Design of Electromagnetic Pulse Crimp Torque Joints [*]

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Abstract

Electromagnetic pulse crimping of form fit joints was investigated using tubes with a diameter of 50 mm and a wall thickness of 1,5 mm, in the aluminium alloy EN AW-6060. The tubes were crimped onto steel internal parts, which were designed to bear torsional loads. Grooved, knurl rolled and knurl cut internal workpieces were used. To assess the torque strength of the connections, a torque test set-up was designed and built.

In a first test series, grooved internal parts were used. The influence of the internal workpiece design and the energy level on the torque resistance was investigated. Related to the geometry of the internal workpiece, the following parameters were varied: the groove depth, the groove width, the edge radius and the number of grooves.

In a second test series, knurl rolled and knurl cut internal workpieces were used. For the joints with a knurl rolled internal part, the influence of the knurl pattern, defined by the pitch, was investigated. For the connections with a knurl cut internal part, the influence of the energy level was studied. The different joint failure mechanisms were determined.

Keywords

Electromagnetic pulse joining, Torque crimp joints, Failure mechanisms.

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1 Electromagnetic pulse joining

The electromagnetic pulse technology uses magnetic forces to deform and/or join workpieces. The energy stored in a capacitor bank is discharged rapidly through a magnetic coil. Typically, a ring-shaped coil is placed over a tubular workpiece. When deforming tubular products, the magnetic field produced by the coil generates eddy currents in the tube. These currents, in turn, produce their own magnetic field. The forces generated by the two magnetic fields oppose each other and a repelling force between the coil and the tube is created. As a consequence, the tube is collapsed onto an internal workpiece, creating a crimp joint or a weld joint. In the electromagnetic pulse crimping process, no atomic bond is created; these joints obtain their strength from the combination of an interference and a form fit. A special profiled internal workpiece is therefore used, with for example grooves.

2 Literature survey

As in most mechanical assemblies, the performance of the manufactured joints is evaluated based on their mechanical strength. Figure 1 shows a torque joint made by the electromagnetic pulse crimping process, and with a torsional resistance higher than the tube base material. The feasibility and performance of such joints has been demonstrated, in for example [1,2,3]. However, a better understanding of the electromagnetic pulse crimping process has to be achieved to obtain large-scale industrial applicability.

Figure 1: *Magnetic pulse crimped torque joint used in the Boeing 737, 747 and 777 aircraft. Left: after torque testing [1]*

As discussed in [4], the transferrable torque of a joint is proportional with the circumferential forces and with the effective length of the joint zone, as long as this length has experienced the full influence of the electromagnetic field. When the joint length is larger than the work range of the coil or field concentrator, multiple pulses can be used. Furthermore, deeper grooves result in a higher transferrable torque, as long as the reduction of the tube wall at the groove edge is less detrimental to the joint strength than the additional interlocking surface is beneficial to the joint strength.

The transferrable torque is proportional to the number of grooves in circumferential direction. This last assumption is justified as long as the different grooves do not affect each other’s strength. When using too many grooves, the width of the grooves is insufficient in comparison with the groove depth, leading to a weaker joint and eventually cutting of the tube during electromagnetic pulse crimping.

Guidelines for design values

In [4], experiments are described with tubes with a diameter and wall thickness of 46 mm and 1 mm resp., in the aluminium alloy EN AW-6063-T5. The following design rules are specified for joint strength optimisation:

- groove depth d: $t < d < 0{,}057 \times D$ [5]
- groove edge radius r: $(0{,}5t \text{ or } t)^* < r < \{0{,}5d \text{ or } \min(t; 0{,}5d)\}$

with: t: tube wall thickness (mm), and D: diameter of the specimens (mm)

*: The lower limit of the groove edge radius is significantly depending on the method of specimen testing. In [4], it was demonstrated that a smaller groove edge radius is allowed for torsion-loaded joints, due to the decreased dependency of the joint strength on the tube wall thickness reduction. A value of 0,5×t or t for the groove edge radius is a good guideline for respectively torque and axial joints.

The groove width should always be minimised because the smaller its value, the more grooves the internal workpiece can contain, leading to a higher torsional strength of the electromagnetic pulse crimped joint. Based on earlier work on axial joints [6], the lower limit for the groove width was determined as 3 to 4 times the groove depth, which results in reliable joints, exhibiting only limited tube wall thickness reduction.

