Nickel
Development
Institute

Electroforming — a unique metal fabrication process

by Ron Parkinson

NiDI Technical Series Nº 10 084

Ron Parkinson
is a consultant to the
Nickel Development Institute

Electroforming – a unique metal fabrication process

Ron Parkinson

Electroforming plays an important role in our daily lives. We have contact with it many times each day and it greatly enhances our lifestyle in a variety of ways. In addition, it is an extremely versatile process. For instance, it is used to produce micro components for the medical and electronics industries and huge components for the aircraft and aerospace industries. For many applications it has become indispensable and yet outside the electroforming community, little appears to be known about the process and its applications. Most metallurgists, engineers and designers are not well informed on the subject as it is rarely, if ever, included in technical courses presented at colleges or universities. Nevertheless it is a unique metal fabrication process and nickel is the dominant metal in this industry.

It is beyond the scope of this publication to provide all details of the procedures used to produce electroforms but the basic principles of the process and the reasons why nickel is so dominant are briefly explained. Applications are described to demonstrate the versatility of electroforming in order that new applications may become apparent to those not already familiar with the process.

The Process

Electroforming has been described in different ways but ASTM B 832-93 describes it simply and concisely as follows: "Electroforming is the production or reproduction of articles by electrodeposition upon a mandrel or mould that is subsequently separated from the deposit." It is, therefore, a method of fabricating parts that are usually free standing once separated from the mandrel and this definition will satisfy all purists in the technology. However, there are now other procedures that are often classified as electroforming. For instance, a piece of the mandrel may be intentionally bonded to or encapsulated by the electrodeposit and therefore become an integral part of the finished product. In addition, it has been used to describe the joining of parts by electrodeposition when conventional welding or brazing techniques are not feasible. This process has also been described as 'electrojoining' or 'cold welding' and in these cases it is necessary to accept a less rigid definition than that used by ASTM. Electrofabrication is another term often used, especially in the electronics industry.

Electrodeposition

Electroforming is an electrodeposition process, similar to electroplating and electrorefining. Therefore, the process requires two electrodes (an anode and a cathode) immersed in a conducting electrolyte containing metallic salts and a source of DC power. As current is passed between the two electrodes, metallic ions in solution e.g. Ni^{++}, are converted into atoms on the cathode surface and these build up layer upon layer, micron upon micron to produce a continuous deposit. It is possible, therefore, to visualize electroforming as the 'growing of parts by electrodeposition' and in fact the process has been described as 'ionic fabrication'. This concept of growing deposits explains why electroforming can be used to make many thin products, such as metal foils, more economically than by normal metallurgical procedures. However, the process is certainly not limited to the deposition of thin deposits. When the required deposit thickness has been obtained, the electroform is separated from the mandrel. The process is shown schematically in *Figure 1*.

In nickel electroforming, the two most common electrolytes used are nickel sulphamate solutions and Watts solutions. In the latter, nickel sulphate and nickel chloride provide the nickel units. It is the versatility of these electrolytes and the range of physical and mechanical properties of the deposits obtained from them that has made nickel so dominant. Properties such as hardness, ductility, strength and internal stress can be varied significantly by changing electrolyte composition and operating conditions, by the use of organic additives or by codeposition of alloying metals such as cobalt. In addition, high deposition rates can be obtained with these electrolytes and this is often an important factor in electroforming.

The two other basic components for electroforming are the anode and the cathode. The anode is typically a suitable form of nickel metal that will dissolve efficiently under the anodic conditions used and thereby replenish the nickel being taken out of solution at the cathode. The cathode is the mandrel upon which nickel is deposited and mandrel quality and preparation are of the utmost importance. The success of electroforming has resulted from the exceptional accuracy that can be obtained in reproducing the shape and surface detail of the mandrel.

Mandrels

A wide range of materials is used for producing mandrels. The range includes many metals and alloys, plastics, glass, wood and fabrics. They can be classified, therefore, as conductors or non-conductors of electricity and so the procedures required to prepare them for electroforming vary greatly. Within each of these two classifications, mandrels can be expendable or permanent.

The selection of a conducting or a non-conducting mandrel determines the procedures required to prepare it for electroforming. Conducting mandrels are usually pure metals or alloys to which the electrodeposit can bond suf-

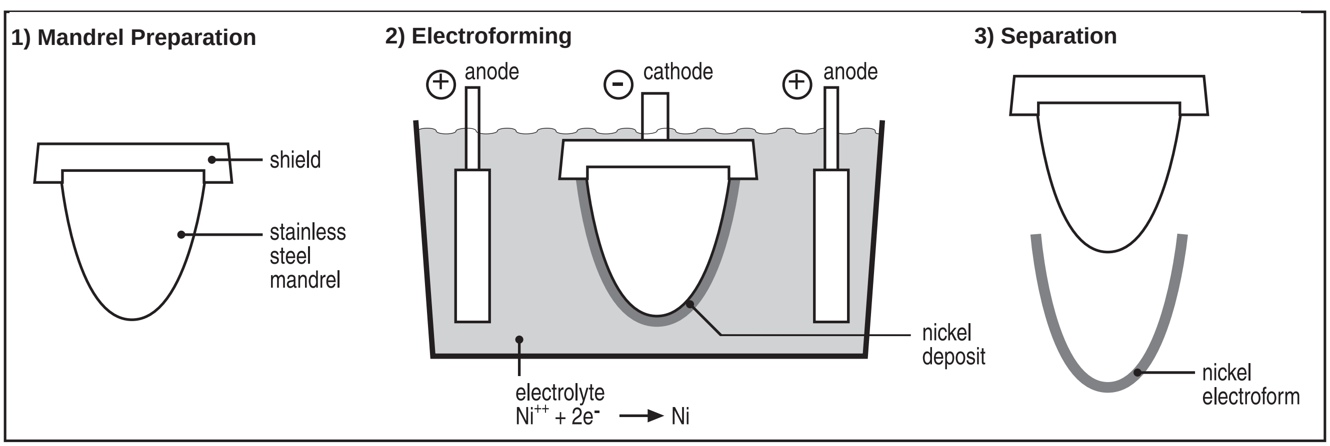

Figure 1 Schematic of an electroforming operation.

ficiently well to prevent premature separation but will allow easy removal of the finished electroform. Stainless steel is frequently used because the natural surface oxide enables these requirements to be met. Other materials may require the application of a thin parting film such as an oxide or chromate to facilitate removal of the electroform. This is not required if the mandrel is expendable i.e. if it is removed by melting or chemical dissolution, for instance.

