Improved Crimp-Joining of Aluminum Tubes onto Mandrels with Undulating Surfaces

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Abstract

Over its history electromagnetic forming (EMF) has probably seen far and away more application in assembling tubes or rings onto (or into) nominally axisymmetric mating elements. The vast majority of these assemblies does not require any significant structural integrity or strength. However, a small fraction of these are designed and fabricated for mechanically-demanding applications. There are two key factors (which seem to be largely independent) that are key in the design and performance of a crimped-electromagnetic tube joint. First is the state of residual stress that exists after the crimped joint is created. A natural interference fit seems to be a fairly general feature of EMF crimp joints. This interference gives a backlash-free joint that will not fret. The second key issue is the configuration of the joint. The fabrication of designed interlocking geometries is required to create a joint that maximizes mechanical strength while minimizing the electromagnetic energy and forces required to create it. Both of these issues will be considered here. Here we consider crimping onto 'textured' surfaces such as screw threads and knurls. We show experimentally that approaches of this type can give joints that exceed the strength of the tube both in torsion and axial loading. Analysis methods based on coupling impact-indentation and break-before-strip criteria can be used to compare joints made in this way with those based on the more traditional large scale deformation of the tube. One of the advantages of forming onto 'textured' surfaces is that a number of small pulses (possibly generated by small and inexpensive capacitor banks) can be used to create a joint that has the strength of the parent tube, without any heat affected zones or distortion. Again, the natural interference fit developed by impact eliminates the potential for fretting.

Keywords:

Joining, Strength, Aluminum, Electro-impulse

1 Introduction

Electromagnetic forming (EMF) is most commonly used to create assemblies by collapsing tubes or rings onto (or into) nominally axisymmetric mating elements. The majority of these assemblies does not require significant structural integrity or strength. However, a fraction of these are designed and fabricated for mechanically-demanding applications. One example of the use of electromagnetically crimped joints in a very demanding application are torque tubes that are used in the Boeing 777 and other recent Boeing aircraft models. Here, aluminum tubes are crimped onto steel yolks. The development of high performance crimp joints via electromagnetic forming has many very attractive advantages. Most important among these:

- The joints can match the strength of the parent tube. This is seen in many photographs in papers and websites [1,2], but has been otherwise poorly documented.
- The joints made are distortion-free and can be very dimensionally accurate because there is little heat input.
- Again, because there is minimal heat input there is no heat affected zone in the joint. Therefore it is possible to reach the strength of the parent tube. This is not typically possible with fusion joints.
- There has been significant interest in using electromagnetically driven high velocity impact to produce impact-welded structures. This is largely due to public statements and advertisements by companies such as Pulsar and Dana. However, high impact velocity is required for impact welding (>500 m/s is typical). This makes the fabrication of robust electromagnetic forming coils and capacitor bank systems difficult.

We believe high strength structural joints can be very cost effectively fabricated by electromagnetic crimping, without requiring the very high pressures normally required with electromagnetic pulse welding. The purpose of the present work is to demonstrate that one can rather easily develop fretting-free joints between cylindrical tubes and nominally cylindrical nodes that do not require excessive energy to form and have the same strength as the parent metal tube. Directions that may lead to comprehensive models of strength are also indicated.

2 Elements of Crimp-Joint Strength and Performance

Despite the fact that electromagnetic crimp tube joining has been extensively practiced, and there are some publications [3] that analyze the creation and strength of these, there is not nearly a sufficient published base of understanding that would allow an engineer to be able to design an EMF crimp joint, nor can its performance be reliably predicted.

There are three key factors that are divided because they require separate analytical approaches that dictate design and performance of a crimped-electromagnetic tube joint.

- There is a state of residual stress that exists after the crimped joint is created. A natural interference fit seems to be a fairly general feature of EMF crimp joints. This interference gives a backlash-free joint that will not fret.

- The second key issue is the bulk configuration of the joint. Recesses in the node to be joined require bulk deformation of the tube to separate the units.
- Lastly, indentation of the surface (with indentation depths on the order of the sheet thickness, or less) is also important. Such surface recesses are the mechanisms by which bolts carry axial loads.

