EQUAL CHANNEL ANGULAR PRESSING (ECAP) PROCESS OF COPPER ELECTRODES FOR RESISTANCE SPOT BRAZING APPLICATION

by

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EQUAL CHANNEL ANGULAR PRESSING (ECAP) PROCESS OF COPPER ELECTRODES FOR RESISTANCE SPOT BRAZING APPLICATION

ABSTRACT

This research was performed to investigate the influence of ECA pressing step on the workability of copper electrode used for resistance spot brazing application. The as- received copper material was characterized using optical microscope observation and X- Ray fluorescence analysis. It was then annealed at $600^{O}C$ for 48 hours followed by ECA pressing using the die with inner angle of 120^{O} and outer angle of 35^{O}. The billets were processed by four passes using route B_C. After each pass, the billets were examined for cracks and polished again before continued for the next pass. Scanning electron microscope was used to characterize the ECA pressed material microstructure and microhardness distribution in transverse and longitudinal sections. The electrical conductivity of ECA pressed samples was also examined. The results showed a significant increase in microhardness value of samples. After four passes, the microhardness observed was 158Hv and 160 Hv referring to transverse and longitudinal section compared to the microhardness of 60Hv of the as- annealed sample. After four passes, the grain size had been reduced from 110µm to the ultrafine fibrous structure of 290nm, in the transverse view. There was also a significant change in electrical conductivity. The electrical conductivity of $1.5X10^{8}$ $(Ohm\text{-}m)^{-1}$ was achieved compared to $6.00X10^{7}$ $(Ohm\text{-}m)^{-1}$ of pure copper standard conductivity. The working performance of processed copper as electrode in resistance spot brazing was studied in comparison to the copper-chrome electrode. The microstructure measurement of brazed joints, the shear tensile strength and microhardness profile observation over the brazing area were evaluated and studied. The processed copper electrode showed an ability to produce comparable joint quality

by means of load at break in shear tensile test and produced relatively good shear strength. The optimum brazing condition for each type of electrode was also established.

PROSES PENEKANAN ECAP ELEKTROD KUPRUM UNTUK APLIKASI PATERI RINTANGAN TITIK

ABSTRAK

Penyelidikan ini dilakukan bagi mengetahui kesan proses ECAP ke atas elektrod kuprum yang digunakan dalam aplikasi pateri rintangan titik. Pencirian kuprum digunakan dilakukan menggunakan mikroskop optik dan analisis X-ray pendaflor. Sepuhlindap terhadap kuprum dilakukan pada suhu 600^0C selama 48 jam diikuti dengan penekanan ECAP menggunakan acuan dengan sudut dalam,120^0C dan sudut luar 35^0C. Penekanan rod kuprum ini dilakukan sebanyak empat kali. Rod kuprum diperiksa sebagai langkah pencegahan retak dan pencanaian dilakukan sebelum proses seterusnya. Mikroskop pengimbas elektron digunakan bagi menentukan pencirian penekanan ECAP bagi taburan mikrostruktur dan kekerasan micro dalam keadaan keratan rentas melintang dan keratan rentas menegak dilakukan pada rod kuprum. Pengkonduksian elektrik bagi penekanan sampel ECAP diperiksa. Keputusan menunjukkan peningkatan mencukupi dalam nilai kekerasan-mikro sampel-sampel. Selepas empat kali penekanan rod kuprum dilakukan, kekerasan-mikronya adalah 158Hv dan 160Hv bagi keratan rentas melintang dan menegak berbanding sampel yang disepuhlindap kekuatan-mikronya adalah 60Hv. Selepas empat kali penekanan rod kuprum dilakukan juga, saiz butir telah berkurangan daripada 110µm kepada sebesar struktur fiber iaitu 290µm pada keadaan gambaran rentas menegak. Terdapat perubahan pada kekonduksian elektrik. Kekonduksian elektrik adalah 1.5×10^8 $(\text{Ohm-m})^{-1}$ telah dicapai berbanding 6.00×10^{-7} $(\text{Ohm-m})^{-1}$ bagi kekonduksian kuprum piawai. Perbandingan proses kebolehkerjaan kuprum sebagai elektrod untuk pateri rintangan titik dijalankan dengan kuprum-chrome elektrod. Pemerhatian mikrostruktur bagi penyambungan pematerian,

kekuatan regangan ricih dan profil kekerasan-mikro dilakukan pada kawasan pematerian yang telah dilakukan. Elektrod kuprum yang telah diproses menunjukkan kebolehan bagi menghasilkan kualiti sambungan yang setanding bagi purata berat berlakunya patah dalam ujian tegangan ricih dan menghasilkan kekuatan tegangan yang baik. Keadaan pematerian optimum bagi taip jenis elektrod dilakukan.

