EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF ELECTROMAGNETIC CRIMPING PROCESS FOR JOINING OF HELICOPTER STRUCTURES

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Abstract

The present study investigates the electromagnetic crimping process as an alternative to thermally welded joints with different form-fit elements like grooves, pockets, and knurlings. The electromagnetic joining technology is based on pulsed magnetic fields to shape components made of electrically conductive materials and it is able to manufacture form-fit or welded joints. First, the analytical methods are presented to design a lightweight helicopter's cyclic stick by the electromagnetic joining process based on maximum applied pilot control forces. Furthermore, approaches to calculate the maximum axial and torsional load transfer between the joining partners are given. The results are used in a two dimensional finite-element simulation to determine the process parameters and to optimize the groove design with respect to shear stresses. A good agreement between the numerical results and the experimental investigations is shown. The pull-out force is set as the failure criterion of the connection and the specific joint strength of different groove shapes is compared with the analytical model. Due to the slight increase of the total weight at the presented weight analysis, proposals for design optimization with focus on the joining zone are made. Despite this fact, the cost analysis shows a reduction of production costs. The achieved main goal of the presented study is the proof of feasibility of substituting thermally welded connections with electromagnetically crimped joints made of lightweight components and the proof of the remarkable potential of reducing production costs and time of aeronautic components.

1. INTRODUCTION

The helicopter industry is subject to a constant pressure for new and further developments of manufacturing technology. Increasing interest in unmanned aircrafts as well as developments in the direction of hybrid-electric propulsion systems are some of the other drivers, which encourage the aircraft industry to permanently look for alternative manufacturing processes for lightweight components to improve cost and weight. Weight saving has a high priority in the aviation industry due to the potential of increasing the payload by means of a lighter design at a constant performance. Increasing competitive pressure on cost and demands resulting from a growing environmental awareness are also motivating helicopter manufacturers for lightweight construction.

Among others, designing components made of light alloys or composite materials, application of hybrid materials and additive layer manufacturing are the methods, which serve for weight saving in aerospace applications. In order to ensure the same or enhanced technical performance of a lightweight design, appropriate manufacturing methods are to be utilized. Innovative manufacturing processes allow the application of lightweight materials effectively to achieve both weight reduction and performance improvement.

Electromagnetic crimping is a joining-by-forming technology for tubes and profiles. The joining effect is based on an undercut in one of the joining partners, which is usually the inner part. After forming the other outer joining partner into this undercut, which is usually a groove, the axial or torsional relative movement is inhibited. The design of form-fit elements has been investigated in several studies, e.g. [1, 2].

The targeted deformation of the outer joining partner is initiated by Lorentz forces as a result of a high impulse current which is discharged via the tool coil. One characteristic of this technique is the very high forming velocity, which can exceed the velocity of sound. The process duration is thus in the sub-second range. Since the formability of many materials is increased under increased forming velocities, this can be beneficial for the filling of the undercut, which is a key parameter for the quality of the joint. The forming velocity can be easily controlled via the discharge energy. Moreover, the process does not require a

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mechanical contact between the tool coil and the part, which allows for forming and joining of coated parts. The electromagnetic compression of the outer joining partner requires a certain level of electrical conductivity of the respective material. For this reason, the process is especially suitable for forming of copper or low-density aluminum alloys. Since the joining process is not based on heat in joining-by-forming processes, also the joining of dissimilar materials is possible. Based on the mentioned advantages of the electromagnetic crimping process, the objective of the presented study is the application of the process for joining of helicopter parts. The process has a great potential for replacing mechanical and thermal joints between profiles and thus support lightweight goals. The study comprises the feasibility analysis of the electromagnetic crimping process for the fabrication of components for aeronautical applications. The analysis is performed at the example of a helicopter's cyclic stick. This stick is responsible for the forward and backward movement as well as the lateral movement capability of the aircraft.