Here we discuss some recent experiments and thinking on each of these three issues and we will suggest directions towards the development of quantitative design methods for crimp joints. The emphasis will be on the issues of the interference fit formed by high velocity forming and the use of surface indentation to create joint strength.

We have recently carried out experimental and analytical studies with the aim of understanding the residual stress state that exists in an axisymmetric crimped joint after formation. There are two important components. The impact creates a natural interference fit and gives a radial distribution to the stress state. Also cooling from the temperatures induced by EMF creates a strain that must be considered. Experiments give a clear trend of increasing interference with increasing impact energy, while modeling results are less clear.

The configuration of the mandrel upon which a tube is crimped is also a matter of concern. In past designs [3,5,7], depressions that were several times the tube thickness in width and depth were considered. This is the approach taken by Boeing and others. Here we consider crimping onto ‘textured’ surfaces such as screw threads and knurls. We show experimentally that approaches of this type can give joints that exceed the strength of the tube both in torsion and axial loading. Analysis methods based on coupling impact-indentation and break-before-strip criteria can be used to compare joints made in this way with those based on the more traditional large scale deformation of the tube. One of the advantages of forming onto ‘textured’ surfaces is that a number of small pulses can be used to create a joint that has the strength of the parent tube, without any heat affected zones or distortion. Again, the natural interference fit developed by impact eliminates the potential for fretting.

3 Interference Fits

Empirically, it is very clear that in high velocity crimp-joining an interference fit between a collapsed tube and mandrel is very common. It is also common if a tube is expanded into a cylindrical cavity. Ultimately, it would be quite useful to have analytical models to predict this level of interference. First, it is useful to have measured data for this. That is the goal here, to measure the level of interference developed in several simple tube-collapse experiments onto varied mandrels.

Fairly simple experiments involving crimping onto mandrels of three different materials were performed. The tube used for crimping is aluminum 6061-T6 with outer diameter of 28.5 mm and wall thickness of 1.67 mm. The crimped tubes had a height of 12.7 mm. These were collapsed onto mandrels with very different elastic stiffness. The stiffest mandrel used was mild steel, 6061-T6 aluminum had elastic properties matching those of the ring, and the reinforced phenolic composite known by the trade name G-10 was used as the last mandrel. A simple single turn coil was used for crimping. High conductivity copper was chosen for this coil design to provide both enough strength and conductivity. The coil is 25.4 mm thick and has a 29.1 mm hole inside to provide concentrated current flow in the internal surface of the coil. The 29.1 mm hole was tapered down to 12.7 mm in height, which is the coil's working area during electromagnetic process. A standard 16 kJ (8.3 kV @16 kJ) Maxwell-Magneform capacitor bank was used as the energy source. Crimps were made at varied bank energies as indicated by fractional energy stored.

After crimping, each sample was strain gauged and the strain gauge was zeroed. Then the ring was cut with a band saw longitudinally at a location diametrically opposed to the strain gage location. See Figure 1 for the overall system used in crimping and strain gauging. The entire ring develops a measured compressive hoop strain at the surface that is measured by the strain gage after cutting. This measured strain as a function of crimping energy is shown in Figure 2. There are two separable components to this strain. First, the ring changes its radius of curvature from that of the mandrel (on the inside) to one that is always larger, as the ring opens up on cutting. Ring opening displacements were measured for each ring after cutting and this can be related to the tensile strain gradient across the ring as:

$$\Delta\varepsilon_{max} = \frac{t}{2}\cdot\left(\frac{1}{\rho_1}-\frac{1}{\rho_2}\right) \tag{1}$$

where t is the ring thickness and ρ represents radius of curvature. The strain change between the inner and outer surface is calculated and presented in Figure 1.