CHAPTER 1

INTRODUCTION

1.1 An overview of study

Resistance spot welding (RSW) is a joining process in which heat for welding is generated by the resistance of the flow of electrical current through the parts being joined. Current is applied and concentrated by a pair of copper electrodes. This pair of electrodes also clamps the two sheets being joined to provide good electrical contact and to provide pressure to contain the molten metal at the faying interface.

Resistance spot welding is widely used in joining sheet steel of thickness up to about 0.125 inch and can be used for many materials including combinations of materials. Many assemblies of two or more sheet-metal stampings that do not require gas-tight or liquid-tight joints can be more economically joined by high-speed resistance spot welding than by mechanical methods. One of the most important applications of resistance spot welding is in automotive industry. The car frame body is constructed by spot welding of individual stamping part, with manual portable welding guns, semi-automatic machines or fully automatic robots [1].

Major advantages of resistance spot welding are high speed and suitability for automation and inclusion in high-production assembly lines with other fabricating operations. With computer-control of current, timing and electrode forces, sound spot welds can be produced consistently at high production rates and low unit labor costs by unskilled operators.

In welding operation, electrodes are important component in spot welding setup. The main purposes of the electrodes were highlighted [2] which are, 1) to conduct the welding current to the workpieces, 2) to transmit the proper pressure to the weld area in order to give good fit during weld formations and 3) to dissipate the heat from the weld zone rapidly.

To meet those requirements, the electrode materials must have high electrical conductivity of at least 80% IACS as to limit the I^2R loss. Low electrical conductivity results in excessive heating and cause the electrode to stick at workpieces. High thermal conductivity is also required to dissipate the heat generated as to minimize local heating and to reduce increment of electrode temperature, facilitate cooling of the weld as to constrain weld nugget formation and minimizing interfacial and surface splash.

In manufacturing, the management of environment issues in becoming more important every year. In particular, industries which use soldering as a major method of electrical bonding are facing stricter lead regulations. As a result, manufacturers planning to obtain quality management and environment management system certification are taking a second look at micro resistance welding.

Micro resistance spot welding is showing to be a promising technique in joining metallic materials. Because only several volts are applied to the work, this increases operator safety and generates almost no excessive heat, smoke and flashes, keeping the working place and environment clean [3]. Reliable quality, good cost-performance, easy operation and easy maintenance are several advantages of micro resistance welding over other welding processes. These advantages help save man-power in various automated production lines

Of all the methods available for metal joining, brazing may be the most versatile, for a number of reasons. Brazed joints are strong; they are often stronger than the two metals being bonded together. Brazed joints are ductile, withstand vibration and shock and are unaffected by normal changes in temperature. Brazed joints are usually easy and rapidly made, with operator skill readily acquired. Brazing is ideally suited to the joining of dissimilar metals.

Brazing is performed at relatively low temperatures, reducing the possibility of warping, overheating or melting the metals being joined. Brazing is economical. The cost-per-joint compares quite favorably with joints made by other metal joining methods. Brazing is highly adaptable to automated methods. The flexibility of the brazing process enables you to match your production techniques very closely to your production requirements.

To employ the advantages of resistance spot welding as well as advantages of brazing techniques, it is a worth try of using a resistance spot brazing technique in joining metal with considerably lower temperature. The joining is expected to give least heat-distortion of workpiece and a faster cooling time due to its relatively low temperature. This also resulted in a longer electrode life which can sufficiently reduce production cost.

Among the methods of fabricating ultrafine grained materials, severe plastic deformation (SPD) techniques, such as torsion straining and equal channel angular pressing, are probably the most promising. The ECA pressing technique was invented in 1972 by a scientist from the former Soviet Union, V.M. Segal [4], and it uses the principle of repeated shear deformation to refine the grain size in metallic materials.

The ECA pressing has a number of advantages [5]: first, very large deformation strain can be obtained after repeated passes without changing the shape of billets. Second, very uniform and homogeneous deformation can be applicable throughout the cross section of the billet. Third, no residual porosity is found in the deformed billets. Fourth, since the size of the billets is only limited by the size of the die and the pressing facility, it is possible to produce massive samples. Fifth, the areas exposed to tensile stresses are limited during deformation.