For reasons of material cost, the groove length should be as short as possible without jeopardising the integrity of the torque joint or the load bearing capacity. Furthermore, the longer the internal workpiece, the longer the necessary axial length of the coil or field concentrator. For an increased work length, the required energy will also increase, together with the equipment cost.

3 Overview of the experiments

Electromagnetic pulse crimping of form fit joints was investigated, using tubes made of the aluminium alloy EN AW-6060 T6. The tubes had a diameter of 50 mm and a wall thickness of 1,5 mm. Solid internal workpieces were used, made of steel S355.
The experiments were performed using a Pulsar model 50/25 system with a maximum charging energy of 50 kJ (corresponding with a maximum capacitor charging voltage of 25 kV) and a discharge circuit frequency of 14 kHz. The total capacitance of the capacitor banks equals 160 µF. The pressure resulting from the magnetic flux induced by a 5-turn aluminium Bitter coil (length: 100 mm, internal diameter: 165 mm) is concentrated over the processing area using a conical field concentrator with a workzone width equal to 15 mm [7,8]. The crimp joints were produced using a single pulse.

In order to study the optimisation possibilities, knowledge concerning the occurring joining mechanisms is required. As the manifesting joining mechanisms are very dependent on the geometry of the internal workpiece, the relation between the occurring joint strength and the workpiece design was examined. In a first phase, crimp connections with internal parts containing longitudinal grooves were investigated. In a second phase, knurl rolled and knurl cut internal workpieces were used as an alternative concept.

To evaluate the performance of the crimp joints, the torsional strength of all specimens was determined using a torque testing set-up (Figure 2). With this device, the torsional resistance of the joints as a function of time and angular displacement was measured.

4 Design of torque joints using grooved internal workpieces

4.1 Design of torque joints with internal workpieces with 5 grooves

In a first test series, internal workpieces were used containing 5 longitudinal grooves, but no axial load bearing capacity (see Figure 3). By using this design of the internal part, it is possible to investigate the pure torque bearing capacity of the crimp connections.

In case of a 5 groove design, 5 parameters are of importance: the groove length, width and depth, the groove edge radius and the energy level. For obtaining an optimal design of the internal part in terms of torsional strength, experiments were performed in which the above mentioned parameters were varied. The groove length was assumed to be constant, and adapted to the internal field concentrator length (15 mm). The proportional influence of this factor on the torque strength justifies the choice to keep it constant in all experiments.
If 3 different parameter values for the 4 other parameters are considered, 3^4 or 81 experiments would be required to obtain a full understanding of the influence of all parameters. To reduce the amount of experiments, a statistical technique, called Response Surface Methodology (also called 'Box-Wilson' method) was used. This allowed a reduction of the number of experiments to 2^4 = 16 designs, and 2 additional experiments using an internal part with a so-called reference design (shown in Figure 4).

Figure 2: *Torque testing setup*

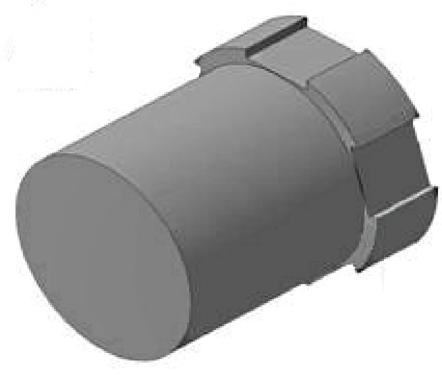

Figure 3: *Design of the internal part*

The parameters values of the reference design and the parameter range were determined as follows:
- Groove length. Since the used field concentrator has a work length of 15 mm, it was decided to keep the groove length constant at 12 mm.
- Energy (defined by the capacitor charging voltage). Based on preliminary experiments, the reference value was chosen equal to 3,9 kJ. The lower and upper value of this

parameter was equal to 3,4 and 4,5 kJ (corresponding with a charging voltage of 6,5 and 7,5 kV).