The targeted deformation of the outer joining partner is initiated by Lorentz forces as a result of a high impulse current which is discharged via the tool coil [3]. One characteristic of this technique is the very high forming velocity, which can exceed the velocity of sound. The process duration is thus in the sub-second range. Since the formability of many materials is increased under increased forming velocities, this can be beneficial for the filling of the undercut [4]. The forming velocity can be easily controlled via the discharge energy [5]. Moreover, the process does not require a mechanical contact between the tool coil and the part, which allows for forming and joining of coated parts [6]. The electromagnetic compression of the outer joining partner requires a certain level of electrical conductivity of the respective material. For this reason, the process is especially suitable for forming of copper or low-density aluminum alloys. Since the joining process is not based on heat in joining-by-forming processes, also the joining of dissimilar materials is possible. The process of electromagnetic crimping of tubes has been investigated previously [7]. It was shown that the achievable joint strength can almost reach the strength of the base material depending on the groove design.

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In the helicopter control system, this type of movement is generated by the cyclic adjustment of the pitch angle of each individual rotor blade. Figure 1a shows the cockpit of an H135 helicopter with the three control units: pedals, collective lever and cyclic stick. The pedals are used for a control of the movement of the aircraft around its vertical (yaw) axis. By using the collective lever, the ascending and descending movement is controlled.

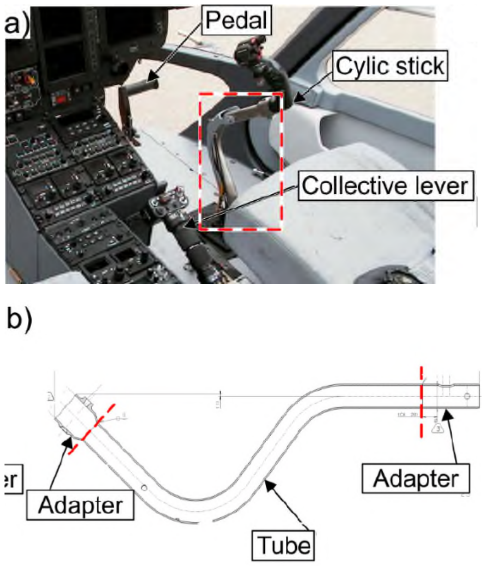

Figure 1 a) Cockpit of an H135 with control devices [8], b) Original component: Cyclic stick made of steel 15CDV6.

2. ANALYTICAL JOINT DESIGN

The original cyclic stick is made of a bent profile with two adapters welded to the profile for connection of the pilot stick to the cyclic shaft and to the cyclic grip, see Fig. 1b. The wall thickness of the tube is sf. The component is made of low carbon steel 15CDV6 and designed for maximum pilot control forces. It is crucial for the safe operation of a helicopter that the control sticks do not fail, e.g. in case of an emergency. The main load on the stick has components in bending and axial pulling directions.

As a prerequisite for the substitution of the steel by a lighter material like aluminum EN AW-6060 T6, the same bending stiffness must be achieved. According to Eq. 1, the bending stiffness depends

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on the Young's modulus E and the second moment of area I_y, which in turn depends on the inner and outer radius in case of a tube.

(1) $S_B = E \cdot I_y$ with $I_y = \frac{\pi}{4} \cdot (r_o{}^4 - r_i{}^4)$

Another constraint is the ergonomic handling of the component. For this reason, the outer diameter of the tube should not exceed a certain value. By the use of Eq. 1, the minimum wall thickness of the tube, which results in the same bending stiffness, was calculated as $s_{f,min}$. In order to save machining operations, deliverable tubes in the dimensions of the maximum outer diameter and with a reduced wall thickness were chosen, although they have a slightly lower bending stiffness than required. Besides the design for maximum bending stiffness, the critical load cases were calculated and compared in terms of strength as well. Solid cylinders made of EN AW-6060 T6 were used as inner joining partners; there was no acceleration gap between the two parts in order to simplify the positioning. Moreover, the influence of a superposed interference fit can be limited in this case [9].

In a second step, the groove, which serves as the form-fit element of the crimped connection, is analytically designed. For the axial loading condition, the analytical framework developed by [7] is applied. Rectangular grooves are considered, with the geometrical specifications depicted in Fig. 2a. The approach is based on the pull-out force, which is the result of the reshaping of the tube during axial tensile loading. For that, the meridional stress $\sigma_{\phi,D}$ in the point D is determined. Strain hardening effects or changes of the tube wall thickness s are neglected and the shaft is regarded as rigid.

