related imperfections may influence the mechanical performance of injection-molded thermoset components. To assess the internal quality of the specimens, exemplary computed tomography (CT) analyses were performed. A representative CT image for PF 1110 is shown in Fig. 5. The CT analysis revealed isolated air pockets within the interior of the screw-in tube, whereas no externally visible defects or surface cracks were detected. Air pockets may cause stress concentrations and may therefore act as potential sites for crack initiation under cyclic loading. However, the available data do not allow a statistically supported correlation to be established between the presence or distribution of air pockets and the observed fatigue life or failure modes. Consequently, their influence on the fatigue behavior cannot be quantified based on the present investigations. The presumably non-reproducible size and location of the air pockets may contribute to the observed scatter in fatigue life.

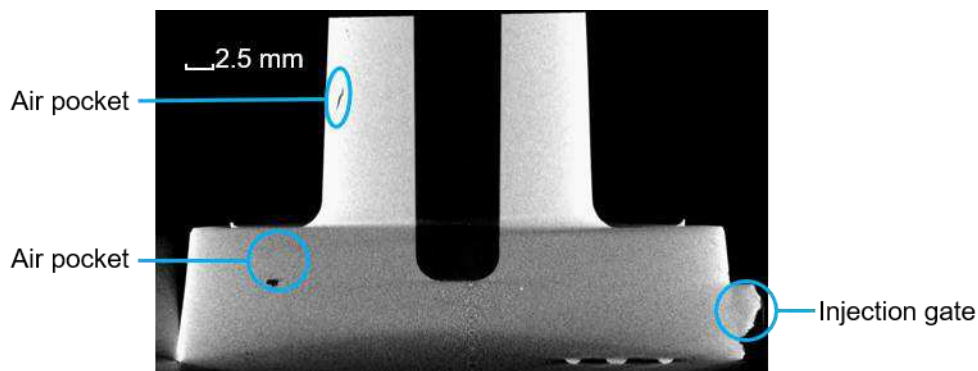


Fig. 5 Representative CT cross-section of a PF 1110 specimen showing exemplary internal voids

Kramer (2024) reported that, during load-increment testing, the measured displacement initially increased approximately proportionally with the applied load for PF 1110 and EP 3685. A disproportionate increase in

displacement occurred only shortly before final failure and was interpreted as an indication of detectable material damage, such as microcrack formation. This behavior suggests that a pronounced reduction in the effective stiffness of the joint becomes macroscopically apparent primarily during the final stage preceding failure. However, the presence of local subcritical damage at earlier stages of cyclic loading cannot be excluded. Accordingly, the dominant damage mechanisms are assumed to develop progressively during fatigue testing, while a macroscopically detectable degradation of the joint occurs only close to final failure. The corresponding damage evolution and resulting failure mechanisms are discussed in Section 3.5.

3.2 Fatigue Strength of the Investigated Materials

Fig. 6 compares the normalized number of cycles to failure of the four investigated thermosetting molding compounds under reference assembly conditions. The reference condition corresponds to the intermediate screw-in speed of 375 rpm and the intermediate tightening factor of $X_M=5/12$.

Using this parameter set, 15 specimens were evaluated for each material. The increased number of repetitions was used to establish a reliable reference value for the normalized cycle numbers and to support the statistical assessment of the experimental scatter. The results indicated that the assumption of normality was acceptable for the subsequent evaluation. Therefore, one-way analysis of variance was applied to assess the influence of the investigated process parameters.

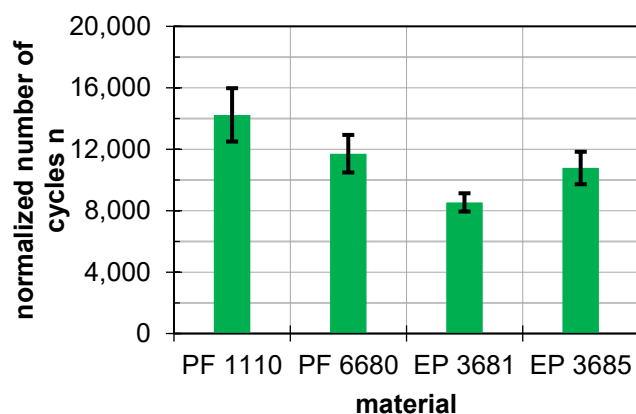


Fig. 6 Normalized number of cycles to failure under reference assembly conditions for PF 1110, PF 6680, EP 3681, and EP 3685