Non-conductors have the disadvantage of having to be made conductive to allow the electrodeposition process to begin. This is done by applying a thin metallic film, usually silver or nickel. A typical procedure is to spray the non-conductive surface with solutions from a dual nozzle spray gun, which react “in situ” to produce a thin silver film by chemical reduction. Electroless nickel or sputtered metallic films can also be used.

The choice of a permanent or an expendable mandrel depends largely on the particular electroform being produced. It becomes a question of design and the number of electroforms required. If no re-entrant shapes or angles are involved, it is possible to use permanent, rigid mandrels that can be separated from the electroform and re-used many times. This is the preferred procedure in high volume production operations. However, if re-entrant shapes or angles are involved, mandrel materials must be used that can be removed by melting or chemical dissolution e.g. in electroforming nickel bellows and waveguides.

The various types of mandrel materials each have their own advantages and disadvantages. The success of an electroforming operation is largely dependent on making a good choice of mandrel type, material and pretreatment and the importance of this will become obvious from the range of applications described.

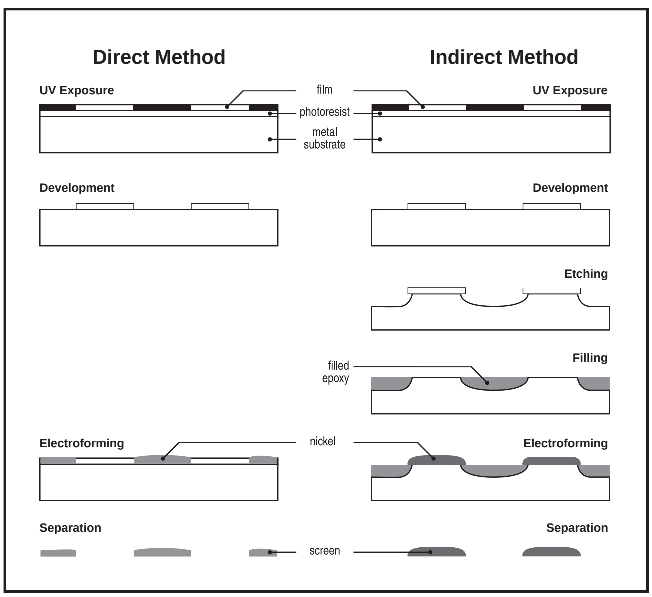

Figure 2 Direct and indirect methods of producing screen patterns using photoresists.

Applications

Screen Products

The production of mesh or screen products is a major part of the nickel electroforming industry. Applications include large, industrial centrifuge screens used in sugar production, small centrifuge screens used in kitchen appliances, razor foils, filters and precision sieve screens. However, the largest application is in the printing industry in which flat and cylindrical, rotary screens are used for printing a variety of products including textiles, wallpaper and carpets. The production of rotary printing screens is the largest, single application of nickel electroforming.

Screen patterns are usually produced using photoresist materials. These are applied to metallic mandrels either as a dry film or as an emulsion, which is subsequently dried and hardened. A high contrast film or mask on which the required pattern has been produced with great precision is then placed over the photoresist. The precision and edge quality can be greatly enhanced by preparing the original artwork on a much larger scale than required and reducing it to final size photographically on the film. On exposure to an appropriate light source, usually ultra violet (UV) light, the exposed areas of the photoresist are cured and become stable to solutions used for developing the pattern. Unexposed areas are dissolved during the development stage and so using this technique, generally referred to as the ‘direct method’, a mandrel for electroforming a simple screen product would consist of a metal substrate with a pattern of discrete islands of photoresist on the surface, corresponding to the holes in the screen. Such mandrels have a life expectancy of only one to five cycles after which the pattern must be produced again.

The preparation of more permanent mandrels that can typically be used for up to two hundred cycles is more complex. This is the ‘indirect method’ and also makes use of photoresists. The coating of the mandrel and the exposure to a suitable light source is similar to the procedure used in the direct method, except that the film is reversed i.e., a positive rather than a negative is used. After development, therefore, the mandrel surface is masked off with photoresist except for the hole area in the pattern. The exposed areas of metal, often copper or brass, are then etched to produce a pit pattern corresponding to the holes in the final screen. The photoresist is then removed and the pitted surface is coated with a resin with good adhesive properties, typically a filled epoxy. The resin is ‘worked’ over the surface to ensure all pits are filled and is then allowed to cure. When fully cured, the resin is machined or sanded in some suitable way depending on the shape of the part so that the only resin remaining is in the etched areas and the remaining metal is exposed. The mandrel surface is now ready to be prepared for electroforming. The ‘direct’ and ‘indirect’ methods of producing screen patterns for electroforming are shown in *Figure 2*.

In recent years an indenting method has largely replaced the etch and fill method, for producing the huge mandrels used for rotary printing screens. The method requires the cylindrical mandrel to be rotated on a lathe, while a special tool produces an indented pattern corresponding to the millions of holes in the finished screen. At this stage, the indented mandrel is similar to the previously described etched mandrel and can be prepared for electroforming in the same way, i.e. coated with a non-conductive resin to fill the indentations and surface finished to display the metal substrate and hole pattern.

Typical rotary printing screens for textiles are 3 - 6 m (10 - 20 ft) long with a diameter of approximately 20 cm (8 in). For carpets, they may be up to 2 m (7 ft) diameter. The most frequently used textile printing screens have a uniform mesh size, usually in the range 40 to 200 mesh. Typically hole size is 125µm and with 60 holes/linear cm, each screen contains millions of holes, all of which are produced with remarkable precision by electroforming. This type of screen is called a 'lacquer' screen. Mandrels are rotated rapidly in a horizontal position during electroforming. Depending on tank design they can be totally or partially submerged in the electrolyte and a 100µm thick screen is produced in about one hour. One essential requirement of the nickel deposit is that it must be deposited in a state of low compressive stress. This reduces the risk of the nickel lifting from the mandrel in the early stages of deposition but more importantly provides a method of separating the finished electroform. The required level of stress is obtained by controlled addition of a stress reducer such as saccharin to the electrolyte.