The interest in ECAP technique has dramatically increased due to its wide range of applications. ECAP has been employed to produce ultrafine and nanostructured materials. ECAP is also able to produce superplastic materials and to fabricate composites.

Many systems of alloy have been successfully developed by ECAP technique. ECAP showed to be a very promising technique in those above mentioned applications. A possibility to produce a material with nano-scaled structure by equal channel angular pressing technique was clearly stated. ECAP technique is applicable to a variety of metals and alloys with a wide range of using purposes.

Microstructures and mechanical properties of copper and some of its alloys have been well-investigated and enabled to achieve very high values. It is worth to make an effort to bring those processed metal and alloys into applications.

1.2 Objectives of the study

The main goal of this study is to investigate the influence of Equal Channel Angular Pressing process on the workability of copper electrode for resistance spot brazing application.

Works are focused on:

1. To improve the hardness and electrical conductivity of copper material via ECAP process
2. To fabricate and study the working performance of ECA pressed copper as electrodes for resistance spot brazing application on Nickel substrate.

CHAPTER 2

LITERATURE REVIEW

2.1 Joining techniques

There are a number of options when it comes to joining metal parts, including adhesive bonding, nuts and bolts, and many other types of mechanical fasteners. Every joining technique has particular design requirements, while certain joint requirements may suggest a particular joining technique. Designs for assembly, automation, and fastener selection impose their own requirements.

Bolting is a common fastening method, for example, but welding may reduce the weight of an assembly. Naturally, joints designed for the two techniques would differ greatly. However, all joint designs must consider characteristics such as load conditions, assembly efficiency, operating environment, overhaul and maintenance, and the materials used [6]

There are a variety of joining methods that do no use fasteners. Alternative methods are especially important for some materials.

Methods to join materials without the use of fasteners include adhesives, welding, and brazing, soldering, clinching, and injected-metal assembly. In addition, materials such as plastics, composites, and metal-ceramic combinations may indicate the use of certain joining methods. For strong and permanent metal joints, the choice usually comes down to either welding or brazing

2.2 Resistance spot welding

2.2.1 An introduction

Resistance spot welding (RSW) is a joining process in which heat for welding is generated by the resistance of the flow of electrical current through the parts being joined. Current is applied and concentrated by a pair of copper electrodes as shown in Figure 2.1. This pair of electrodes also clamps the two sheets being joined to provide good electrical contact and to provide pressure to contain the molten metal at the faying interface. For steel, the power supply generally supplies alternating current, and the time of current application is typical measured in the number of cycles of alternating current. The main process variables are welding current, number of current cycles, electrode force, and electrode characteristics (e.g., electrode geometry and material).