For all materials, the results show considerable scatter, which is generally consistent with fatigue testing of heterogeneous thermoset molding compounds [16]. Nevertheless, clear material-dependent differences can be observed. Under reference assembly conditions, PF 1110 reached the highest mean of normalized number of cycles to failure, with approximately 14,200 cycles, followed by PF 6680 with approximately 11,700 cycles. Among the epoxy resin-based compounds, EP 3685 achieved approximately 10,780 cycles, whereas EP 3681 reached approximately 8,500 cycles. Thus, the phenolic resin-based compounds generally exhibited higher long-term dynamic performance than the epoxy resin-based compounds. These results indicate that both the material system and filler composition have a pronounced influence on the fatigue behavior of directly screwed thermoset joints. The differences may be related to the material-specific formulation and reinforcement system. PF 1110 and EP 3685 both have a filler content of 80 wt.% and 75 wt.%, whereas PF 6680 and EP 3681 have lower filler contents of 60 wt.% and 70 wt.%, respectively. In addition, EP 3681 contains a substantially higher proportion of glass beads and a correspondingly lower proportion of glass fibers. This composition may result in reduced resistance to fatigue crack propagation, which could have contributed to the comparatively low number of cycles to failure observed for EP 3681. Overall, differences in filler content and reinforcement composition may affect local stiffness and fatigue damage mechanisms, as reported for short-fiber-reinforced polymer composites [17].

3.3 Influence of Screw-in Speed

The failure modes observed during the fatigue tests were tube rupture (TR) and screw pull-out (SP), as schematically shown in Fig. 7. Fig. 8 shows the normalized number of cycles to failure as a function of screw-in speed for all four investigated materials. The three screw-in speed levels are arranged from left to right in increasing order, corresponding to 250 rpm, 375 rpm, and 500 rpm. In addition, the observed failure modes are

indicated in the bars. Thus, the diagrams show not only the fatigue performance but also the number of valid tests and the associated failure behavior.