As a failure criterion, the force $F_{y,T}$ is taken into account, which leads to the first relative movement between the joining partners in axial pull-out testing. As described by [4], this yield force can be referred to the cross-sectional area of the tube in order to calculate the yield strength. In order to obtain the specific joint strength $\sigma_{y,J}$, the joint strength is referred to the yield strength of a tube during quasi-static tensile testing:

(2) $\sigma_{y,J} = \sigma_{\phi,D} / \sigma_{y,T}$

The diagram in Fig. 2b shows that the specific joint strength increases with an increase of the groove height h and a decrease of the groove width w. The values are normalized to the maximum specific joint strength. The maximum transferable load occurs with a minimum groove width and a maximum groove height. The radius at the groove edge (R_{r2}) was considered in numerical investigations with respect to shearing during the compression of the tube.

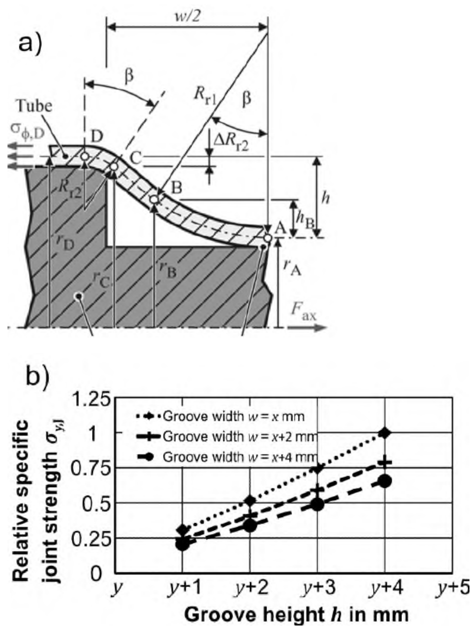

Figure 2 a) Dimensions of the circumferential rectangular groove for the determination of σϕ,D (according to [9]), b) specific joint strength depending on the width and the height of the groove.

3. NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

Numerical simulations with LS-DYNA were performed to further enhance the joint design and to analyze the process of electromagnetic crimping in detail. 2D models were used for this purpose. Measured current curves from experiments were taken as input. The material behavior of the aluminum was described by a quasi-static flow curve determined by tube tensile testing and extrapolated to higher strains with the Voce approach [10]. The strain rate dependent material behavior was taken into account using the model of Cowper and Symonds [11]. The respective parameters have been determined inversely for an electromagnetic tube compression process without inner joining partner. For that, measured radial velocity curves of the tube center at different discharge energies were taken as the basis. In the optimization tool LS-Opt, the strain rate parameters were varied until the numerical velocity curves matched the experimental ones. A similar approach has been presented by [12].

In the simulation of the electromagnetic joining process, rigid shafts were modeled. Here, the focus was on the variation of the groove dimensions and the radius at the groove edge, see Fig. 3a. Moreover the influence of the groove radius on stress peaks in the tube were analyzed, see Fig. 3b. It was found that a small radius (R_{r2}=z) leads to the highest stresses. An increase of the radius at the groove edge leads to a stress reduction of more than 20 %.

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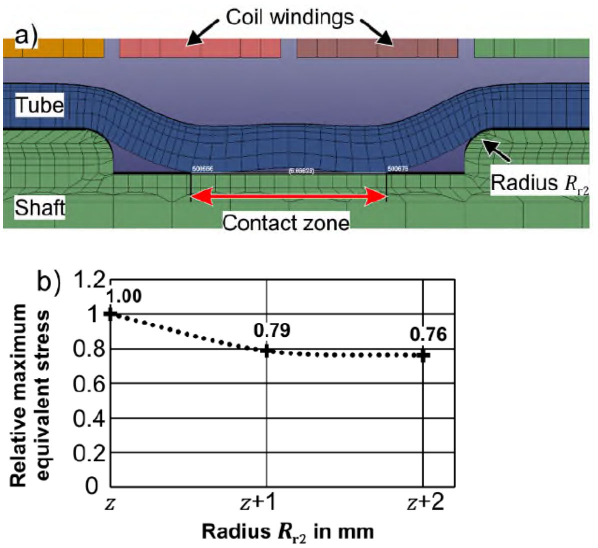

Figure 3 a) Determination of the contact zone from the numerical model, b) equivalent stress depending on the groove radius.