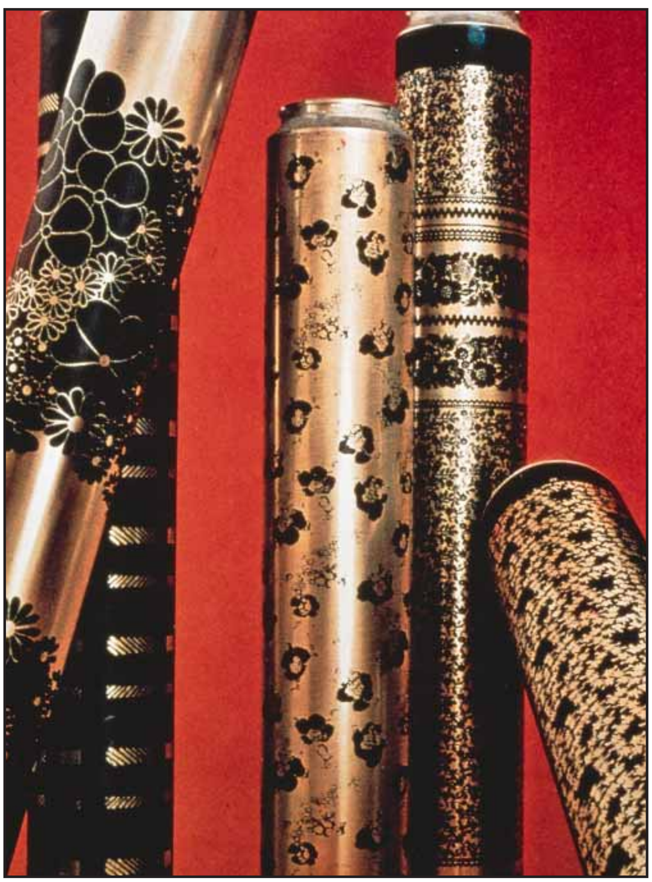

Figure 3 Typical lacquer screens.

The removal of a thin, fine mesh screen from an untapered, cylindrical mandrel that may be 6 m (20 ft) long appears to be a major problem, yet it is quite simple. After removal from the electroforming tank and rinsing, the cylinder is rotated along its axis and pressure is applied to the surface by a pad. The pad traverses the full length of the cylinder and the pressure causes release of the compressive stress and sufficient expansion of the nickel deposit to allow it to be easily withdrawn from the mandrel. It is possible that at least two hundred screens can be produced from a mandrel before any maintenance is required.

For printing, a screen is required for each colour in the pattern and so the more colours and more complex the pattern, the more screens are required for printing. The screens are installed in the printing machine and rotate in precise synchronization with each other as the material to be printed passes beneath and in contact with them. Each colour, therefore, requires its own pattern on the screen, which consists of an open mesh area through which ink can flow and a sealed area which prevents flow. Typical lacquer screens are shown in *Figure 3*. The ink is forced through the open area of the screen from the inside as it rotates and contacts the material to be printed. As the name implies, the pattern on lacquer screens is produced by lacquer applied to the electroformed screens. The entire screen is coated with a photoresist lacquer and the pattern produced by standard photoresist techniques. Alternatively, the patterns can be produced by a computer controlled laser engraving technique, in which the lacquer is burned off from the required open areas using carbon dioxide lasers. A series of electroformed lacquer screens in use on a textile printing machine is shown in *Figure 4*.

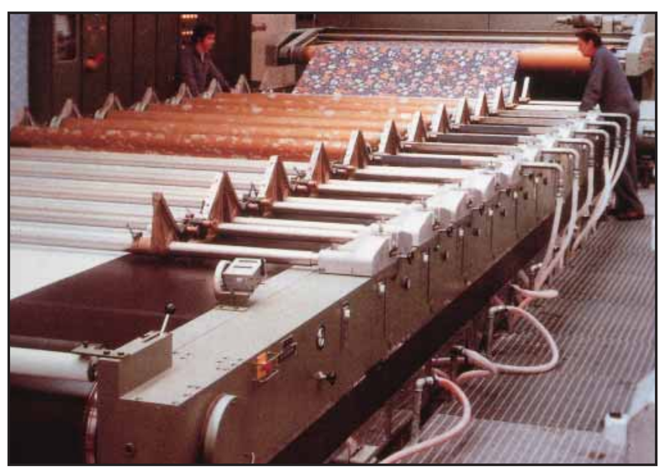

Figure 4 Textile printing machine using electroformed nickel screens.

Many other screen products are produced on mandrels prepared using photoresist techniques. For instance, electric razor foils are electroformed on flat stainless steel, nickel or brass mandrels that produce up to one thousand foils per cycle. The pattern ensures that the foils are attached to each other so that the whole sheet can be removed together and individual foils can then be separated in much the same way as postage stamps. The same technique is used for segments of permanent coffee filters and other small screen products. At a typical current density of 8A/dm^2, the required thickness of 50µm for razor foils is obtained in about thirty minutes.

The precision and reproducibility attainable by nickel electroforming cannot be matched by other screen production methods. For instance, nickel sieves are produced with hole sizes as small as 3µm and a thickness of 25µm. In addition to the advantages of reproducibility, electroformed sieves have extremely sharp edge definition without burrs and unlike woven screens they present no opportunity for material entrapment. A comparison of electroformed and woven fine screens is shown in *Figure 5*.

Electroformed nickel screen products also find use as templates and masks in critical situations where it is essential to obtain uniform application of coating materials. In this area, nickel electroforming has found a growing application in the electronics industry as a method of producing screens or stencils for fine pitch surface mount technology. The application is an excellent example of the many ways in which electroforming screen products can solve design problems, especially when precision and consistency are major factors.

The trend in the electronics industry has been very strongly towards more complex devices and smaller circuits. This means designers have greatly reduced the area available for leads as smaller pin connections and tighter spacing are required. Devices with over a hundred leads with sizes as small as 175µm and separated by only 325µm are not uncommon. The precise application of solder paste to these lead areas is a key factor in determining the extent to which the size of these devices can be reduced. It is imperative that the amount of solder at each location or pad is the same and that it is insufficient to cause shorting between leads. Electroformed nickel masks have solved this challenge and demonstrated their superiority over competitive methods such as chemical etching, electropolishing and laser cutting. Typically, stencils have thicknesses up to 300µm but electroforming places no lower limit on thickness and screens with 400 lines/cm can be produced at a thickness of 3.75µm. Electronic designers and assemblers have realised significant improvements in using electroformed stencils and these have translated into less rework, higher yields in assembly and increased product quality.