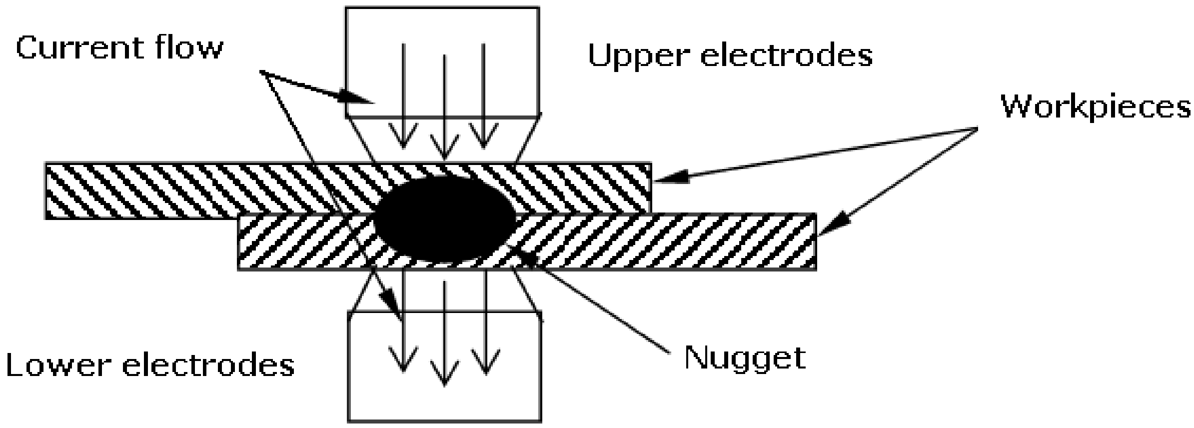

Figure 2.1-Spot weld illustration

Resistance spot welding is widely used in joining sheet steel of thickness up to about 0.125 inch and can be used for many materials including combinations of materials. Many assemblies of two or more sheet-metal stampings that do not require gas-tight or liquid-tight joints can be more economically joined by high-speed resistance spot welding than by mechanical methods. One of the most important applications of resistance spot welding is in automotive industry. The car frame body is constructed by spot welding of individual stamping part, with manual portable welding guns, semi-automatic machines or fully automatic robots [1]. One resistance spot welder can be seen in figure 2.2.

Figure 2.2 – Resistance spot welder

Major advantages of resistance spot welding are high speed and suitability for automation and inclusion in high-production assembly lines with other fabricating operations. With computer-control of current, timing and electrode forces, sound spot welds can be produced consistently at high production rates and low unit labor costs by unskilled operators.

2.2.2 The formation of a resistance spot weld

The operation of spot welding involves a coordinated application of current of the proper magnitude for the correct length of time. This current must pass through a closed circuit. Its continuity is assured by forces applied to the electrodes, which are shaped to provide the necessary density of current and pressure. The entire sequence of operations is required to develop sufficient heat to raise a confined volume of metal, under pressure, to temperature must be such that fusion or incipient fusion is obtained, but not so high that molten metal will be forced from the weld zone. The rates of the rise and fall of temperature must be sufficiently rapid to obtain commercial welding speeds, but neither rate may be permitted to be so rapid that either inconsistent or brittle welds will be produced. The rates of rise and fall of temperature and the time of maintenance at temperature are determined by the characteristics of the metals being welded and by the capacity of available equipment.

The heat required for any resistance welding process is produced by the resistance offered to the passage of an electric current through the workpieces, in exactly the same manner as in any other electrical heating device. The amount of heat generated depends upon three factors: (1) the amperage, (2) the resistance of the conductor and (3) the duration of current. These three factors affect the heat generated as expressed in the formula (2.1) below.

$$Q = I^2Rt \tag{2.1}$$

where Q is the heat generated (J), I is the current (A), R is the resistance of the work (Ω), t is the duration of current (s)

The welding cycle is divided into four to five time segments: squeeze, preheat, weld, postheat, hold and off. These are shown in Figure 2.3 [7]. The time is expressed in cycles, where 1 second equals 60 cycles (60 Hz frequency of the AC voltage used).