- Groove depth. Based on the design rules in [4], the following parameter range was found for the groove depth: 1,5 mm < d < 2,85 mm. As the influence of the tube wall reduction on the joint strength is not so big, it was decided to use larger values for the parameter range: 2,3 mm < d < 3,3 mm. The reference value was set equal to 2,5 mm.
- Groove width. As the ratio groove width/groove depth ≈ 3…4 provides a reliable form fit [6], the groove depth was varied at the values 8 and 12 mm. The reference value was equal to 10 mm. For aluminium tubes with a diameter of 50 mm and taking into account a sufficient width of the collar in between the grooves, the possible number of grooves can vary between 4 and 8. In this test series, the amount of grooves was equal to 5.
- Groove edge radius. In [4], the following range for the groove edge radius r is provided: 0,5×t < r < {0,5×d or min(t;0,d)}. This results in a range of 0,75 mm < r < 1,25 mm. A groove edge radius of 1 mm was chosen as the reference value. Since the range obtained by the design rule is very small, it was decided to widen this range, and the lower and upper limits were set at 0,5 and 1,5 mm respectively.

Figure 4 shows the drawing of the reference design. An example of a crimped connection is shown in figure 5.

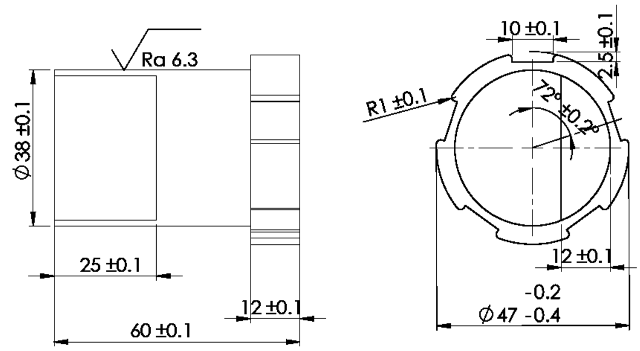

Figure 4: *Drawing of the reference design with the according parameter values*

Figure 5: *Example of a torque crimp connection (internal workpieces with 5 grooves)*

The crimp connections were mechanically tested in the torque test set-up to determine the torsional joint strength. For all connections, a torque versus angular displacement curve was obtained. The torque strength of the crimp connection with the reference design was equal to 215 Nm. In this test series, a maximum torque strength of 305 Nm was measured. The investigation of the influence of the parameters led to the following conclusions:

- The influence of the energy level is low in the investigated range. It can be expected that the influence of the energy is low as long as no severe tube wall reduction at the groove edges is observed after the crimping operation.
- Two failure mechanisms were observed; more specific bending of the tube out of the groove, with and without cracking of the tube wall. A higher joint strength is observed for the first failure mechanism (with tube cracking).
- A small groove edge radius is more beneficial. The large difference in joint strength proves the importance of this parameter. A similar conclusion was also found in [4].

- A significantly stronger joint is formed when using a groove width of 12 mm. A wider groove enables a better interlocking of the tube with the groove edge.
- The influence of the groove depth on the joint strength is not clear. Certainly, it is smaller than the influence of the groove width.

4.2 Design of torque joints with internal workpieces with 8 grooves

A test series was performed dedicated to the design of the internal workpieces with 8 grooves. Based on the results of the previous test series, it was decided that:

- A large groove width was used; this parameter was chosen equal to 12 mm.
- The groove length was again equal to 12 mm.
- A small groove edge radius was used; and chosen equal to 0,5 mm.
- The energy level was again varied between 3,4 and 4,5 kJ (corresponding with a charging voltage of 5,5 and 6,5 kV).
- In the previous test series, the influence of the groove depth was not completely clear; so 4 different groove depths were used for the internal parts: between 2,3 and 3,8 mm, in steps of 0,5 mm.

A drawing of the internal part with a groove depth of 2,3 mm is shown in Figure 5.