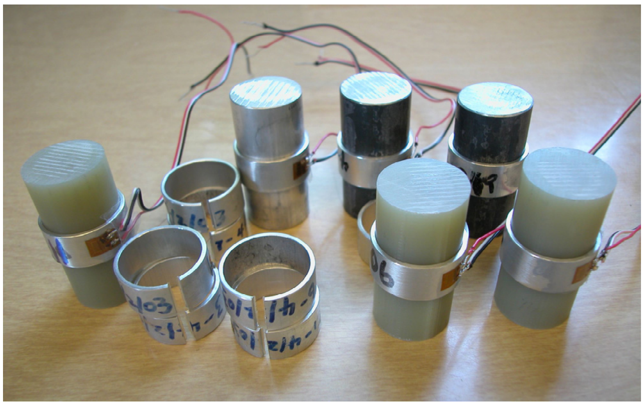

Figure 1: *Photograph of typical crimped rings, mandrels, and strain gauges*

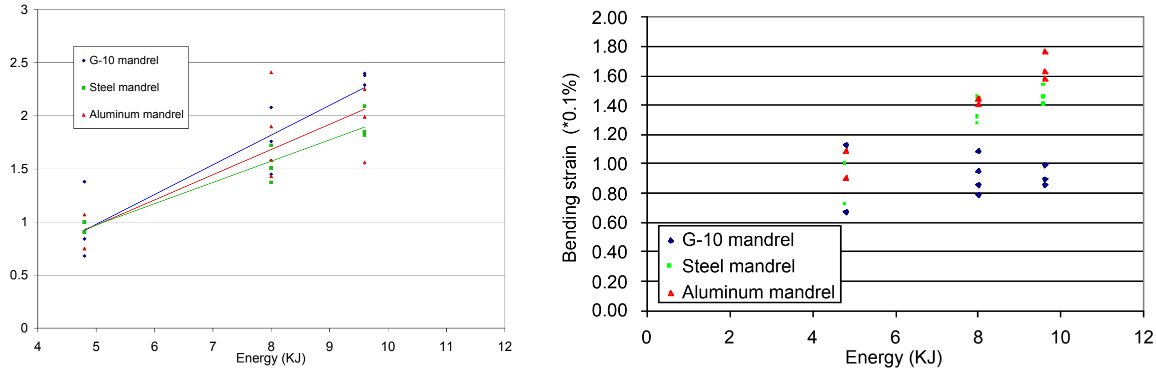

Figure 2: *Raw data showing: The strain measured by the strain gage (left) and the strain contributed by bending as measured by opening of the ring after cutting (right)*

By subtracting the bending strain from the strain measured at the surface gauge, we can estimate the pure extension strain that exists on the inside surface of the gauge prior to cutting. This is shown in Figure 3. This shows that there are significant interference strains for all three mandrels and the level of interference increases with increasing discharge energy and also increases as the stiffness of the mandrel decreases. These strains are also on the same order as one may expect based on thermal contraction. Ring heating is often on the order of 30°C. In the case of aluminum, cooling from this temperature can cause a contraction of about 0.07%. It seems that this is not a sufficient explanation for the interference fits observed, however because one can also develop interference by expanding rings into hollow cylinders.

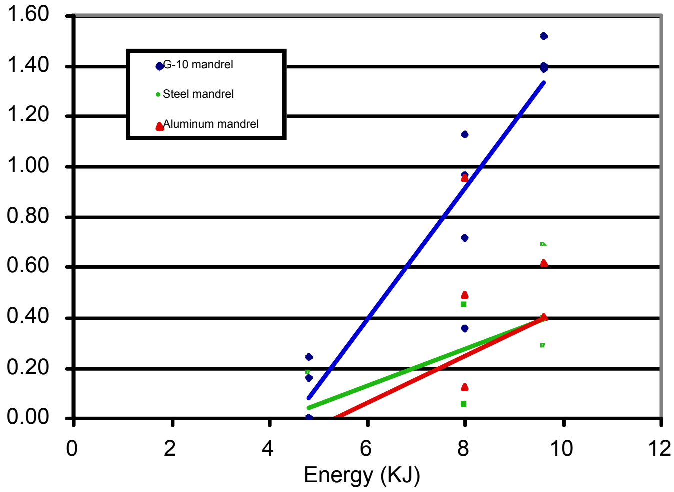

Figure 3: *Measurement of the overall interference strain developed on ring crimping for each mandrel as a function of discharge energy*

4 Surface Indentation

4.1 A Brief Theory of Indentation Joining Mechanics

As pointed out in the introduction there are two basic ways one can fabricate a tube joint based upon interlocking shapes. These two basic mechanisms are distinguished largely upon the way we analyze them. If one is to make the bulk of the tube interlock with features that are larger than the tube thickness one can use the approach published by Golovashenko [8]. Another approach is based upon forming into the tube sheet indentations that have a height less than that of the tube thickness. The examples we will study here are based on indentation onto a screw thread, knurled surface or axially-grooved screw thread.