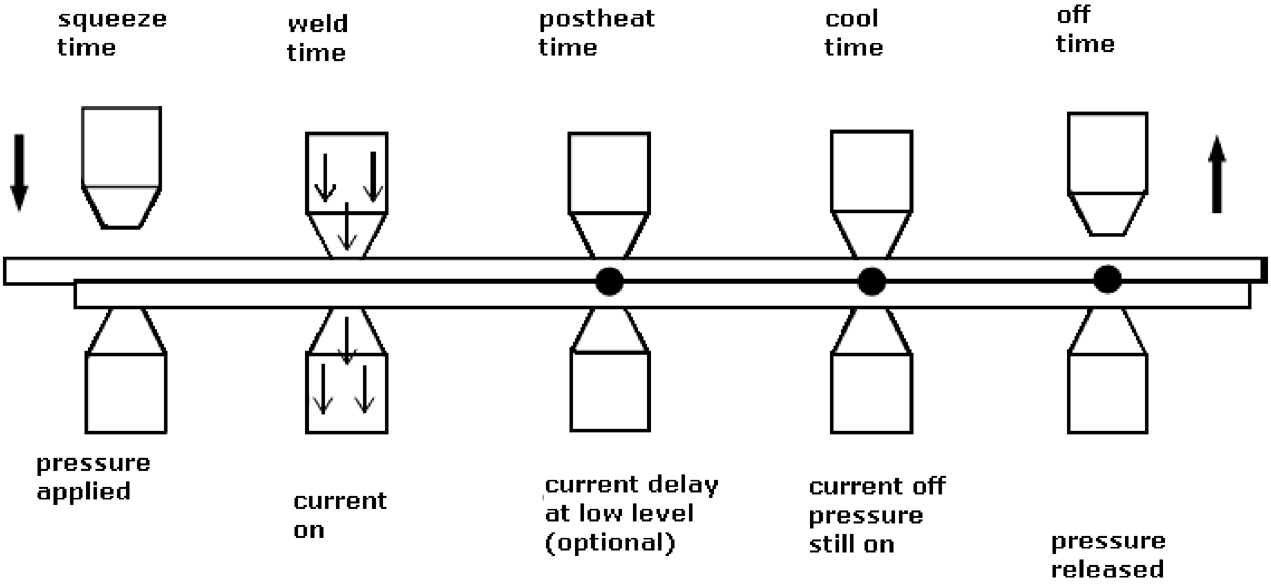

Figure 2.3 -Welding cycle

- ***Squeeze time*** is the time between the initial application of the electrode pressure on the work, and the first application of current in making spot weld. It provides time for the solenoid-actuated head cylinder valve to operate and for the welding head to bring the upper electrode in contact with the workpiece and develop full electrode force.

- ***Preheat*** is a low current applied in the time interval before the full welding current is applied. Preheat is an optional segment. It reduces thermal gradients in the metal.

- ***Weld time*** is the interval during which the welding current flows through the circuit.

- ***Postheat time*** is the interval during which current is on at a low level. It is used chiefly for grain refinement (tempering) on hardenable carbon and alloy steels. It is optional

- ***Cool time*** is the interval during which, after the welding current is off, the electrode force is held on the workpiece until the metal of the spot weld has solidified.

- ***Off time*** is the interval from the end of the hold time until the beginning of the squeeze time for the next cycle. It is the time needed to retract the electrodes, remove or reposition workpiece.

All of the segments are usually expressed in cycles, meaning the number of cycles in a 60-cycle system, where one cycle is 1/60 second.

2.2.3 Function of electrode and selection of electrode material

In welding operation, electrodes are important component in spot welding setup. The main purposes of the electrodes were highlighted [8] which are, 1) to conduct the welding current to the workpieces, 2) to transmit the proper pressure to the weld area in order to give good fit during weld formations and 3) to dissipate the heat from the weld zone rapidly.

To meet those requirements, the electrode materials must have electrical conductivity of at least 80% IACS as to limit the I^2R loss (note: 100 %IACS or International Annealed Copper Standard refers to electrical conductivity of annealed copper at temperature of $20^{O}C$. The unit is for expressing the conductivity of nonmagnetic materials by testing using the eddy-current method. Generally used for temper and alloy verification of Aluminum). Low electrical conductivity results in excessive heating and cause the electrode to stick at workpieces. High thermal conductivity is also required to dissipate the heat generated as to minimize local heating and to reduce increment of electrode temperature, facilitate cooling of the weld as to constrain weld nugget formation and minimizing interfacial and surface splash.

Copper is pre-eminent in the electrical component industry because it has high electrical conductivity. However, because of its poor tensile strength, even at modest temperatures, design problems arise when copper is used in electrical applications [9]. There is now an increased demand for a copper based material having both high electrical conductivity and high mechanical strength at elevated temperatures. Therefore, three primary mechanisms have been identified used to strengthen copper alloys in industry: solid solution strengthening, dispersion strengthening and precipitation strengthening.

In solid solution strengthening, atoms of the alloying constituents replace copper atoms in the matrix causing distortion. Typically, solid solution strengthening is used in combination with cold work to reach a given strength level, which become the foundation of Cu-Zn, and Cu-Sn-P alloys [10]. The dissolved solutes disturb the periodicity of the copper lattice on an atomic scale and rapidly reduce the electrical conductivity, as well as thermal conductivity [11].

Precipitation strengthening copper such as Cu-Cr and Cu-Cr-Zr alloys has been formed by dissolving alloying elements in copper metal at high temperature before quenched to saturated solid solution [12]. In the following aging treatment, atoms of the alloying constituent formed microscopic particles in the copper matrix. These particles have been reported to be more efficient than the solid solution atoms in providing strength while maintaining electrical conductivity [13]. The first alloy system developed using this concept was Cu-1%Cd with the hardness of 115Hv and moderate electrical conductivity i.e 85% IACS. Then, Cu-1%Cr system was introduced with the hardness of 150Hv and the electrical conductivity of 80% IACS. People realized that the usage of precipitation strengthened copper at high temperatures observes coarsening of dispersed phase. This phenomenon which has been known as

Otswald ripening caused an increase in the mean free path for dislocation movement and resulted in strength reduction [14].