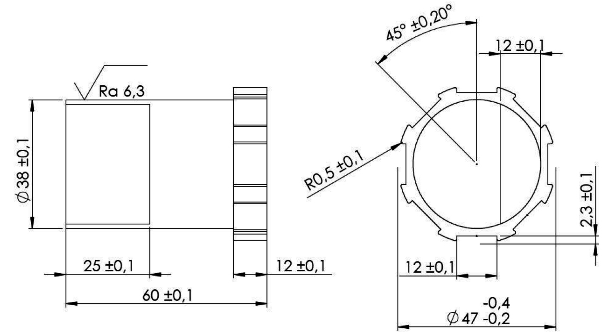

Figure 5: *Drawing of an internal workpiece with 8 grooves (groove depth 2,3 mm)*

The torque-angle curves obtained during torque testing of the 8 torque joints looked very similar to the ones obtained for the 5 groove design torque joints. Visual inspection of the workpieces after testing led to the conclusion that now only 1 failure mechanism was present. The failure mechanism consisted of bending of the tube out of the groove, together with cracking of the tube (see Figure 7). All tested specimens showed cracks at the groove edges. Since the design of the internal workpieces with 8 grooves was based on the best performing design with 5 grooves, which failed due to cracking of the tube wall, this was an expected observation.

An analysis of the influence of the parameters on the torque strength was carried out. Only the charging voltage and the groove depth were varied, as the influence of the other parameters was clear.

The influence of the energy level was again very small (<2% difference).

It was clear that a groove depth of 3,8 mm resulted in lower torque values (463 Nm). This is the consequence of a too big tube wall thickness reduction at the groove edges, as shown in Figure 8. A groove depth of 3,3 mm resulted in the highest torque value (526 Nm). A clear trend of the joint strength as a function of the groove depth remained however undetectable.

Figure 7: *Close-up of the groove zone of a test specimen before (left) and after (right) torque testing*

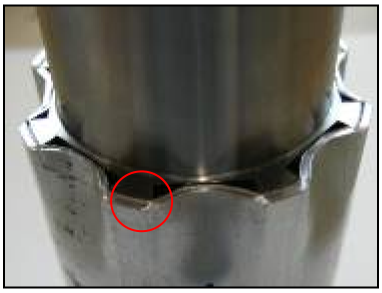

Figure 8: *Reduction of the tube wall at the groove edge*

All torque joints using internal workpieces with 5 or 8 grooves showed a joint strength lower than that of the tube base material. Figure 19 shows the relative joint strength of the connections, calculated as the absolute joint strength divided by the tube base material torsional strength. On average, a ratio of 1,617 was found between the torque strength of crimp joints with 5 and 8 grooves. This ratio is approximately equal to the groove ratio (8/5 = 1,6), which demonstrates the linear relation of the joint strength and the number of grooves, as expected from literature.

4.3 Conclusions concerning torque joints using grooved internal parts

- For both test series, the influence of the energy level is low for the investigated ranges. A limited amount of tube wall thickness reduction is allowed, as long as the beneficial effect of the additional interlocking capacity is not detrimental for the joint strength. This extra interlocking capacity forces the tube to fail by bending of the tube out of the groove, with cracking of the tube wall. A higher joint strength is observed for joints that fail by this failure mechanism. The maximum joint strength is observed at a lower angular displacement than for joints failing due to bending of the tube out of the grooves.
- A small groove edge radius (0,5 mm) and a large groove width (12 mm) are preferred.
- The groove depth has less influence on the joint strength than the groove width, but the optimal groove depth value remains undetermined.
- For similar grooves, a direct proportional relation exists between the joint strength and the amount of grooves, as was stated in literature. This conclusion applies to the range of 5 to 8 grooves. Experiments with designs with a larger amount of grooves should be performed to confirm further proportionality.

5 Design of torque joints using knurled internal workpieces

5.1 Design of torque joints using knurled rolled internal workpieces

In a first phase, preliminary experiments were performed with knurled rolled internal workpieces. The knurl zone had a length of 25 mm. With this size, a large region influenced by sufficient magnetic pressure to plastically deform the tube onto the inner workpiece is used and a maximum joint contact surface is generated. No clearance between the internal part and the tube was present, which means the tube internal surface and the knurl pattern made contact prior to the crimping operation. Three different knurl sizes were used, defined by the pitch: 1,2; 2 and 3 mm. All crimping experiments were done with an energy of 5,12 kJ. An example of an internal workpiece is shown in Figure 9.

The coarse knurl pattern provided the maximum torsional resistance (376 Nm), which is 2 times higher than for a fine knurl pattern (164 Nm).

