Analysis of elastic-plastic interference-fit joints

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Abstract

This paper presents an examination of the elastic-plastic interference fit joints for simple and complex pin-tube geometries. Mechanics of the process is studied in detail through physical trials and numerical models. Results show there are three distinct stages as the pin is pushed into the tube and that an optimum geometry maximising the joint strength exists.

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1. Introduction

In automotive industry, increasing product complexity has driven the development of new joining processes for mechanical parts. Typical examples are welding, adhesive bonding and mechanical fastening used to joint components in a product assembly. Joining by interference fits belongs to a wider group of mechanical joining processes, some examples of which are self-pierce rivets, mechanical clinches, pin joints and threaded connections.

In interference-fit joints, difference in geometry of two mating parts leads to contact pressure at the interface. This contact pressure holds the two parts together through friction, creating a mechanical joint. Strength of this joint depends mainly on the coefficient of friction, interference pressure and contact area. Such joints are used in a wide variety of applications, from automobile to aerospace industry.

This study focuses on analysis of elastic-plastic interference fit joints formed by pressing a solid and a grooved pin into a tube. This paper presents an examination of the elastic-plastic interference fit joints for 2 geometries; a simple geometry, where a solid pin is pressed into a tube and a complex geometry where a pin with grooves along...
its axis is pressed into an axisymmetric tube. The second geometry is typically used in diesel fuel injector systems, where the grooved pin acts as a fuel filter.

The paper starts with a brief literature review, identifying key contributions in this area. This is followed by a brief description of physical trials and numerical modelling of the joining process. Next, a detailed analysis of the process is presented. Lastly, a set of conclusions is drawn from the results of the physical trials and numerical analysis.

Before describing the trials, modelling and analysis, the existing literature needs to be reviewed. There is a large number of publications on interference fits, however only the key publications are considered here.

It is useful to start with previous literature reviews. Two previous reviews of work on fastening and joining methods, including interference fits have been identified. Mackerle (2003) provides a catalogue of publications on fastening and joining methods with one section on interference fits. While the author provides a useful list of references, the review is limited to a list only and the author does not review any papers, making the usefulness of this publication limited. Mori et al. (2013) give an extensive overview of joining processes, including interference-fit joints. For ring-tube joining by expansion, they point out that the optimum forming pressure is reached just before the ring starts to deform plastically and that any further increase in forming pressure leads to negligible increase in interference pressure and strength of the joint, and that it is possible to increase the joint strength by increasing surface roughness or cleaning the contacting areas. The remaining literature is grouped under three headings; investigations using experimental, analytical and numerical techniques.

Experimental techniques have focused on determining contact pressure and the friction coefficient. To estimate the contact pressure in interference fits, both Croccolo et al. (2011) and Kim and Lee (2006) measured the circumferential strain on the bushing by applying a strain gauge to the outer diameter of the bushing, which then allowed them to estimate the contact pressure through analytical equations. Croccolo et al. (2012) used this setup to determine the friction coefficient in interference fits between aluminium and steel, and shows that the friction coefficient for dry press-fitted aluminium-steel joints is 0.46. Lewis (2005) used ultrasound measurements to measure the contact pressure and showed that a central region of uniform pressure with higher pressure at the edges exists, and that the magnitude of the uniform pressure agrees well with Lamé analysis.

Analytical techniques used to design interference fits are based on the equations established by Lamé, which are based on a two-dimensional stress analysis in the elastic range. However, Lamé’s solution is limited by its simplifying assumptions.

The analytical models have been used to investigate the contact pressure and stress distribution in interference fits, the effect of surface roughness and thermal cycles. Yang et al. (2001) point out the importance of surface roughness in interference fit and demonstrate experimentally that the extraction load varies by up to 300% for Ra values of 0.24-6.82 μm. Zhang et al. (2000) analysed an interference fit of a ring gear and a stepped shaft using both numerical and analytical methods and conclude that the Lame’s equations underestimate the contact pressure by up to 78%. To estimate contact pressure between two different materials, Croccolo et al. (2012) developed an analytical model and report that if the stiffness of the two parts is close, the actual interference is likely to be less than the estimated interference. Lippmann (1992) used an analytical model to show that contact pressure changes with temperature; the increase in temperature leads to a decrease in yield stress causing plastic deformation in the fit, therefore reducing the load capacity of the joint.