The concept we will follow here is derivative of what has been used in the design of bolted joints. In the design of a bolted joint an axial force is carried by the bolt and produces a normal axial stress through most of the bolt. At the threaded end this axial stress becomes a shear stress through the threads. A bolt will have full structural efficiency if, when tested destructively, it fails by normal rupture of the bolt and opposed by stripping the threads. The length of bolt that must be engaged to ensure that the bolt will fail in tension can be easily estimated. First we assume that the area that must be sheared, A_s, is equal to the length engaged by the nut $A_s=\pi Dl$. Here, D is the nominal diameter of the bolt and l is the length of the nut. This assumes that the entire area engaged by the nut must be sheared at once. The shear force that the bolt can hold is related to the shear flow stress, τ_o, of the material as $F_s=\pi Dl\tau_o$. The axial force $F_a=\sigma_o\ \pi(D/2)^2$, of course. We note that typically the shear stress of a material is about 1/2 the axial stress (Tresca criterion) and based on this we can find the nut length that ensures axial failure instead of shear as being about one-half the diameter of the bolt. Note that within the important assumption that the bolt is well-engaged by the nut; the pitch or depth of the thread is unimportant.

One of the things we would like to do presently is to 'optimize' the fabrication of a high velocity crimp created by the axial implosion of a tube onto a mandrel with a textured surface. Let us be a bit more specific as to what 'optimize' may mean. First, we would like to make a joint that has as much or more axial and/or torsional strength than the tube we will join to a mandrel. (Note: joint strength beyond the breaking point of the tube has no value). We would also like to make this joint using the minimum electromagnetic energy expenditure. Higher energy expenditure requires larger capacitor banks and more expensive/elaborate coils. Higher-level considerations (a bit beyond the scope of the present article) are that we may desire joints that remain tight after a given impact or joints that are fatigue resistant.

As impact velocity will scale with energy input, next we create a simple model for estimating the impact energy required to form a fully-engaged indentation joint. Let us assume a tube with thickness, t, made from a material with density ρ, and axial flow stress, σ_o, is imploded towards a mandrel. The mandrel can be taken as non-deformable and has a textured surface where the texture has an amplitude of depth d, and a wavelength λ. The kinetic energy per unit of area of the tube, $E_k=0.5\ t\ r\ v^2$, where v is the tube inward velocity. The tube will decelerate upon striking the textured surface and kinetic energy will be dissipated as plastic work in generating indentations in the metal surface. The plastic work done in creating the indented surface can be taken as the integral of the force acting on the deforming tube integrated over the depth of penetration of the mandrel pattern into the tube. An exact calculation of this integral is very difficult because of many real-world complications (chiefly, difficulties in knowing friction and the appropriate constitutive behavior of the materials). However, there are clear bounds on this integral. First, the total depth of possible indentation is d, and a plastically deforming surface will take the shape of a rigid, arbitrarily-shaped surface at a pressure of $3\sigma_o$. Thus, the maximum possible amount of energy that would be absorbed plastically while engaging the surfaces is $3\sigma_o d$. The actual value would be some fraction, F_1, of this value (which depends upon details such as coefficients of friction and the shape of the undulating surface that is to be joined. Based on equating kinetic energy and that absorbed on impact through an efficiency factor, E, one can estimate the impact velocity required to engage the tube and mandrel as:

$$V = \sqrt{\frac{6F_1\sigma_o d}{Et\rho}} \tag{2}$$

For typical values (a 2 mm thick aluminum tube engaged onto 1 mm deep grooves using F_1 = 0.5 and E = 0.5) we estimate impact velocities on the order of 150 m/s required for full engagement. Note that terms such as E and F_1 are very difficult to estimate accurately (but not too difficult to bound), the scaling relationship provided by Equation (1) is quite useful. It basically says that as the depth of the indentations decreases, the required impact velocity for engagement decreases. Note that traditional screw theory states that the strength of the joint does not depend on depth of engagement. Thus, as long as the joint is robust, this analysis indicates that a rather shallow surface texture is desired to minimize the kinetic energy required to make the joint.