In dispersion strengthened copper, such as Cu-ThO_2 and Cu-Al_2O_3, advantage is taken on the strengthening effect of hard secondary phase particles on a soft matrix. If these strengthening phases are thermodynamically stable [15] and insoluble in the matrix metal at both processing and application temperature [16] the resulting dispersion strengthened alloy is improving the tendency toward thermally induced softening. High electrical conductivity of dispersion-strengthened copper, with high resistance towards mechanical property degradation during exposure to elevated temperatures, is an extremely attractive design option.

2.2.4 Micro welding – a promising technique

In manufacturing, the management of environment issues in becoming more important every year. In particular, industries which use soldering as a major method of electrical bonding are facing stricter lead regulations. As a result, manufacturers planning to obtain quality management and environment management system certification are taking a second look at micro resistance welding.

Because only several volts are applied to the work, this increases operator safety and generates almost no excessive heat, smoke and flashes, keeping the working place and environment clean [3]. Reliable quality, good cost-performance, easy operation and easy maintenance are several advantages of micro resistance welding over other welding processes. These advantages help save man-power in various automated production lines

2.3 Brazing techniques

2.3.1 An introduction

Brazing is a method of joining two pieces of metal together with a third, molten filler metal. The joint area is heated above the melting point of the filler metal but below the melting point of the metals being joined; the molten filler metal flows into the gap between the other two metal pieces by capillary action and forms a strong metallurgical bond as it cools.

Of all the methods available for metal joining, brazing may be the most versatile, for a number of reasons. Brazed joints are strong; they are often stronger than the two metals being bonded together. Brazed joints are ductile, withstand vibration and shock and are unaffected by normal changes in temperature. Brazed joints are usually easy and rapidly made, with operator skill readily acquired. Brazing is ideally suited to the joining of dissimilar metals. You can easily join assemblies that combine ferrous with nonferrous metals, and metals with widely varying melting points. Because brazed joints have a very clean, well-finished appearance, brazing often is the preferred bonding process for manufacturing plumbing fixtures, tools, heavy construction equipment and high-quality consumer products. Brazing is performed at relatively low temperatures, reducing the possibility of warping, overheating or melting the metals being joined. Brazing is economical. The cost-per-joint compares quite favorably with joints made by other metal joining methods. Brazing is highly adaptable to automated methods. The flexibility of the brazing process enables you to match your production techniques very closely to your production requirements.

In virtually all brazing applications, heat is applied directly to the parts which are to be brazed, not directly to the brazing alloy. Many different heat sources can be used; flames, furnaces, electricity (through resistance or induction heating), radiant (infrared) sources, even molten salt baths. When gas flames are used, the process is termed torch brazing.

Although brazing, soldering and welding are similar in many respects, there are important differences. Soldering generally can be done at lower temperatures (below 450^{O}C), but does not produce as strong a joint. Welding, a higher-temperature process in which the two metals to be joined are actually melted and fused together, requires the most heat energy. Welded and brazed joints are usually at least as strong as the metals being joined. The welding process is ideal for applications which benefit from highly localized, pinpoint heating. But it is more difficult to apply to linear joining, not as easy to automate, and not easily adaptable for joining metals with different melting points.

2.3.2 Micro resistance spot brazing

To employ the advantages of resistance spot welding listed in 2.2.4 session as well as advantages of brazing techniques, it is a worth try of using a resistance spot brazing technique in joining metal.

Similarly to resistance spot welding, resistance spot brazing takes use of a pair of electrodes to conduct current and pressure to a pair of workpieces but with presence of a filler metal which enables us to lower the joining temperature. The brazing temperature is nearly the melting temperature of filler metal and considerably lower than that of base metal.

The joining, therefore, is expected to give least heat-distortion of workpiece and a faster cooling time due to its relatively low temperature. This also resulted in a longer electrode life which can sufficiently reduce production cost.

2.4 Theory of Severe Plastic Deformation

2.4.1 Ultrafine grained materials

Ultrafine grained materials (UFG) usually refer to materials with grain sizes of ~ 1 micrometer or submicrometer level by comparison to coarse -grained materials. In some cases, ultrafine grained materials also refer to nanocrystalline materials with grain sizes in the range of 10-100nm. Currently considerable interest is focusing on fabrication of ultrafine grained materials and extensive work has been conducted to evaluate the characteristics of UFG materials.