Numerical methods have been used to predict joint quality, to design of the fitting process and examine the joint behaviour in service. Wang (1994) compared the performance of lugs under various clearance and interference values and concludes that using a carefully adjusted interference fit increases the durability of the joint. Yang et al (2001) used an elastic two-dimensional model to model the surface asperities on both the pin and the bushing, and report that the in spite of high stresses tending to crush the asperities, they tend to persist even under high pressures.

Having described the key contributions in academic literature for this process, physical trials are described next.

2. Physical Trials

Two sets of physical trials were done. The first set was performed to determine the material behaviour. The second set of trials are physical trials of the joining process, which are later used to validate the numerical model of the process.

2.1. Material characterization
Simple compression test has been done to determine the flow curves of the pin and tube material. Pin and tube materials are two different types of widely available non-alloyed free-machining steels, representative of steels used in interference fit joints.

The flow curves obtained from the compression test, have been evaluated up to the strain value of 0.5 but in a typical metal forming process, this value may reach a value of up to 3. Therefore, flow curves were extrapolated using Ludwik-Hollomon equation, results of which are shown in Fig. 1. There is a significant difference between pin and tube's flow curves. Both of them start from the same yield stress value but the work hardening behaviour differs. While the tube material hardens quickly, the pin is almost perfectly plastic.

![Fig. 1. Compression test results and fitted curves.](image)

2.2. Joining trials

Interference in an interference fitted assembly provides tight intimate contact between mating parts, held permanently by the frictional force produced by the contact pressure between the mating parts. Broadly, there are three types of fits, based on the amount pin-tube interference; clearance, transition and interference fits. The clearance fits allows for some relative motion, while the interference fit provides a tight joint between the two mating parts. This study focuses on interference fits.

Two separate geometries are examined here. A simple, axisymmetric pin-tube geometry and a relatively complex geometry with a grooved pin. Details of both geometries along with physical trials are described below. To study the joining process, experiments on three pin-tube and three grooved pin-tube sets were performed, by pushing the pin into the tube at room temperature. Three different cases were considered: high, medium and low interference. Specimen geometry and setup is shown in Fig. 2 and the dimensions are given in Table 1.

Experiments were performed under controlled conditions on a Zwick/Roell uniaxial tension-compression testing machine. Each experiment was repeated five times and each pin-tube set was carefully centred using a centring tool.

![Fig. 2. Pin-tube geometry (left) and tools (right).](image)

| Case | Tube diameter (mm) | Tube height (mm) | Pin diameter (mm) | Pin height (mm) | Interference (μm) |
|------|--------------------|------------------|-------------------|----------------|------------------|
| 1. High | 3.49               | 30               | 3.57              | 23             | 75               |
| 2. Medium | 3.51              | 30               | 3.56              | 23             | 55               |
| 3. Low | 3.52               | 30               | 3.55              | 23             | 30               |
3. Modelling

3.1. Simple Geometry

The joining process has been investigated using both experimental and numerical methods. Experiments were described in the previous section. This section describes details of the numerical models and their validation against experimental results.

The case of simple geometry was modelled as a two-dimensional axisymmetric problem, with 4-node bilinear full integration axisymmetric elements, using Simulia Abaqus commercial finite element software. Numerical analysis parameters are shown in Table 2. The element type is CAX4 which is a 4-noded bilinear axisymmetric element. Specimen dimensions were given previously in Table 1.

3.2. Grooved geometry

The previous section described the numerical model used for the simple geometry. This model is useful in studying the basic mechanics of the process. However, such simple geometry is of limited applicability in industrial applications. One example of a geometry used in the industry is the grooved pin, shown in Fig. 3b. Such grooved pins are used at the fuel inlet in diesel fuel injectors, where the grooves filter out fuel particles. The filter is held in place by a frictional force created through an interference fit with the main body of the injector. In operation, the filter itself is subject to high pressures, which in high-end fuel injectors can reach the levels of up to 2000 bars. As such, strength of the joint created by an interference fit is critical to the performance of the fuel injector as a whole.

To study the mechanics of such joints, in particular joint strength, a three-dimensional model of the grooved filter and the tube was setup. Geometry of the grooved pin and the tube is shown in Fig. 3. The filter has three grooves, so only one sixth of the geometry is modelled, as shown in Fig. 3b.

| Mesh Size       | Global element size of 0.1 mm with locally refined mesh of 0.025 mm at pin-tube interface |
|-----------------|------------------------------------------------------------------------------------------------|
| Mesh Type       | Continuum axisymmetric 4-node bilinear full integration element (2D) and 8-node brick element (3D) |
| Analysis type   | Elastic-plastic                                                                                |

Fig. 3. Simple and grooved geometry.