4.2 An Experimental Study of Indentation Joining

Experiments were performed to characterize the strength of the union developed with mandrels with different surface configurations. The tubes subjected to crimp were made of Aluminum 6061-T6 alloy and had a total length of 64 mm with an outer diameter of 28.5 mm and wall thickness of 1.47 mm. Two different types of mandrels were used in the experiments: with knurled and threaded surfaces. The threaded mandrels can only effectively resist axial forces, while the knurled geometry was chosen because it is a commonly-available surface configuration that may resist axial and shear loading. The screw threads have a much sharper apex angle than the knurled surfaces.

The knurled mandrels were made of 12L14 low carbon steel. Cylindrical mandrels of three diameters were machined and subsequently knurled to obtain the desired surface finish. Diameters 20.8, 21.59 and 22.6 mm and length of 38.1 mm were knurled obtaining two different surface finish sizes that we will refer to as coarse and fine knurls. From the 22.6 mm in diameter mandrels, coarse and fine knurls were obtained and only fine knurls were machined in the 21.59 and 20.8 mm cylinders. Threaded rods of two pitch sizes (standard coarse and fine one inch diameter screw threads) were used in the second set of experiments. Samples that were 50.8 mm long were cut in each case. Examples of the knurled and threaded mandrels along with treaded mandrels with axial grooves for shear resistance are shown in Figure 4. The same capacitor bank and coil that were used in the interference-fit part of this study were used for joining here. Figure 5 shows an example of a crimp joint made using the coarse screw thread that was subsequently tested in compression, causing the tube to fail. Also shown in that figure is a cross sectional image of that part showing how the tread indents into the tube. Lastly is an image of a joint made from a knurled surface.

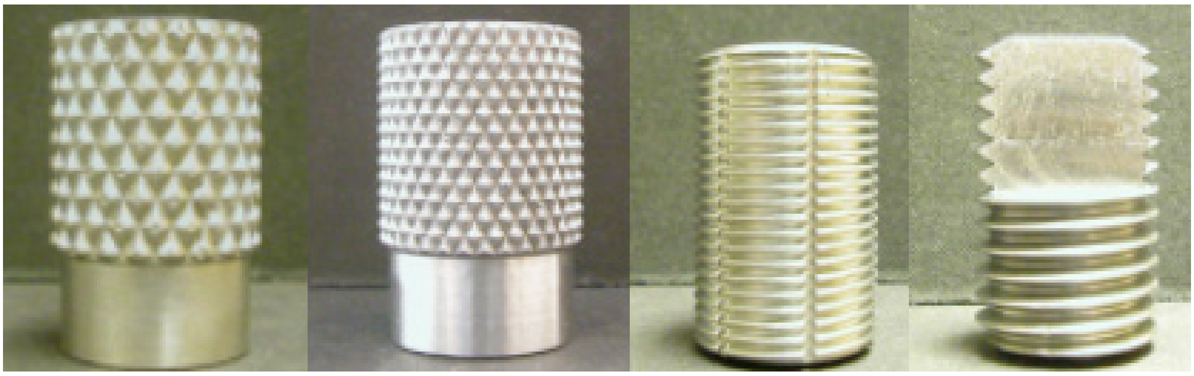

Figure 4: *Example of some of the mandrel surfaces. Left to right: coarse knurl, fine knurl, fine screw thread with axial grooves, and coarse screw thread*