The analytical and numerical investigations were validated by experiments. A Maxwell Magneform Series 7000 pulse generator with a maximum discharge energy of 12 kJ was utilized. This machine was connected to a ten-turn direct-acting compression coil. The tube with a wall thickness $s_{f,min}$ and the shaft parts were degreased and positioned coaxially inside the tool coil, see Fig. 4a. The width and the height of the groove as well as the radius of the groove edge were varied. In previous tube compression experiments, the discharge energy level was determined. The compression velocity of the tube was not high enough for impact welding effects to occur. Each joining experiment was repeated three times. Figure 4b shows an example component joined by electromagnetic form-fit joining.

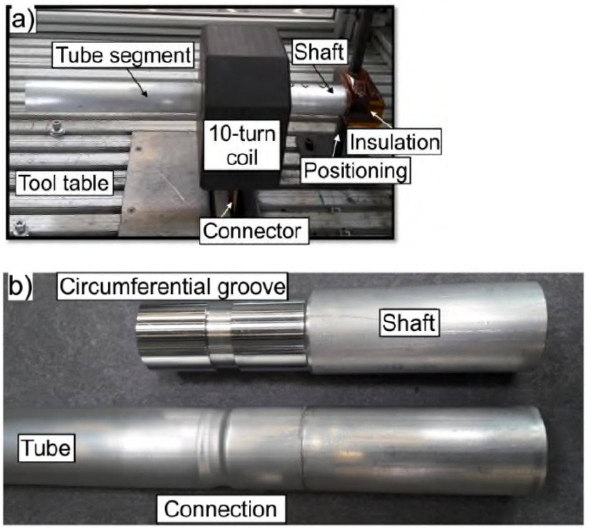

Figure 4 a) Experimental setup, b) Inner joining partner with circumferential groove and connected parts.

The contact zone of the connections was measured by a tactile measurement system. In Fig. 5a it can be seen that the length of the contact zone increases with an increase of the groove width. The numerical results show a good agreement with the experiments. In Fig. 5b the analytical results regarding the specific joint strength are compared to the experimental results.

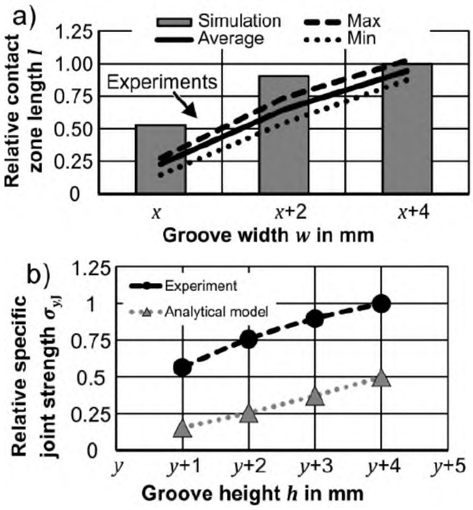

Figure 5 a) Influence of the groove width on the length of the contact zone, b) Influence of the groove height on the specific joint strength.

The failure occurred in the tube material at the edge of the groove. The trend of an increasing joint strength with an increasing groove height can be captured by the analytical model. However, the strength values differ significantly. In the experiments, approx. 50 % higher values can be obtained.

These deviations may result from the fact that strain hardening effects as well as changes of the tube wall thickness during the process are not considered in the analytical model. Thus, the analytical approach allows for a conservative design.

A circumferential groove is not suitable for the transfer of torsional loads. In order to avoid this drawback, special specimens were designed. Two different approaches were tested. For the first approach, cams interrupted the circumferential grooves. So-called spline shafts with two and three cams were designed, see Fig. 6a. The second approach comprises the knurling of the contact area between tube and shaft next to the circumferential groove, see Fig. 6b. For the quasi-static torsion tests, two identical shafts were joined with one tube, see Fig. 6c. The specimens were tested with an angular velocity of 0.25°/s. The axial force was set to zero. In Fig. 6c, the effect of the knurled area on the transmission of torsional loads is depicted. A specimen with a

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circumferential groove without any knurled zone fails at about 12 % of the maximum torsional moment for the same groove geometry with knurling, see Fig. 6d.

Also the axial joint strength can be significantly increased, due to the additional undercuts formed by the knurling tips. The specific joint strength reaches up to 90 % of the base aluminum in pull-out tests.

