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Openable electromagnetic actuator as a non-contact, agile tool for crimping operations

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Abstract

This work focuses on using electromagnetic forming (EMF) for creating a conformal interference fit between an aluminum outer tube and a coaxially aligned inner part using a novel tool known as an openable actuator, or simply O-actuator. The utility of the O-actuator is in applications where it is impractical or impossible to remove a crimped assembly from a traditional helical actuating coil. In this work, a fully conformal joint between aluminum alloy type 6061 tube of circular starting geometry and AISI 1018 steel hexagonal rod was created with an input electrical energy of 8 kJ.

Keywords: Conformal joining; Electromagnetic forming; Impulse forming

1. Introduction

Impulse metal forming methods operate at relatively high strain rates in comparison to traditional hydro/mechanical techniques. In many applications, impulse processed components exhibit desirable properties such as reduced springback, shock hardening, better dimensional tolerances, and smaller burrs in sheared workpieces [1]. The various types of impulse forming include explosive [2], pulsed laser [3], vaporizing foil actuator [4], electrohydraulic [5], and electromagnetic [6]. Electromagnetic forming (EMF) is based on the principles of Faraday's law of induction and Lorentz forces. Electrical energy is stored in a capacitor bank, which is discharged through an actuating coil, which is generally termed as the primary coil. The rapid change of electrical current produces a transient magnetic field. The changing magnetic field induces an electrical current in a proximally located conductive workpiece, which acts as the secondary coil. The currents in primary and secondary coils are opposite in direction. Therefore, the Lorentz force generated between them is repulsive and causes the workpiece to be driven away from the primary coil. The electromagnetically generated pressure could be used for various impulse-based processes including shearing, embossing, impact welding, mechanical joining, or forming. In the present work, a conformal interference joint is formed between an outer tube and an inner part. Industrial examples of the application include electromagnetically swaged torque tubes by Boeing [7] and axial torque joints created for the automotive industry [8].

Openable actuators are also known as separable coils and other researchers have pursued various designs with the particular intent of allowing the removal of closed frame structures. The concept proposed in a 1967 patent by Deeg uses a primary driving coil like the O-actuator, but there is an electrical connection between the separable halves [9]. Golovashchenko deployed a design utilizing two direct acting coils in series [10].

This letter examines an alternative openable electromagnetic actuator, dubbed the O-actuator. The O-actuator

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may be used for the formation of conformal joints, e.g., crimping electrically conductive tubes onto various materials. It is especially useful in applications where it would be impractical or impossible to remove the finished assembly from a permanent helical actuating coil, this point is illustrated in Fig. 1.

2. O-actuator

The O-actuator is a field shaping transformer consisting of three separable major components; a helical driving coil and two annular blocks, which are shown in Fig. 2. The driving coil is easily replaceable in the event of component failure.

A helical driving coil fits into a groove in the bottom block and a workpiece is placed into the smaller cut out. The top block of the openable actuator is then put in place and the entire assembly is clamped together. Each piece of the actuator is electrically insulated from the others with polyimide tape or insulating varnish. Electric current through the primary driving coil induces secondary currents in the two blocks of the O-actuator. The secondary currents then induce tertiary currents in the workpiece. Fig. 3(a) illustrates the relative direction of current flow. The opposite direction of the secondary and tertiary currents generates magnetic repulsion between the workpiece and O-actuator, causing compression of the workpiece tube onto the component part within.

The openable actuator is particularly suited for applications in which the resultant crimped assembly would be impossible to remove from a fixed solenoid type actuator, such as when attached nodes or tube bend radius will not fit through the working diameter of the tool. Ouroboric closed frame assemblies however are not removable. Another example of an assembly not removable from a fixed solenoid is shown in Fig. 3b.

Magnetic pressures in electromagnetic actuators contribute to their failure [11]. However when a helical coil is used to drive a transformer of this type, radial expansion of the coil is suppressed both mechanically and electromagnetically. The field shaper mechanically retains the diameter of the coil and electromagnetically opposes its expansion, which can contribute to increased longevity of the driving coil. Significant design consideration must still be given to restrain inter-turn axial compression. Forming with transformer (field shaping) actuators is energetically inefficient in comparison to direct acting coils, so the driving coil must be of robust design to accommodate greater input energies and subsequently increased magnetic pressures.

3. Characterization and application

The circular blocks of the tool have an outside diameter of about 200 mm, an inside diameter of 100 mm and were machined from 6061-T6 aluminum. When the 63 mm tall annular segments are aligned and clamped together, two mid plane radial through holes are formed; a 63 mm diameter bore accommodates the driving coil and 25.4 mm diameter hole is used for the workpiece. The working zone is recessed from both the inner and outer diameters to concentrate the current density to an active length of 20 mm. The driving coil is a 5 turn helix wound from 4.8 mm square alloy 360 brass wire. Inter-turn spacing is 2 mm and the 63 mm diameter coil was potted in castable polyurethane (Adiprene® LF 950A).

A Rogowski current waveform transducer (Power Electronics Measurements Ltd. Powertek CWT) was used to measure currents in the various parts of the O-actuator. This was accomplished by moving the probe to different locations over multiple shots with an input energy of 2 kJ.

A commercial Maxwell Magneform capacitor bank pulse power supply was used in these experiments. This supply has a capacity of 16 kJ at the maximum charging voltage of 8.66 kV and utilizes 8 capacitors totaling 426 μF, each triggered by an ignitron switch. An internal inductance of 100 nH and inherent circuit resistance of about 10 mΩ gives a short circuited rise time in of about 12 μs.

Crimp joints were formed with input energies of 4, 6 and 8 kJ. Aluminum 6061-O tube with 0.8 mm wall thickness and 25.4 mm diameter was formed on to hexagonal 1018 steel rod stock cut to 75 mm lengths. The hexagonal rod segment was fixed coaxially within the tube prior to discharge. If the driving coil fails, it can be replaced. However, energies greater than 8 kJ were not attempted so as not to exceed the design limit of the driving coil.

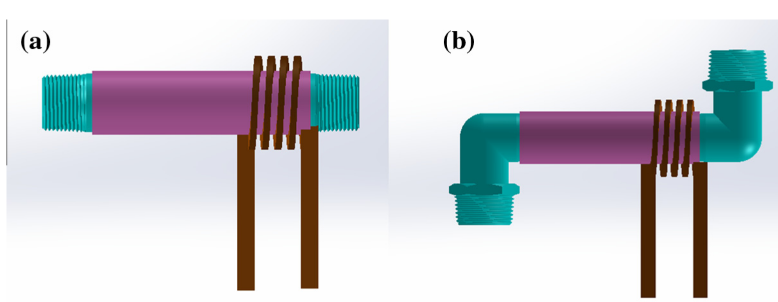

Fig. 1. (a) Pictorial of a crimped assembly removable from a fixed helical actuator, and (b) non removable assembly.