The occurring failure mechanism was the same for all the test specimens. The internal workpiece started to slide in the tube and a wear mechanism developed. The steel knurl pattern made indentations in the internal surface of the aluminium tube. This wear mechanism could be observed in the torque curve as well (see Figure 10). A decrease of the torsional strength is detectable in the figure in the form of a decreasing amplitude of the load variation.

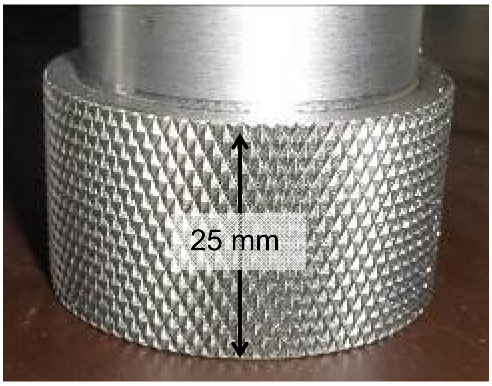

Figure 9: *Internal workpiece with a knurl zone of 25 mm*

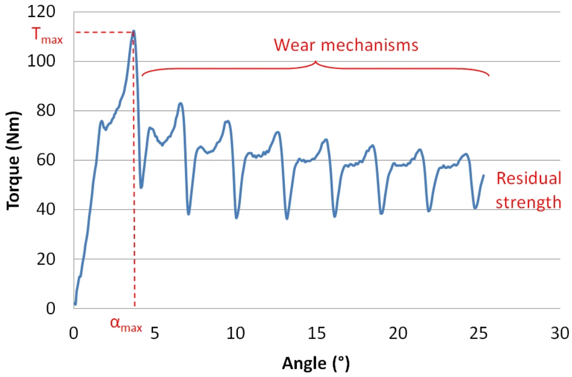

Figure 10: *Torque versus angular displacement of a knurled test specimen*

5.2 Design of torque joints using knurled cut internal workpieces

The length of the knurled cut internal surface was chosen equal to 25 mm (see Figure 11). This allowed to compare the results with the preliminary experiments using a knurl rolled internal part. The pitch size of the grooves was 2 mm, and a groove depth of 1 mm was created. The initial gap between the tube and the internal workpiece was equal to 1 mm. This allows the aluminium tube to impact with a higher velocity onto the internal workpiece. The influence of the energy level was investigated, which was varied between 5,12 and 20,48 kJ.

Since the grooves have dimensions comparable to the tube wall thickness, a limited amount of tube wall shearing into the grooves is possible, allowing interlocking to be achieved (see Figure 12).

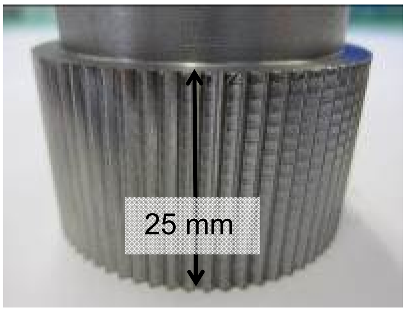

Figure 11: *Internal workpiece with a knurl groove geometry*

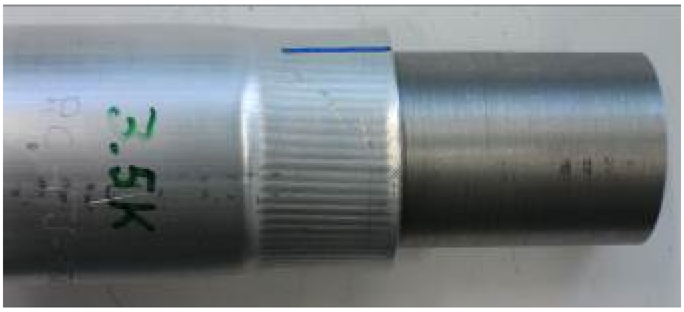

Figure 12: *Example of a torque joint with a cut-knurled pattern*

For every value of the charging energy, two experiments were performed. Every connection was mechanically tested. As can be seen in Figure 13, no influence of the energy level on the torque strength can be observed. Only for a charging energy of 5,12 kJ, somewhat lower torque values were measured. This implies that the energy level can be chosen in a broad range.