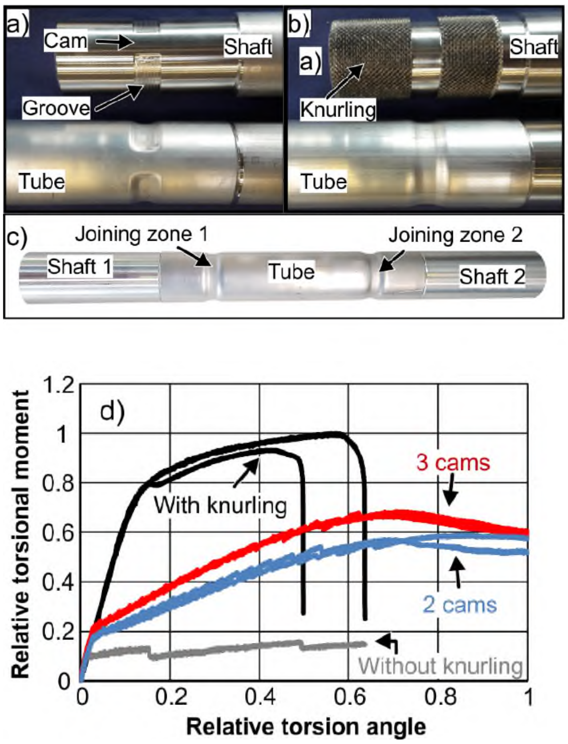

Figure 6 a) Spline shaft, b) knurled part with circumferential groove, c) torsion test specimen, d) result of the torsion test of specimens with and without knurling and with two and three cams.

The number of the cams at the spline shafts influences the maximum torsion moment. With three cams, a torsional strength of approx. 70 % of the maximum torsion moment with knurling can be achieved. The two cam specimens had a torsional load capacity which was approx. 60 % of the maximum torsion moment with knurling, see Fig. 6d. It can be seen, that the failure does not occur immediately as in the knurled specimens. The axial load bearing capacity of the spline shafts is lower than that of specimens with a circumferential groove.

Besides form-fit joining, also welding is possible with an electromagnetically accelerated tube. The so-called magnetic pulse welding process leads to high quality weld seams. With a properly designed process, failure during axial and torsional testing occurs in the aluminum tube [13].

4. EVALUATION OF THE NEW SOLUTION

The assessment of the quality of the proposed solution comprises different aspects. As it was shown, the bending strength of the joined structure fulfils the requirements. However, the increase of the tube diameter compared to the original part and the use of solid cylindrical adapters leads to an overall increase of the mass of the part by 7.5 %. In further designs, the wall thickness of the shaft as well as the overlap between tube and shaft will be optimized. The overlap was set to a certain value in order to facilitate the pull-out and torsional testing. However, the groove width is less than one third of this overlap length, so this has potential for mass savings.

As it was shown in [14] for magnetic pulse welding, polyurethane inserts can be used to reduce unwanted deformations of thin-walled shafts in electromagnetic joining processes. Prestressing of these plastic inserts enhances their functionality. Moreover, they can be easily removed after the joining process and reused. By this way, even hollow adapters could be applied, which would decrease the weight further and allow for cables being laid inside of the component.

The costs of the proposed solution are expected to be lower or at least comparable than the original manufacturing route. This is mainly due to the lower price of the aluminum compared to the steel alloy and a shorter production process time. Further advantages of the new process route are the reduction of fire risks due to the non-thermal joining process and the possibility to combine different materials. Since the electromagnetic joining process is contactless, increased surface qualities are expectable.

5. CONCLUSION

The presented analytical, numerical and experimental investigations demonstrate the feasibility of the electromagnetic crimping process for the production of joints in the aerospace industry. At the example of a cyclic stick, the original steel profile was replaced by an aluminum tube. The thermal welding of adapter parts at both tube ends was substituted by electromagnetic form-fit joining. The dimensions of the aluminum tube were designed to have the same load carrying capability as the original steel part.

The form-fit element in the shaft was designed based on analytical and numerical analyses. Both axial and torsional loading was taken into consideration. It was proven that the pull-out strength can be as high as 90 % of the strength of the aluminium tube material. Knurlings turned out

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to significantly increase both the torsional and axial load carrying capabilities due to the additional undercuts formed by the knurling tips.

The achieved objective of the presented study was the proof of feasibility of substituting thermally welded connections with electromagnetically crimped joints made of light metal alloy components.

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