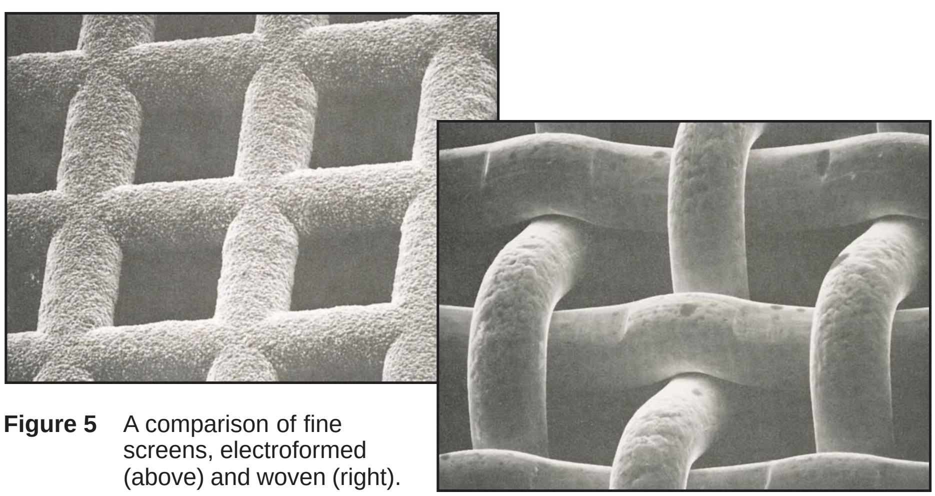

Figure 5 A comparison of fine screens, electroformed (above) and woven (right).

Moulds

Electroformed moulds of all sizes are produced for many applications and their production now represents a large part of the industry. Electroforming is the best way of reproducing surface detail and in some cases it is the only way that the necessary precision and accuracy can be produced economically. Perhaps the best example of this are the moulds or ‘stampers’ used for injection moulding of polycarbonate resins in the production of compact discs (CDs) or other optical read-out discs. But the applications of electroforming are not limited to small moulds with submicron replication requirements and in fact, the size of the mould that can be produced is usually limited only by the size of the electroforming tank. For instance, one-piece moulds for entire aircraft wing sections have been produced by electroforming.

Nickel moulds are used in compression, injection, layup, resin transfer moulding (RTM), rotational, slush, vacuum and blow moulding of plastics for instance. They have also been used for moulds in the glass, rubber and powder metallurgy industries, for die-casting of low melting point alloys and many other applications. They can provide high strength in high pressure applications such as compression and injection moulding and excellent corrosion resistance when this is a factor.

Electroforming is not the answer to all mould making problems. However, it should be considered by designers when there is a requirement for:

- Extreme accuracy of surface detail;
- Multiple impression dies in a single mould;
- More than one mould;
- Good wear and corrosion resistance;
- A complex die cavity.

A typical procedure for producing a mandrel for an electroformed mould begins with a model of the finished product. The electroformed mould can only be as good as the model or pattern from which it is produced. In some cases the original model is made from wood and surface detail is produced on it. For instance, if a rotational mould for producing vinyl skins with a leather texture and appearance is required, a selected piece of leather will be bonded to the model. Similarly if a particular wood grain is required as in the production of hardboard, the model surface is a carefully selected piece of wood with the required grain.

The original model is rarely used to produce the electroform. Instead, the surfaces are sealed if porous, and a plastic mould is made to replicate in reverse the shape and surface texture of the model. The mould would typically be a fibre-glass reinforced thermoset plastic or an RTV silicone rubber. From this part, another similar plastic casting is made, which should now be a perfect replica of the original model. This will be used as the mandrel on which the electroformed moulds will be made.

This is the traditional method of producing mandrels for mould production but there are others. For instance, when hundreds of moulds of simple shape are required, permanent stainless steel mandrels could possibly be machined. Or in the production of CDs, where extremely fine surface detail must be perfectly replicated, very special procedures are required, as described later.

Figure 6 Electroformed nickel mould for wing skins for Harrier Jump-jet.

Figure 7 Nickel mould for automotive body component.

Moulds are usually electroformed in nickel sulphamate solutions at low current densities, especially large, complex moulds. The usual objectives are to obtain zero or low tensile stress in the deposit and to optimize current distribution and therefore thickness uniformity. It is important that low stress, typically less than 35MN/m^2, be obtained to ensure that the nickel deposit does not separate from the mandrel in the early stages. Separation not only destroys the electroform but can create huge costs in wasted time and materials. For instance, if large moulds are involved that must be built up to a thickness of 1.5 cm (0.6 in), it is possible that the loss in time could be as much as four weeks and the metal loss as much as two tonnes.

Electroformed nickel moulds are used extensively in many different industries. The automotive and aircraft/aerospace industries not only create a high demand for electroformed moulds, but their requirements often include some of the largest moulds produced anywhere. For instance, they have been used for producing radomes, huge jet engine housings, wing and body fairings and the truly impressive mould for producing the upper and lower graphite/epoxy wing skins for the Harrier jump-jet. These 8.5 m (28 ft) long moulds, shown in *Figure 6*, were electroformed to a thickness of approximately 5 mm (0.2 in) and enabled the production rate of the composite skins to be increased by 30% over that obtained with machined steel moulds. This application is an excellent example of large scale electroforming that engineers and designers should consider when reviewing the process.

In the automotive industry, electroformed moulds are used for producing structural and decorative components. For instance, truck cabs, body panels and protective side strip moulding are all made in electroformed nickel moulds. A large nickel mould for producing reinforced plastic body components for the automotive industry is shown in *Figure 7*. Interior applications are mostly for nickel rotational moulds, which are used for producing vinyl skins for dashboards, door panels etc. One of the very attractive features of these moulds is that the surface texture of the mandrel is perfectly replicated in reverse on the electroform. This enables any surface texture, such as leather, to be produced on the vinyl skin.