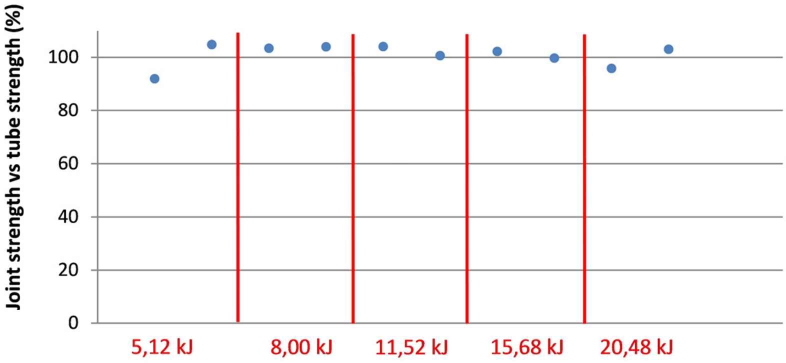

Figure 13: *Relative joint strength of the tested knurl groove joints.*

The following failure mechanisms were observed.

Failure mechanism 1: Sliding of the internal workpiece in the tube

The obtained torque-angle curve was similar to the curve obtained for the crimp connections with the knurled rolled internal parts (see Figure 10). A maximum torque value close to the theoretical tube strength was reached. Further angular displacement causes the internal workpiece to rotate inside the aluminium tube, causing wear at the internal surface.

Failure mechanism 2: Buckling of the tube, without cracking of the tube in the joint zone

The torque-angle curve of a specimen failing by this mechanism is shown in Figure 14. The repeating pattern observed in the previous case is no longer present. The decreasing torque value is no longer due to failure of the torque joint, but due to buckling of the aluminium tube (as shown in Figure 15).

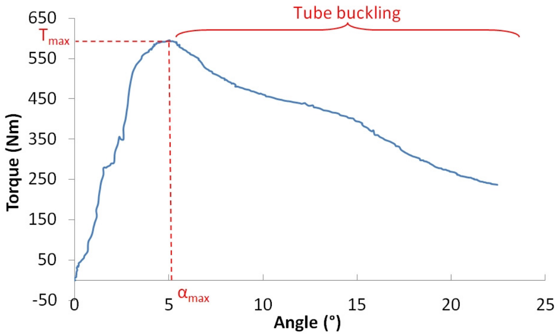

Figure 14: *Failure mechanism 2: torque versus angular displacement*

Figure 15: *Failure mode 2: tube buckling, without cracking*

Failure mechanism 3: Buckling of the tube, with cracking of the tube in the joint zone
The torque-angle curve of a specimen failing by this mechanism is shown in Figure 16. Although the load on the joint decreases due to buckling of the tube, this particular joint failed due to cracking of the tube shortly after the buckling initiated (Figure 17).

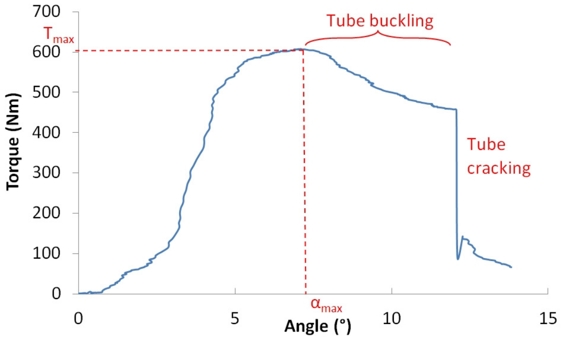

Figure 16: *Failure mechanism 3: torque versus angular displacement*

Figure 17: *Failure mode 3: tube buckling, with cracking*

Failure mechanism 4: Buckling of the tube, with cracking of the tube in the joint zone when using an internal support during torque testing
A steel support was placed inside the aluminium tube during torque testing. In the torque tests executed without the internal support, the maximum tube load is maintained for only a very short time, as the tube starts buckling from the moment the maximum load is reached. Placing a steel support inside the tube causes the tube to remain its strength, even for a higher angular displacement.
The torque-angle curve of a specimen crimped at 8 kJ is shown in Figure 18.

After a first maximum is reached, the tube starts buckling until the internal tube surface makes contact with the internal support. When sufficient contact between tube and support has been established, a reinforcement of the aluminium tube is noticed in the torque-angle curve. This reinforcement continues until cracking of the tube in the joint zone is observed.