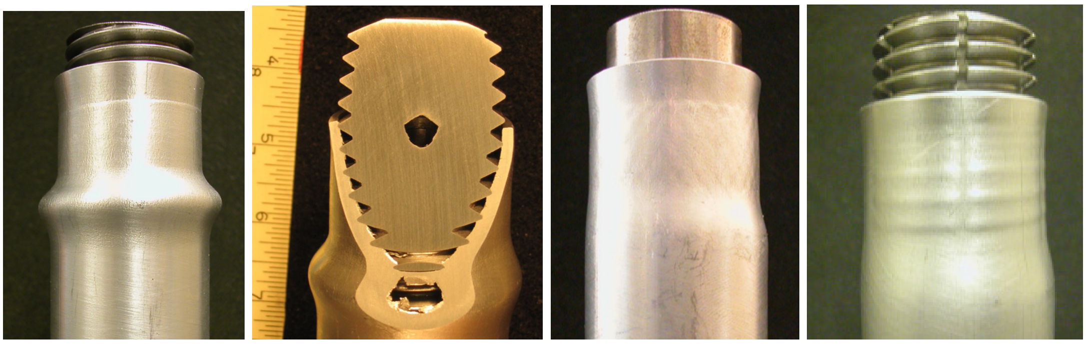

Figure 5: *Examples of crimp joints based on surface impression. From left: joint based on a 25.4 mm coarse screw thread tested in compression (14 kJ impulse onto a coarse thread screw); angled cross section of similar joint; a joint based on a knurled mandrel*

If one is to follow the approach described above to design a system to join tubes by crimping we would like to optimize impact velocity, and join a mandrel that has a fine pitch and has features that would fully engage the surface. Figure 6 shows predictions of the tube velocity-time profile expected in these experiments. Note that at discharge energies of more than about 10 kJ, the optimal standoff is predicted to be between about 1 and 1.5 mm. Also, we find that it is important to center the mandrel, tube, and coil about a single axis. If centering is poor one can develop a joint that has some slop. Further research is required to understand conditions that do and do not develop slop.

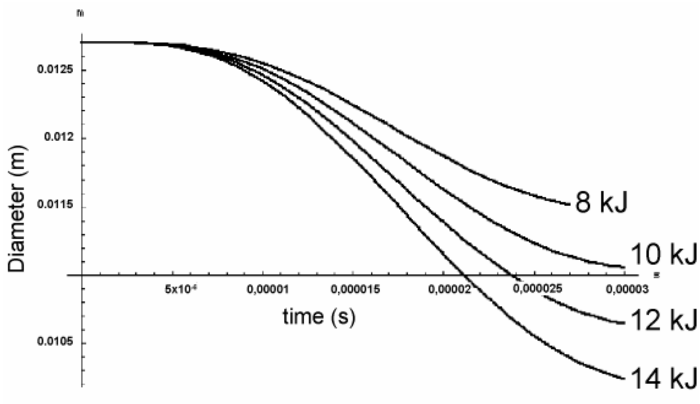

Figure 6: *Simulations of tube radius as a function of time using our capacitor bank system and launch energies of 8, 10, 12 and 14 kJ. Note that impact velocity would be relatively constant for a range of mandrel diameters and that the optimum standoff will increase with increasing launch energy*

Figures 7-9 show the results of axial strength testing of tubes that have been crimped as described. Figure 7 shows the effect of varied tube-mandrel gap and the same mandrel surface. The 1.5 mm gap is generally predicted to have the largest impact velocity (Figure 6) and it shows the highest axial strength. At other studied gap distances the tube is beginning to decelerate significantly. Figure 8 shows that, as predicted by Equation (2), the fine knurled surface generally creates the strongest joint when impacted at the same nominal velocity. The use of multiple impulses to improve joint strength was also studied. When multiple EM impulses were applied to the same section of tube, strength is not increased significantly. However, if the crimp length is increased by moving down the tube, joint strength is increased as shown in Figure 9. However, the strength is not increased linearly with crimp length, as predicted by the simple theory.