The increasing interest in UFG materials arises mainly for two reasons. Firstly, it is known that in all alloys the Hall-Petch effect [17, 18] contributes to the strengthening at room temperature by the relationship shown in formula (2.2)

$$б_c = б_i + kd^{-m} \qquad (2.2)$$

where $б_c$ is the flow stress, $б_i$ is the stress characterizing the resistance to the dislocation movement within the grain, k is a constant depending on the mechanism of slip transition through the grain boundary, d is the grain size and m is an exponent approximately equal to 0.5 depending on the nature of the alloy [19]. It is thus possible to conclude that UFG materials have larger strengths than coarse grained materials.

Secondly, it has been established that the retention of ultrafine grained sizes at high temperatures, typically sizes of 0.01-10 micrometer at temperature >0.5 T_m, where T_m is the absolute melting point, favors flow in the form of a grain boundary sliding accommodating diffusion-controlled processes and thus offers a potential of achieving superplastic materials.

2.4.2 Methods of fabrication of ultrafine grained materials

Several methods have been developed to attain ultrafine grained materials and nanocrystalline materials. Traditionally, small grain sizes are obtained using appropriate thermomechanical processing (TMP) methods, where a continuous recrystallization process termed as geometric dynamic recrystallization (GDR) is usually observed [20, 21, 22]. However, TMP methods can only produce materials with grain sizes in range of 1-10 micrometer and the refinement of grain sizes is achieved by specific processing route involving specially designed heat treatments which lead to an increase in the expense. Therefore, the TMP methods are not suitable for the production of UFG materials.

Later, inert gas condensation [23, 24], high-energy ball milling [25, 26, 27] and sliding wear [28] were developed to produce UFG materials. These methods are very effective to refine grain sizes, even to the nanometer level, and avoid extensive heat treatment procedures. However, all these methods involve the compaction of nano-powders to attain a solid sample and thus are not capable of producing bulk samples in a fully-dense condition. Therefore, these methods are not sufficiently ready to explore industrial applications of UFG materials.

Recently, methods of severe plastic deformation (SPD) were introduced in producing ultrafine-grained materials [29, 30, 31, 32]. Unlike conventional plastic deformation methods, such as cold rolling or drawing, methods of SPD can readily attain very refined microstructures at low temperatures with the imposition of a high pressure, and the structures consist of a large number of high angle boundary grains in the submicrometer range giving dramatic changes in properties. Furthermore, methods of SPD are capable of producing bulk samples in a fully-dense condition, therefore showing a potential for use in industrial applications.

2.4.3 Theory of Severe Plastic Deformation

Equal channel angular pressing (ECAP) [33, 34, 35, 36] and high pressure torsion (HPT) [37, 38, 39] are two typical SPD methods. The ECAP method was firstly introduced by Segal and co-workers [40] where a sample is constrained within a channel and pressed through a specially designed die to impose a large strain. The HPT method was developed [41] where a disc is subjected to a large strain in torsion under an applied high pressure.