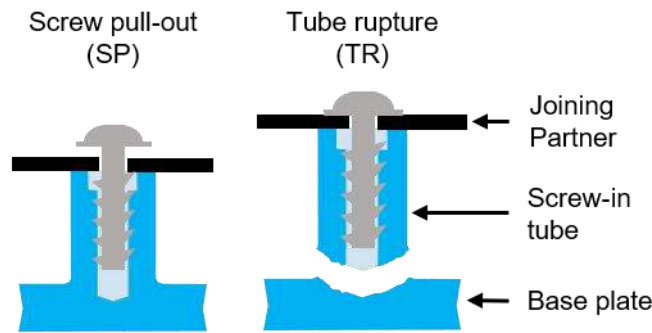


Fig. 7 Illustration of the failure modes observed during the fatigue tests

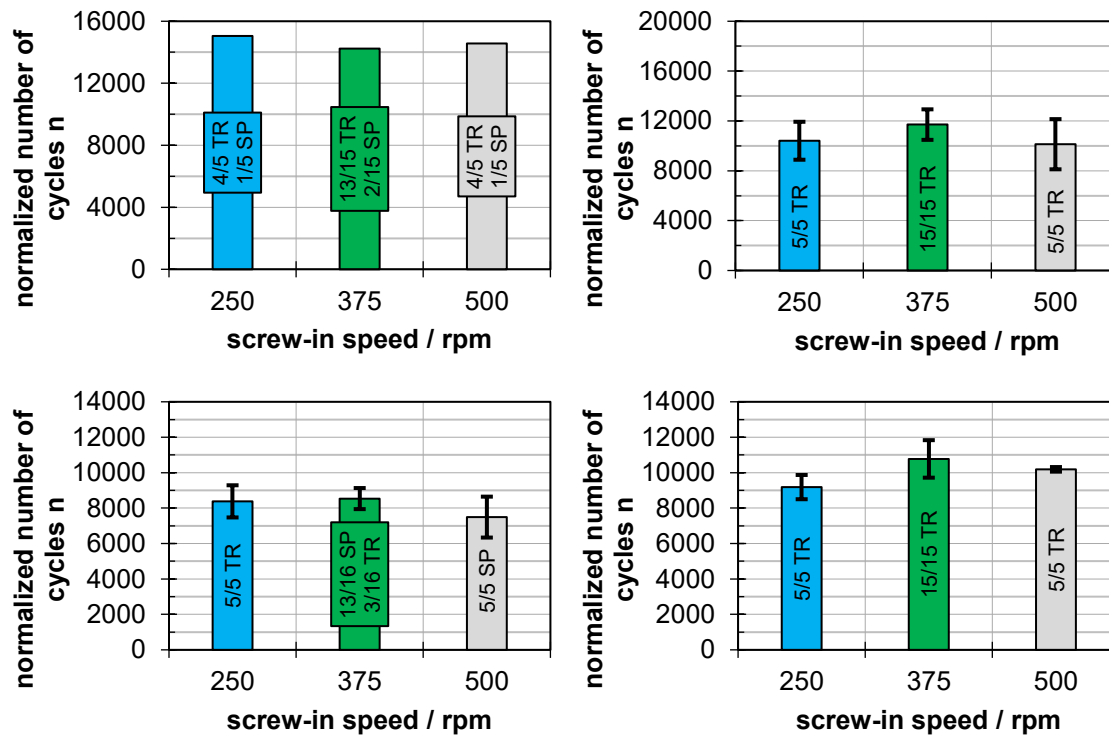


Fig. 8 Influence of screw-in speed on the normalized number of cycles to failure and observed failure modes for PF 1110 (top left), PF 6680 (top right), EP 3681 (bottom left), and EP 3685 (bottom right).

Within the investigated range, no consistent dependence of the normalized number of cycles to failure on screw-in speed was identified. For three of the four materials, the highest mean value was obtained at the intermediate screw-in speed of 375 rpm. However, the corresponding standard deviations overlap with those of the other speed levels to a large extent. Therefore, this observation should not be interpreted as a systematic or generally valid optimum.

The statistical evaluation, shown in Table 5, supports this interpretation. After applying the Bonferroni correction for multiple comparisons, none of the investigated materials showed a statistically significant influence of screw-in speed on the normalized number of cycles to failure. Accordingly, the graphical trends and the statistical analysis both indicate that screw-in speed did not have a clearly detectable effect on long-term dynamic strength within the investigated parameter window.

From a technical perspective, this result is relevant because excessive screw-in speeds can increase heat generation during direct screw fastening in plastics, which may damage the thread-forming zone [19] and may also impair the reliable detection of screw-head contact prior to tightening [2]. Possible damage mechanisms include frictional heat generated at the screw-polymer interface during thread formation, radial stresses in the screw-in tube caused by material displacement, and local overstressing of the polymer in the region between the thread flanks [21, 22]. This is particularly relevant for thermosets because their hardness and brittleness impose special requirements on direct assembly [23]. However, within the investigated process window between 250 rpm and 500 rpm, such an effect was not reflected in a consistent reduction in long-term dynamic strength. The results therefore do not

provide evidence that the investigated screw-in speeds caused damage to the formed thread for the tested material–screw combinations.

Table 5 Results of the one-way ANOVA for the influence of screw-in speed and tightening factor X_M on the normalized number of cycles to failure.

Material	Screw-in Speed:	Tightening factor X_M :
	p-Value	p-Value
PF1110	0.634	0.086
PF6680	0.072	0.0001
EP3681	0.049	0.018
EP3685	0.008	0.890

3.4 Influence of Tightening Torque

Fig. 9 presents the normalized number of cycles to failure as a function of the tightening factor X_M . The three levels were $X_M = 4/12$, $X_M = 5/12$, and $X_M = 6/12$. As described in Section 2, the tightening factor defines the position of the applied tightening torque between the driving torque and the over-torque of the respective material. Thus, increasing X_M corresponds to increasing tightening torque and, consequently, to a higher initial preload force [24].