Electroformed moulds also enable many home products to be produced economically. For example, they are used to produce plastic bathtubs, sinks and shower enclosures. A major home application is in producing moulds for panelling and exterior siding. Hardboard used for siding is actual wood that has been processed to greatly expand the fibres and then compression moulded under high pressure. The result is an extremely strong, durable product with 50%

higher density than that of the original wood. By installing electroformed moulds on the platens of the press, their surface texture is produced in the hardboard. Therefore, from any selected natural wood surface, the texture and grain can be reproduced by electroforming and transferred to the hardboard during compression. Moulds may be as large as 7.5 x 2.5 m (25 x 8 ft) and the nickel thickness is typically 6.3 to 12.7 mm (0.2 to 0.5 in). A typical mould still attached to the mandrel is shown in *Figure 8*.

Applications in recreational products include moulds for a variety of watercraft such as canoes, paddle boats, and surfboards. Many injection moulds for contemporary golf club grips, where texture and feel are so important, are also electroformed nickel. These tubular moulds are produced on expendable plastic or aluminum mandrels. Although most applications for electroformed nickel moulds are in the plastics industry, nickel/cobalt moulds have been used very successfully in the glass and zinc diecasting industries.

Two of the best examples of the ability to perfectly replicate surface detail in moulds are found in products which we encounter every day, i.e. optical read-out discs, such as CDs, and security holograms on credit cards. Neither would be available to us without electroforming.

The moulds or ‘stampers’ used for producing audio records have been made by electroforming since about 1930. Over many years great process improvements occurred that provided the high quality sound available from LPs. However, the development of compact discs required tremendous additional refinements to be made that have resulted in the exceptional sound quality that we now experience. The need for refinement is evident by comparing LP and CD surfaces.

An LP surface has a continuous spiral groove, typically 50µm deep and 50µm wide with a spacing of up to 100µm between the grooves. CD surfaces have a spiral track of small pits that are typically 0.4µm wide and 0.12µm deep, with about a 1.6µm spacing between the pits. These sub-micron pits are shown in *Figure 9* and there are approximately 30 billion of them on a CD, all of which must be perfectly reproduced. Refinements for CD stamper production include the need for clean-room conditions, sealed electroforming tanks and greater control of the nickel deposit properties such as thickness and stress. In addition, the starting surface for the two types of records are very different. For LPs the original sound is transcribed onto a nitrocellulose lacquer on an aluminum disc and for CDs it is transcribed by laser onto a photoresist film on a polished, optically flat glass disc. For both, it is then necessary to reproduce these surfaces through three electroforming stages to obtain the stampers for compression moulding of LPs or injection moulding of CDs. The original transcribed surface is replicated in reverse in the first electroforming stage. This produces one ‘master’ and this surface now becomes the mandrel for the second stage. From each “master”, approximately ten electroforms are produced. These are referred to as ‘mothers’ and similarly, several ‘stampers’ are electroformed from each ‘mother’. In this way, a sufficient number of identical stampers is produced to operate the many moulding machines required to meet production requirements. In CD production the electroforming stages are fully programmed to control nickel properties such as stress and thickness. High deposition rates are obtained at current densities of up to 30A/dm^2 so that stampers with a thickness of 295±5µm are electroformed in about 45 minutes. The reliability of electroforming in reproducing such great detail through three stages of replication has enabled the CD industry to grow to the point where many plants around the world routinely produce over 100 million CDs per year.

Electroforming has also played a key role in the emergence of holography into every day use. The three-dimensional holographic imaging on credit cards is produced by embossing aluminized plastic film with an electroformed nickel ‘stamper’ or embossing tool. These tools are obtained by three electroforming stages similar to

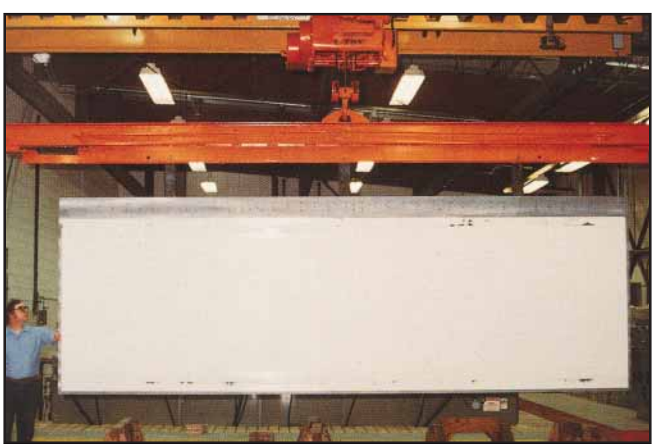

Figure 8 Large nickel mould for compression moulding of hardboard panels.

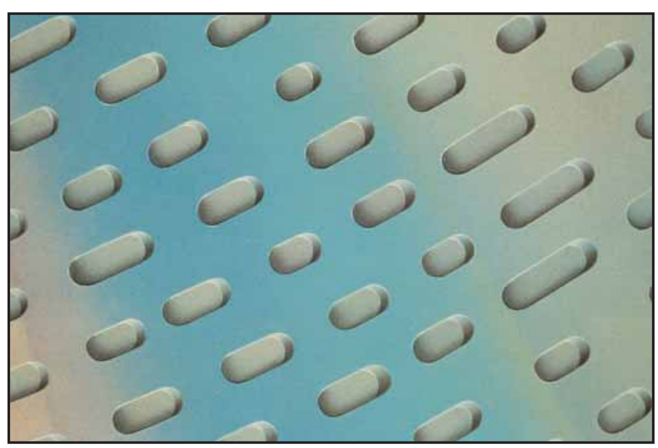

Figure 9 Submicron pits on CD surface produce high quality sound. Perfect replication is dependent on nickel electroforming.

those used for CD production and the pattern consists of a series of very fine lines, as shown in *Figure 10*, varying in width and depth with both dimensions less than 1µm. Electroforming is the only economically acceptable method of producing embossing tools for security holograms.