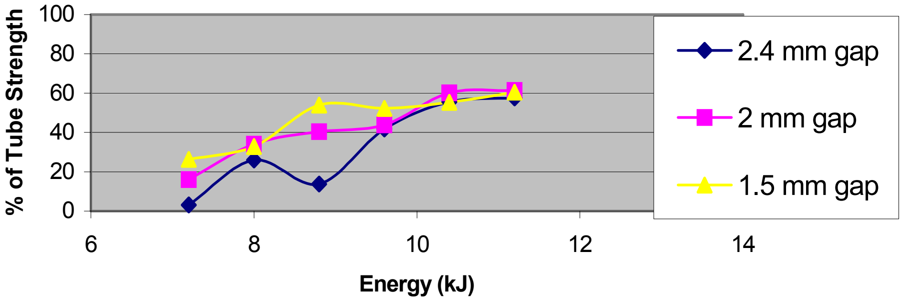

Figure 7: *Axial strength of high velocity crimp joints made onto fine knurled surfaces. Of the gaps studied the smallest is predicted to have the highest impact velocity and it also has the highest strength*

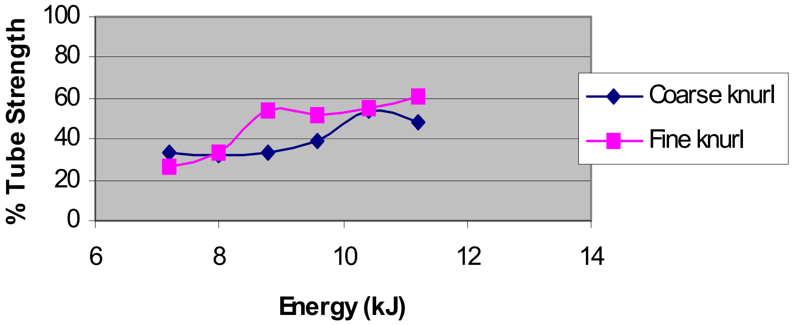

Figure 8: *Axial strength of joints made by collapse onto knurled surfaces with a fixed gap of 1.5 mm*

Often, torsional strength in tube-to-mandrel crimp joints. The threaded joints have very little intrinsic torsional strength. However, when crimping onto the fine knurled mandrel at 14 kJ with a 1.5 mm gap, we were able to produce a joint that had the full torsional strength of the tube. Also, by cutting grooves in threaded joints significant torsional strength can be attained, as shown in Figure 10.

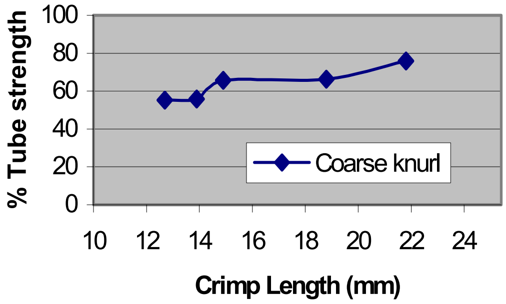

Figure 9: *Compressive axial tube strength on a coarse knurled surface using a 1.5 mm gap and 14 kJ discharge energy*

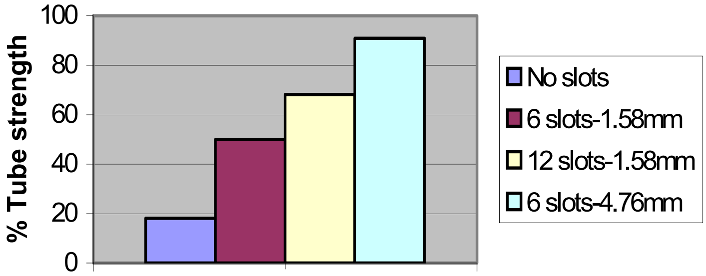

Figure 10: *Torsional strength developed by cutting grooves in threaded mandrels (see Figure 5)*

5 Conclusions

Crimp joining offers a particularly effective, low-cost, and efficient way of joining tubes to mandrels. Two aspects are especially appealing. First, high velocity forming typically develops a natural interference fit that resists motion. Second, by forming onto undulating surfaces (such as screw, threads, cut screw threads, and knurls) joints that have the strength of the parent tube in torsion and tension can be created at modest impact velocities and have been demonstrated. This combination of high strength and simplicity makes this kind of joining unique.

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