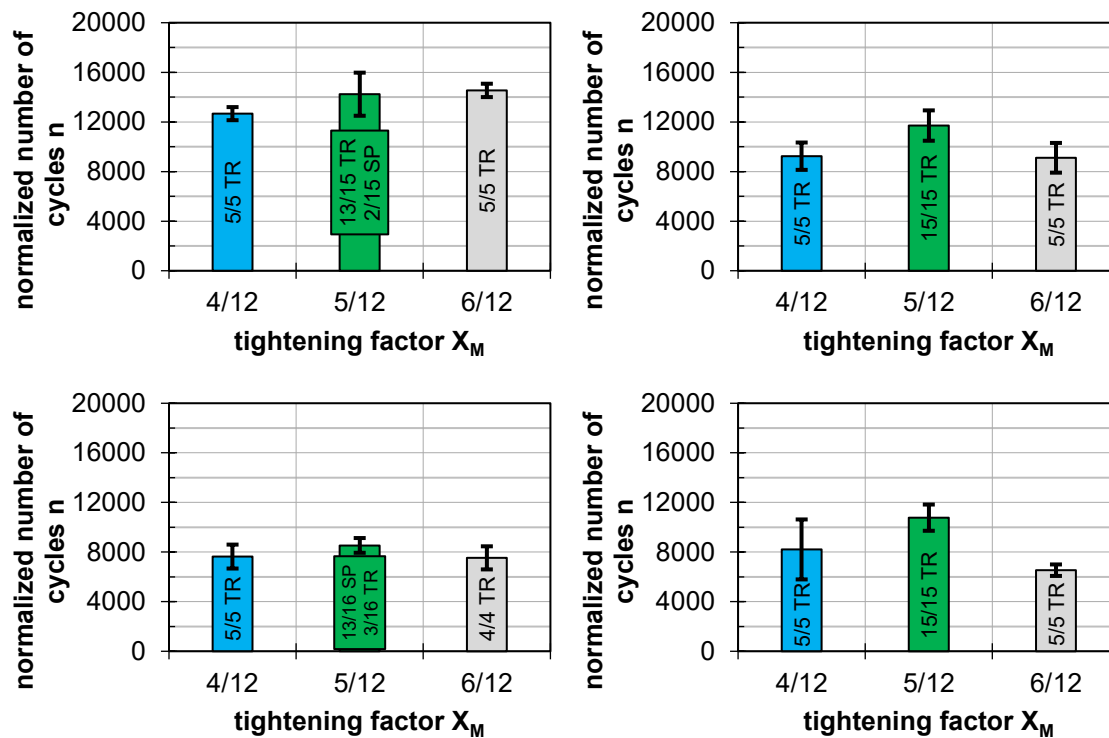


Fig. 9 Influence of tightening factor X_M on the normalized number of cycles to failure and observed failure modes for PF 1110 (top left), PF 6680 (top right), EP 3681 (bottom left), and EP 3685 (bottom right).

The results show no consistent trend across all four materials. For three of the four materials, the highest mean number of cycles was obtained at $X_M = 5/12$. However, the scatter of the results and the overlap of the standard deviations indicate that this tendency cannot be interpreted as a general process–property relationship. A monotonic increase or decrease in long-term dynamic strength with increasing X_M was not observed. Although PF 6680 showed a statistically significant effect, the absence of a coherent trend suggests that this effect should not be interpreted as a generally transferable process–property relationship. From an application perspective, the absence of a consistent detrimental influence of increasing X_M is important. Excessive tightening torque may cause damage to the screw-in tube or to the formed internal thread [25]. Conversely, a higher tightening torque is often desirable because the residual clamp load during service depends on the initial clamp load [26]. Within the investigated parameter range, increasing the tightening factor up to $X_M = 6/12$ did not generally reduce the long-term dynamic performance of the joints. This suggests that the tightening factor may be

selected with regard to functional requirements such as clamp load, sealing, or positioning, provided that the validated process window is maintained.

3.5 Analysis of Failure Modes

The observed failure modes provide further insight into the mechanical behavior of the joints. During load-increment testing, two main failure modes were observed, namely screw pull-out and tube rupture. Screw pull-out describes failure of the internal thread formed in the thermoset material. Tube rupture, in contrast, refers to fracture of the surrounding screw-in tube. This fracture occurred either at the transition between the screw-in tube and the base plate or within the screw-in tube itself. Fracture at the transition region was observed more frequently.

Tube rupture was the dominant failure mode for the investigated specimens. This observation is central to the interpretation of the parameter study. If screw-in speed or tightening torque had caused severe damage to the thread-forming zone, a higher proportion of screw pull-out failures would be expected, particularly at the more severe process settings. Instead, most specimens failed by fracture of the screw-in tube or the adjacent material. This indicates that the long-term dynamic strength was governed primarily by the fatigue resistance of the screw-in tube structure rather than by the load-bearing capacity of the formed internal thread.