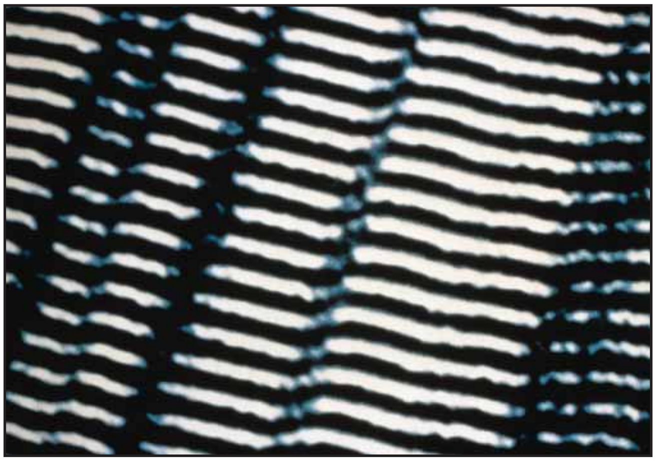

Figure 10 Electroformed nickel embossing tools for holograms have a pattern of submicron grooves.

Aircraft/Aerospace Applications

There are many impressive applications for electroforming in these industries other than the production of moulds. The process is widely used to produce nickel or nickel alloy components directly. These include lightweight, precision parts such as waveguides and antennae, erosion shields for helicopter and aircraft engine blades, bellows and heat shields for aerospace and missile applications, fuel liners and manifolds for propeller driven and jet powered aircraft and regeneratively cooled thrust chambers for rocket engines.

Electroforming is the only practical way to produce the twists and transitions that are characteristic of many waveguides, while maintaining the internal dimensional precision and surface finish. For complex waveguides, expendable mandrels such as aluminum are frequently used. Aluminum can be prepared with a 3 to 5 microinch finish that is often required to be reproduced on the inside of waveguides. If the waveguide shape is simple enough to allow for a mandrel to be withdrawn from the electroform, a permanent stainless steel mandrel might be used.

Nickel electroforming has long been used as a method of producing erosion shields for components such as helicopter blades. By electroforming, it is possible to reproduce the precise airfoil contour and to control current distribution so that the thickest deposit is at the leading edge where erosion problems are most serious. In this type of application, it has generally been shown to be advantageous to deposit the nickel in a state of compressive stress as this has a positive effect on fatigue resistance by inhibiting crack propagation.

Electroformed nickel bellows also provide an excellent example of the precision and quality afforded by this process. Electroformed bellows are made in a range of sizes and have a variety of applications, e.g. for metallic hermetic seals, volume compensators, pressure and temperature sensors and flexible connectors. Some very small bellows are shown in *Figure 11*. One of the major applications is in flexible electromagnetic interference (EMI) shielding in aircraft and satellites. Quality is such that extremely small, electroformed bellows with a wall thickness of only 25µm can be joined to other components by various welding techniques to produce gas-tight assemblies with leak rates of less than $1x10^{-9}$ml/sec. The fact that the physical properties of electroformed nickel can be controlled by the deposition conditions is again most advantageous. Aluminum is usually used as an expendable mandrel as it can easily be machined to the convoluted configurations and sizes required for this application and then dissolved out of the electroform in sodium hydroxide.

Figure 11 Precision bellows of all sizes can be produced by nickel electroforming.

Designers in the aerospace industry have worked closely with electroformers to resolve some difficult fabrication problems. An impressive example of this is in the use of electroforming to create internal cooling passages in hardware of complex shape. The technique has been successfully used in Europe and North America for producing regeneratively-cooled thrust chambers and nozzle extensions for advanced rocket engines in which the weight of the chamber per unit of power produced is of critical importance. In these assemblies, it is normal for the fuel to flow through channels in the chamber wall to lower the operating temperature of the liner for longer thermal fatigue life, while the fuel itself is preheated, before being injected into the combustion section. All material properties are critical, particularly high and low temperature strength and heat conductivity. Electroforming with nickel has provided satisfactory properties and lightweight. Typical applications have been in the third stage of the Ariane space launcher and the main engine of the NASA Space Shuttle.

To provide a brief description of the process does not do justice to the technology and creativity involved in this development but the general procedures are as follows. The inner part of the chamber, or liner, has been made from stainless steel, nickel, copper or specially developed alloys and is normally produced by spinning or machining. Alternatively, electroformed nickel or copper have been used. Cooling channels are cut along almost the entire length by electrical discharge machining or milling to a depth that leaves only about 0.9 mm (0.04 in) of stock between the bottom of the channel and the inner surface of the chamber. The component, therefore, has little strength prior to the nickel electroforming stage. The channels are then filled with wax, which is preferably loaded with filler to reduce shrinkage and provide good sanding properties. Prior to electroforming with nickel, the wax must be made conductive by burnishing with silver and the metal ribs must be activated to obtain the best possible bonding of the nickel. Nickel sulphamate electrolyte is used with very low chloride content and deposit thickness may be as great as 1.2 cm (0.5 in). The electroformed nickel shell not only closes out the passages and provides the required strength but when necessary coolant feed ports, for instance, can be grown into it. The sequence of operations is shown schematically in *Figure 12* and the machined channels in the liner can be seen in *Figure 13*.

After electroforming, the exterior part must be machined to drawing requirements and the wax removed by melting and flushing with hot solvent. Since electrodeposition provides a method of obtaining metallurgical bonding at near ambient temperatures, unlike thermal fusion techniques such as welding or brazing, the deposit properties remain excellent. Induced bond failure may be expected to occur in the weaker of the joined metals. Typical room temperature and cryogenic properties of nickel deposits for this application are as follows.

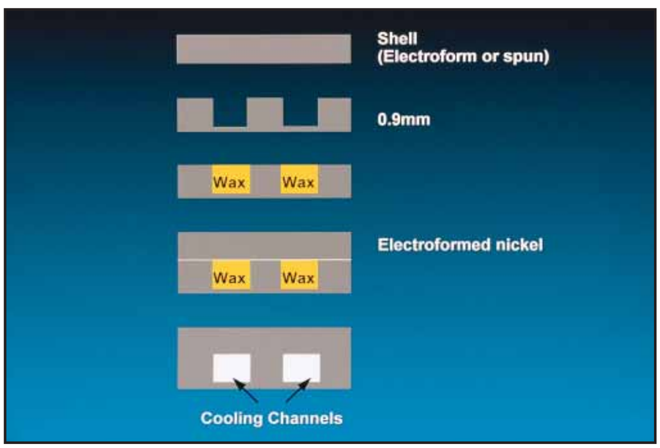

Figure 12 Stages in the electroforming of internal passages.