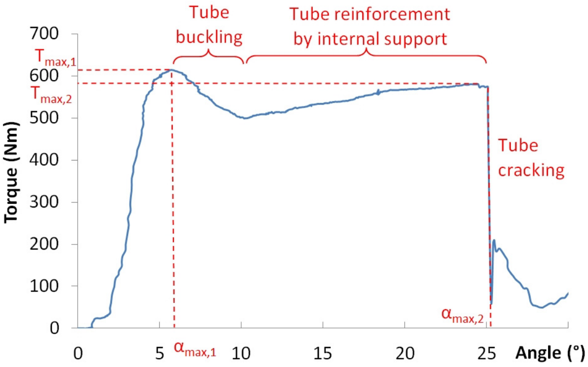

Figure 18: Failure mechanism 4: torque versus angular displacement

5.3 Conclusions

- The joint strength of crimp joint with a knurl cut internal workpiece is high, most of the crimped connections showed a strength equal to that of the tube base material.
- The influence of the energy level on the joint strength is low.
- Within the investigated range of the energy level (5,12 - 20,48 kJ), no detrimental effects of a tube wall reduction has been discovered. Still, the energy should not be set higher than required to obtain the full joint strength.

6 General conclusions

An overview of the relative strength of all tested torque joints is shown in Figure 19. The maximum measured torque strength of a connection using an internal part with 5 grooves was equal to 307 Nm. In case of a connection with 8 grooves, the maximum torque measured was equal to 527 Nm. Based on the average torque strength of all connections, a linear relationship between the torque strength and the number of grooves was observed.

The strength of the connections with a knurl rolled internal part significantly increased for a larger pitch of the knurl pattern. The coarse knurl pattern provided a maximum torque resistance which was 2 times higher than for a fine knurl pattern (376 Nm vs. 164 Nm).
The torque strength of the crimp connections with a knurled rolled internal part showed a large variation, dependent on the parameters used. Generally, the best performing connections had a strength approximately equal to that of the connections using an internal part with 5 grooves.

The crimp connections using a knurl cut internal part exhibit the highest joint strength, equal to the tube base material strength. Since the grooves of the knurl pattern have dimensions comparable to the tube wall thickness, shearing of the tube wall into the grooves was observed, creating a strong interlock of the tube with the internal part.

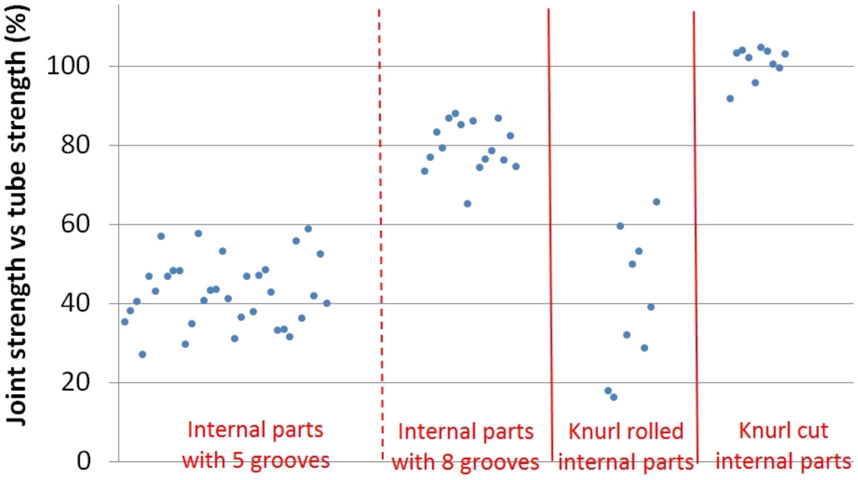

Figure 19: *Overview of the relative joint strength of all tested joints*

It was also concluded that for all designs, the influence of the energy level on the joint torque strength is low in the investigated range. For torque connections using longitudinal grooves, it is advisable to use a small groove edge radius and a large groove width. The groove depth has less influence on the joint strength.

Three types of failure mechanisms appeared during torque testing. In order of increasing joint strength, we can distinguish:

- The internal workpiece slides in the tube.
- The tube cracks at the joint.
- The tube buckles, and the joint does not fail. Instead, the tube base material fails.

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