For tube rupture, crack initiation may be promoted by local stress concentrations in the screw-in tube, especially at the transition to the base plate. The axial load introduced through the screw is transferred from the engaged thread flanks into the wall of the screw-in tube and subsequently into the base plate. The transition between the comparatively thin-walled screw-in tube and the base plate represents a potential stress concentration. The frequent occurrence of fracture in this region indicates that it represents a critical section of the load path.

In addition to the stresses resulting from the external cyclic load, the stress state introduced during the fastening process has to be considered. The core hole is slightly tapered due to the draft angle required for demolding. Consequently, the effective core hole diameter decreases with increasing screw-in depth. As the screw penetrates further into the screw-in tube, an increasing amount of material is cut and displaced. This increases the radial and circumferential stresses within the lower section of the screw-in tube. The combined effect of the assembly-induced stresses and the cyclic stresses caused by the external tensile load may promote crack initiation near the transition between the screw-in tube and the base plate.

Local stress concentrations may initially lead to microscale damage within the polymer matrix or at the interfaces between the matrix and the fillers. Depending on the local material structure, this damage may include matrix microcracking, filler–matrix debonding, or the growth of existing imperfections. Under continued cyclic loading, neighboring damaged regions may interact and coalesce, resulting in the formation of a larger crack. Subsequent crack propagation progressively reduces the effective load-bearing cross-section of the screw-in tube. Once the remaining cross-section is no longer sufficient to withstand the applied load, rapid final fracture occurs.

This proposed sequence represents a mechanism-based interpretation of the observed macroscopic failure images. The individual stages of microcrack initiation, crack coalescence, and crack propagation were not directly observed by interrupted testing or time-resolved CT analysis. Therefore, it cannot be concluded whether a single dominant crack developed continuously or whether several locally distributed damage regions formed before final fracture. The proposed damage development is consistent with the displacement behavior reported by Kramer (2024) for PF 1110 and EP 3685 during load-increment testing.

In the case of screw pull-out, failure is associated with local overstressing of the material at the thread flanks and insufficient resistance of the formed internal thread against the cyclic load transferred by the screw. Screw pull-out is the result of progressive damage to the formed internal thread. The tensile load is transferred from the screw to the thermoset material through the thread flanks. This creates local contact and shear stresses in the thread.

The initial stress state within the thread engagement is influenced by the tightening factor X_M . An increase in X_M results in a higher tightening torque and generally in a higher initial clamp load. At the same time, the contact pressure at the thread flanks and the radial and shear stresses within the formed internal thread may increase. Due to the limited ability of thermoset materials to redistribute local stresses through plastic deformation, a high tightening torque may promote local matrix damage, microcrack initiation, or partial overstressing of individual thread flanks. Such local damage may reduce the load-bearing capacity of the formed thread even if no immediate macroscopic failure occurs during the fastening process [2, 24, 25].

However, a lower tightening factor is not necessarily associated with improved fatigue performance. A lower tightening torque generally results in a lower initial clamp load. If the clamp load is insufficient to maintain firm contact between the joining partners during cyclic loading, increased relative movement may occur within the joint. This may alter the load distribution and increase the cyclic stresses transmitted through the screw and the formed internal thread. Accordingly, a high tightening factor may increase local assembly-induced stresses, whereas a low tightening factor may increase relative movement and cyclic loading of the thread engagement.

Within the investigated parameter range, however, neither mechanism resulted in a consistent reduction in fatigue performance across all investigated materials.

Under cyclic loading, repeated loading and unloading of the thread flanks may lead to progressive material degradation. Local damage may initially be restricted to individual, highly loaded thread sections. As the effective load-bearing area of these thread flanks decreases, the applied load has to be redistributed to the remaining intact thread sections. This redistribution increases the local stresses within the remaining thread flanks and may accelerate further damage. Eventually, the formed internal thread is no longer able to transfer the applied axial load. Progressive shearing or stripping of the internal thread then occurs, resulting in pull-out of the screw.

The air pockets identified by the CT analyses may additionally influence the local damage development. Air pockets may generate local stress concentrations, particularly when located close to a highly loaded thread flank or within the transition region of the screw-in tube. Under cyclic loading, such stress concentrations may promote microcrack initiation or subsequent crack propagation. Air pockets may therefore contribute to the development of both tube rupture and screw pull-out, depending on their size and position relative to the local stress field. However, the CT analyses were conducted only exemplarily and were not systematically correlated with the subsequent crack initiation sites or fracture surfaces of the individual specimens. Therefore the identified air pocket cannot be directly assigned as the cause of either screw pull-out or tube rupture.