	20°C	-196°C
Ultimate Strength (MN/m^2)	180	1000
Yield Strength (MN/m^2)	510	615
Elongation (% in 5cm)	12	21

A machined electroformed thrust chamber for the Ariane launcher is shown in *Figure 14*.

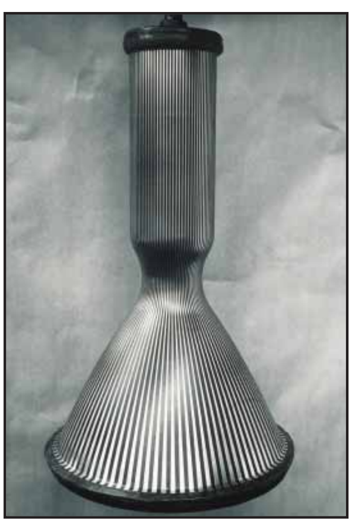

Figure 13 Channels machined in the metal liner of a rocket thrust chamber, for the NASA Space Suttle.

Figure 14 A machined electroformed thrust chamber for the Ariane launcher.

Other Applications

There are many other interesting applications for nickel in electroforming. For instance, there are obvious advantages in producing nickel foil by electroforming rather than by standard metallurgical processing and the thinner the foil the greater the advantage. Foil is produced on titanium cylindrical mandrels, rotating with their axes in a horizontal position, while partially submerged in a nickel sulphamate electrolyte. The foil is peeled from the mandrel as it exits the electrolyte and deposition restarts at the re-entry point. Deposition is continuous, therefore, and foil thickness is controlled by the diameter and rotational speed of the mandrel and the current density. The electroforming of nickel foil is shown in *Figure 15*. Nickel foil is produced at typical thicknesses of 6 to 200µm and current densities as high as 45A/dm², corresponding to deposition rates of up to 0.5 mm (0.02 in) per hour. Applications for nickel foil include solar energy absorbers, high temperature gaskets, pressure control membranes and fire resistant barriers.

Figure 15 Electroforming of nickel foil.

Another example of the use of rotating mandrels is in the production of seamless nickel photoreceptor belts for high speed copying machines. This application has now been phased out due to changes in technology but testament to the success of this application is the fact that millions of belts have been produced over the last twenty years, typically at a rate of about 600,000 per year. In this process, permanent chromium plated aluminum mandrels were used, rotating on a vertical axis and at current densities of 30A/dm², the 125µm thick belts were produced in only eighteen minutes. In removing the electroforms from the mandrels, advantage was taken of the difference in thermal expansion between nickel and aluminum.

The intricate designs produced by master engravers for bank notes are perfectly reproduced through several electroforming stages before the final nickel printing plate is installed on the press. The nickel, deposited at quite low current densities, is often hardened by the use of organic additives to the nickel sulphamate electrolytes. Most currency around the world is produced with nickel printing plates. In the U.S., for instance about four thousand plates are electroformed each year for printing over six billion notes.

In the past few years, the production of nickel foam by electroforming has been of great interest and demand has grown enormously. It has been widely used for many years for filters, as a carrier for catalysts, for oil-mist separators in refrigeration equipment and for electromagnetic shielding but the major application is now in rechargeable battery systems, such as nickel-cadmium and nickel-metal hydride batteries. The nickel foam electrode is an alternative to the sintered electrode and foam is now produced in continuous lengths at several plants around the world.

Basically, production is very simple. The mandrel material is polyurethane foam with controlled porosity, onto which nickel is electroformed and the organic material is subsequently burned out. However, practically, the process is more complex. Practical and economic considerations demand that the foam be produced on a continuous basis, which means that rolls of foam mandrel material are unwound and pass through the processing tanks under automatically controlled conditions. Initially, the expendable foam mandrel must be uniformly coated with an electrically conductive layer and both graphite and electroless nickel have been used. Nickel sulphamate electrolytes are normally used under standard conditions to produce low stress. Current density is maintained at low levels initially, typically 2-5A/dm², but may be increased to levels as high as 10A/dm² as the thickness of the nickel deposit increases. Following the electroforming stage, pyrolysis is used to remove the polyurethane foam. Obtaining maximum porosity, while maintaining adequate strength and ductility in the nickel foam is a major requirement of this innovative application for nickel electroforming. The skeletal structure and high porosity of the foam is shown in *Figure 16.*

The LIGA Process

Recently much work has been done in developing a process for electroforming micro components, much smaller than could be imagined before this era of miniaturization. This is the LIGA process originating in Germany with the name being derived from the three production stages - lithographie (lithography), galvanoformung (electroforming), and abformung (moulding). The process was originally

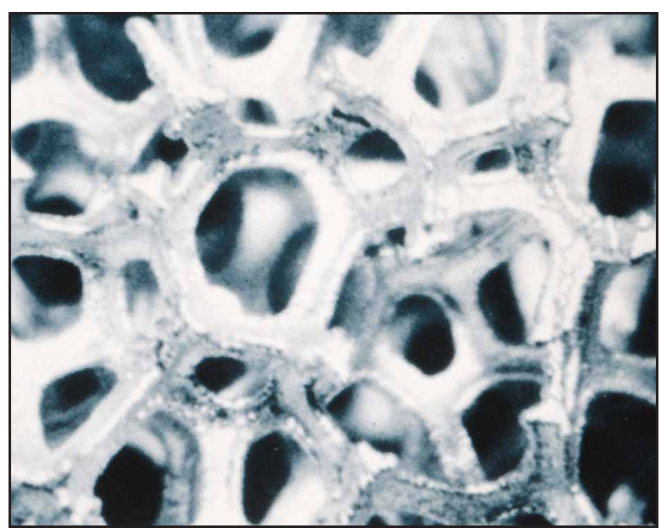

Figure 16 The skeletal structure of electroformed nickel foam.

developed for electroforming small moulds for plastic parts but is now also used for the direct production of micro metallic components. The great interest in the LIGA process has developed from the recognition that electroforms can be made with very high aspect ratios (height to width ratios) and with vertical walls. For instance, parts with a width of only several microns can be electroformed to a height of 3 mm (0.1 in) while maintaining parallel, vertical walls and great precision.