3.3. Model Validation

Finite element model of the joining process is a convenient tool for improving the process. However, before a detailed study of the process is performed, the model needs to be validated.

Model validation was done in two steps. First, a mesh sensitivity analysis was performed, followed by iterations to determine the friction coefficient through comparison with physical trials as described in Section 2. Mesh sensitivity was performed by gradually reducing element size while monitoring the maximum joining force. Fig. 4a shows the results; a plot of force and computational time against element size. It is seen that as the element size is reduced, the force values converge to a value. However, at the same time, the computational time increases rapidly, as expected. There is clearly a trade-off between the accuracy of the simulation and the computational time. Element size of 0.025 mm was chosen since any further reduction in element size beyond this point will result in a change of less than 3%, which is considered acceptable at this stage. An extensive study of the numerical parameters and their effects was conducted, including element formulation, contact and stepping parameters,
however the results are not presented here for the brevity. Furthermore, all of the force values are shown relative to the simple geometry case, due to confidentiality.

All of the analyses described have been performed for a constant Coulomb friction coefficient of 0.1, a value typically used for lubricated steel-to-steel contact. In this step, however, a set of iterations was done to determine the friction coefficient. The friction coefficient was determined through comparison with the results of joining trials for both simple and grooved geometry (Fig. 4b and c). The coefficient of friction was determined as 0.14, for both geometries. In both cases, the model agrees well with the experiments; for the simple geometry, the agreement is to within 10%, while for grooved geometry the maximum difference is just under 15%. This is considered acceptable at this stage, however these results also suggest that the model needs to be improved. Ideally, the difference should be close to the 3% from the sensitivity analyses.

4. Analysis

In this section, using the information from both physical trials and numerical trials, a brief analysis of the process is presented. Fig. 5a below shows a force-displacement curve representative of the joining process. An important observation can be made from this figure. The force curve can be split into three regions; first, elastic deformation region, where the contact is initialised and the pin touches the tube without permanent deformation; second, plastic deformation region where the pin deforms plastically and the contact area between the pin and tube gradually increases as the pin is pushed into the tube, leading to an almost linear increase in joining force; third and last, the region where both pin and tube deform plastically, leading to a drop in the joining force. This behaviour is observed for both simple and grooved geometry.

Fig. 5b and 5c below show the force-displacement curves for the simple and grooved geometry, for three different interference values, 33, 55 and 77 μm. One key conclusion to be drawn from both figures is that maximum interference does not provide maximum joint strength; instead the joint force seems to reach the maximum around the average overlap value. This is expected, since at high interference values, the tube tends to deform plastically at an early stage, reducing the effective interference and therefore the contact pressure and the friction force holding the two parts together. Finally, comparing the force for the simple geometry and the grooved geometry, it is seen that the force in the grooved geometry is approximately one half of the force for simple geometry. The ratio of the two forces is in direct proportion to the pin-tube contact area. Perhaps surprisingly, this suggests that using a solid pin, as compared to the grooved pin, offers no advantage.
5. Conclusions

Three main conclusions can be drawn from this study:

It has been shown that due to highly localised deformation at the interface, a relatively small element size is required for accurate modelling of the joining process; the element size of 0.025 mm should be used at the tube-pin interface. This value is less than 1% of the pin diameter.

The model agrees with the physical trials to within 15%, which at this stage is considered acceptable. However, the model needs to be improved. Given that both material properties and numerical parameters were determined very carefully, the main point to be considered in future work is modelling of the friction behaviour. Coulomb’s friction model is limited, and may be overestimating the frictional force at high contact pressures. A more appropriate model could be the model proposed by Bay-Wanheim (1976), which relates the frictional stress to contact pressure, allowing accurate modelling of frictional stress in high-pressure sliding contact.

Analysis of the process has led to three main conclusions. First, as the pin is pushed into the tube, both pin and the tube deform elastically at early stage. At mid-stage, tube is elastic, with the pin deforming plastically. At the late stage as both pin and tube deform plastically, the force starts dropping by up to 20%. Second, maximum interference does not provide maximum joint strength; instead the joining force seems to reach the maximum around average interference value. Third, the force in the grooved geometry is approximately one half of the force for simple geometry, in direct proportion to the pin-tube contact area.

Lastly, it should be mentioned that the effect of surface quality, various material combinations and lubrication has not been examined here. These parameters were identical for all experiments, however no variation on these parameters has been studied yet.

As a final note, it should be stated that due to confidentiality, all of the force-displacement graphs in this paper have been shown relative to the simple geometry. For more details about the analyses the corresponding author should be contacted.

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