In addition to air pockets, variations in local fiber orientation, filler distribution, glass-fiber and glass-bead content, filler-matrix adhesion, and local stress conditions may influence the fatigue resistance of the highly filled thermoset materials [16, 17]. These material-related inhomogeneities may affect the location and time of crack initiation and may therefore contribute to the considerable scatter observed in the number of cycles to failure.

Because screw pull-out occurred less frequently than tube rupture, the available number of specimens is not sufficient to quantify the influence of the failure mode on the achieved number of cycles with statistical confidence. The occurrence of screw pull-out primarily for EP 3681 nevertheless indicates that the relative resistance of the formed internal thread and the surrounding screw-in tube depends on the investigated material system. For this material, the internal thread became the limiting structural region for several parameter combinations, whereas the screw-in tube predominantly governed failure for the other materials.

The absence of a consistent relationship between the tightening factor X_M and screw pull-out indicates that the investigated tightening factors did not systematically produce a critical level of assembly-induced thread damage. Instead, screw pull-out appears to result from the interaction between the initial stress state generated during fastening, the cyclic load transfer through the thread flanks, and the local fatigue resistance of the respective material.

The predominance of tube rupture is consistent with the statistical results. Since neither screw-in speed nor tightening factor showed a consistent influence on fatigue performance, the tested joints appear not to be primarily limited by process-induced damage in the thread-forming zone. Instead, the failure behavior suggests that the fatigue resistance of the screw-in tube and the surrounding thermoset material controlled the long-term dynamic performance under the investigated loading conditions. Nevertheless, screw pull-out demonstrates that the formed internal thread may become the limiting region for individual material systems. Manufacturing-related inhomogeneities may additionally influence local crack initiation and contribute to the observed experimental scatter.

4 Conclusion and Outlook

Four industrially relevant thermosetting molding compounds were examined, namely the phenolic resin-based materials PF 1110 and PF 6680 and the epoxy resin-based materials EP 3681 and EP 3685. Based on the experimental results, the following conclusions can be drawn:

- The material system has a pronounced influence on the long-term dynamic performance of the directly screwed joints. Under reference assembly conditions, the phenolic resin-based materials reached higher normalized numbers of cycles to failure than the epoxy resin-based materials. In addition, PF 1110 showed higher fatigue performance than PF 6680, while EP 3685 reached higher cycle numbers than EP 3681.
- Tube rupture was identified as the dominant failure mode during load-increment testing, whereas screw pull-out occurred less frequently. This indicates that the long-term dynamic strength was mainly governed by the fatigue resistance of the screw-in tube and the surrounding thermoset material, rather than by failure of the formed internal thread.
- Within the investigated parameter window, no statistically significant and technically consistent influence of screw-in speed on the normalized number of cycles to failure was identified. Increasing the screw-in speed from 250 rpm to 500 rpm did not lead to a reproducible reduction in long-term dynamic strength for the tested material–screw combinations.
- The tightening factor X_M did not show a generally transferable influence on long-term dynamic strength. A statistically significant effect was identified only for PF 6680 after correction for multiple comparisons. However, no consistent trend between tightening factor and fatigue performance was observed.
- From an industrial perspective, higher screw-in speeds, such as 500 rpm, may be considered to reduce assembly time within the validated parameter window. Higher tightening factors, such as $X_M = 6/12$, may also be considered when higher initial clamp loads are required, for example for application-specific functions such as sealing or component positioning.

Future work should systematically investigate the influence of screw-in tube geometry and injection molding parameters on long-term dynamic strength. Relevant geometric parameters include screw-in tube outer diameter, wall thickness, bore diameter and screw engagement length. Relevant injection molding parameters include mold temperature, injection flow rate, holding pressure, holding time and curing time. These parameters may affect local stress concentrations, fiber orientation, filler distribution, weld-line formation, void content, residual stresses, and crack initiation in the screw-in tube [27]. Furthermore, manufacturing-related imperfections such as air pockets and weld lines should be systematically correlated with crack initiation, failure modes, and fatigue life.

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6 Statements and Declarations

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