Basically the process for producing mandrels is similar to the photoresist method described for screen production but materials and exposure conditions are markedly different. PMMA (polymethylmethacrylate) replaces the photoresist, X-rays replace the UV light and a thin gold mask replaces the photographic film. Typically the process begins with the application of a layer of PMMA to a metallic substrate. Layer thickness is dependent on the height requirements of the finished part and the energy of the synchroton X-ray radiation source. The mask typically consists of a silicon or beryllium wafer on which the pattern is produced in gold, 30-35µm thick. The wafer materials must be invisible to X-rays, while the gold acts as an absorber to block them. After exposure the PMMA is developed and the irradiated areas are dissolved away, down to the metallic substrate. Electrodeposition can then begin on the exposed areas of the substrate to produce a part with parallel, vertical walls, defined by the PMMA. The maximum thickness, or height, of the electroform is therefore determined by the thickness of the PMMA.

This is a very simplistic view of the LIGA process and many technical challenges have to be met in each application. For instance, the development of say, a 25µm feature through a PMMA thickness of 3 mm (0.1 in) and the subsequent deposition of nickel in such a narrow slot present enormous solution transfer problems. Nevertheless, the challenges are being met and many micro components have been produced for a wide range of industries. For instance, applications are to be found in microfiltration systems, micro optics, ultrasonic sensors, fuel injection and in jet printer nozzles, micro actuators and micro motors. Specific examples include precision gear wheels smaller than the eye of a needle and a micro turbine/cutting tool designed to pass along diseased arteries to remove accumulated plaque. Progress in this technology has been promoted by the enormous interest in miniaturization and the number of applications is expected to increase. A selection of small components produced by LIGA technology is shown in *Figure 17*.

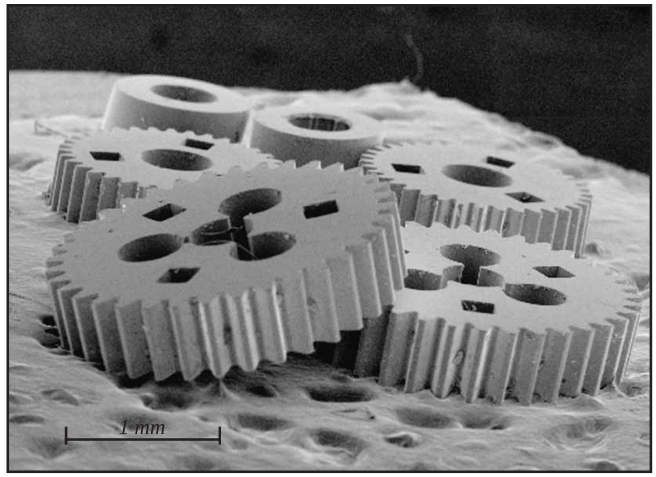

Figure 17 Gears and spacers for micro-magnetic motor applications.

Summary

This general review of electroforming has been prepared to introduce the subject to those who are not familiar with the capabilities of the process. It was not the intention to describe the details of the process such as mandrel selection, design and preparation or electrolyte composition and operating conditions or separation techniques for removing the electroform but rather to bring forth the importance of these parameters with reference to many successful electroforming applications.

Electroforming is a unique metal fabrication process that is indispensable in producing many items with which we have daily contact. It is also sufficiently versatile that it is used successfully to produce huge components for the aerospace and automotive industries and yet is able to perfectly replicate surfaces with submicron size features. It is used to produce many types of screen products and moulds of all sizes. It is the only practical method of producing many complex forms such as waveguides and bellows and the range of applications continuous to expand.

Electroforming is an electrodeposition process in which nickel is the material of choice for most applications. Nickel can be deposited with a wide range of mechanical properties by controlling the deposition conditions, by the use of electrolyte additives or by alloying. Nickel electrolytes have the advantages of being easy to control and they are capable of fast deposition rates. Nickel and its alloys will continue to dominate this industry and by increasing the awareness of the electroforming process amongst designers, engineers and metallurgists, continued growth should be assured.

The Nickel Development Institute is an international nonprofit organization serving the needs of people interested in the application of nickel and nickel-containing materials.

North America
Nickel Development Institute
214 King Street West - Suite 510
Toronto, Ontario
Canada M5H 3S6
Telephone 1 416 591 7999
Fax 1 416 591 7987

Europe
Nickel Development Institute
42 Weymouth Street
London, England W1N 3LQ
Telephone 44 171 493 7999
Fax 44 171 493 1555

Nickel Development Institute
European Technical Information Centre
The Holloway, Alvechurch
Birmingham, England B48 7QB
Telephone 44 152 758 4777
Fax 44 152 758 5562

Japan
Nickel Development Institute
11-3, 5-chome, Shimbashi
Minato-ku, Tokyo, Japan
Telephone 81 3 3436 7953
Fax 81 3 3436 7734

Central & South America
Nickel Development Institute
c/o Instituto de Metais Não Ferrosos
R. Pirapora, 310
São Paulo-SP, Brasil 04008-060
Telephone 55 11 887 2033
Fax 55 11 885 8124

India
Nickel Development Institute
55A Uday Park (First Floor)
Khel Gaon Marg
New Delhi 110 049
India
Telephone 91 11 686 5631
Fax 91 11 686 3376

Australasia
Nickel Development Institute
150 Drummond Street, Suite 3
Carlton, Victoria 3053
Australia
Telephone 613 9650 9547
Fax 613 9650 9548

South Korea
Nickel Development Institute
Olympia Building, Room 811
196-7 Jamsilbon-Dong, Songpa-Ku
Seoul 138 229, South Korea
Telephone 82 2 419 6465
Fax 82 2 419 2088

China
Nickel Development Institute
Room 677, Poly Plaza Office Building
14 Dongzhimen Nandajie
Beijing, China 100027
Telephone 86 10 6500 1188 (ext. 3677)
Fax 86 10 6501 0261

Members of NiDI

Companhia Níquel Tocantins
Empresa de Desenvolvimento
de Recursos Minerals "CODEMIN" S.A.
Falconbridge Limited
Inco Limited
Morro do Níquel S.A.
Nippon Yakin Kogyo Co., Ltd.
Outokumpu Oy
P.T. International Nickel Indonesia
Pacific Metals Co., Ltd.
QNI Limited
Sherritt International Corporation Inc.
Shimura Kako Company, Ltd.
Sumitomo Metal Mining Co., Ltd.
Tokyo Nickel Company Ltd.
WMC Limited

Printed on recycled paper in Canada

Oct 98/5.0