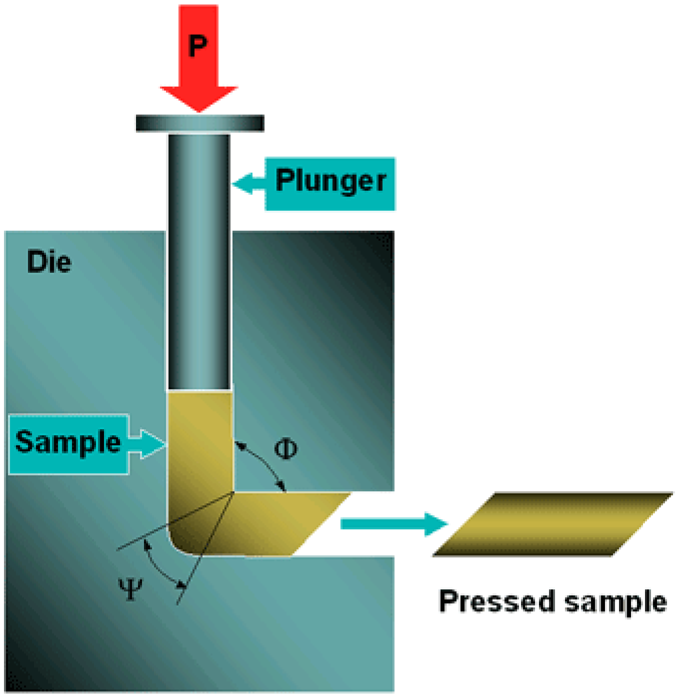

Figure 2.4 -Principle of ECAP technique

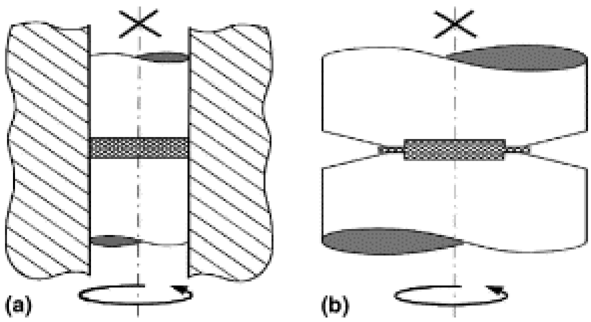

Figure 2.5 – Principle of High Pressure Torsion technique

The principles of the two SPD methods are shown in figure 2.4 and 2.5, respectively. In practice, the two SPD methods are essentially similar straining processes: both of them impose a large shear strain into the sample through a high pressure without any changes in the shape of the sample. However, it was found that the HPT method is especially effective in producing ultrafine intermetallic materials while the ECAP method is easy to use with metals. Based on principles of ECAP and HPT methods, a few novel techniques of SPD have been developed, such as accumulated roll bonding (ARB) [42, 43] and cyclic-extrusion-compression (CEC) [44].

2.5 Principles of Equal Channel Angular Pressing

Among the methods of fabricating ultrafine grained materials, severe plastic deformation (SPD) techniques, such as torsion straining and equal channel angular pressing, are probably the most promising. The ECAP technique was invented in 1972 by a scientist from the former Soviet Union, V.M. Segal [4], and it uses the principle of repeated shear deformation to refine the grain size in metallic materials.

The ECAP has a number of advantages [5]: first, very large deformation strain can be obtained after repeated passes without changing the shape of billets. Second, very uniform and homogeneous deformation can be applicable throughout the cross section of the billet. Third, no residual porosity is found in the deformed billets. Fourth, since the size of the billets is only limited by the size of the die and the pressing facility, it is possible to produce massive samples. Fifth, the areas exposed to tensile stresses are limited during deformation.

2.5.1 Concept of ECAP

As shown in fig 2.4, the basic principle of the ECAP process is to press a sample through a die having two intersecting channels, where the two channels have identical cross-sections so that the cross-section of the sample experiences no change during pressing.

As shown in figure 2.4, a specially-designed die is used in ECAP and two internal angles Φ and Ψ are defined as the curvature associated with the two channels [45] where Φ corresponds to the angle between the two intersecting channels and Ψ is the angle at the outer arc of curvature of the two intersecting channels.

On passage through the die, the sample undergoes straining by simple shear as illustrated schematically in fig 2.6. The simple shear is imposed at the shearing plane of the sample between to adjacent segments labeled 1 and 2. Simple shear is considered a “nearly ideal” deformation method for structure and texture formation in metal working and it enables the sample to be subjected to a large amount of strain without the damage that occurs in conventional metal working such as rolling. Also, the unchanged cross-section of the sample makes it possible for the sample to be processed by ECAP repetitively and thus to accumulate very large shear strain.

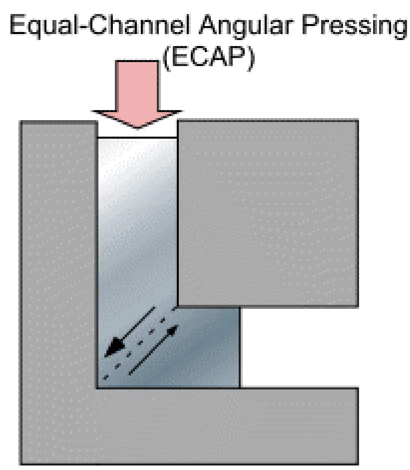

Figure 2.6-The principle of shearing in the sample during ECAP

2.5.2. Strains obtained during ECAP

In ECAP, a sample is pressed through a die in which two channels of equal cross-section intersect at an angle of Φ and an additional angle of Ψ defines the arc of curvature at the outer point of intersection of the two channels [46]. In the case of no friction between the die walls and the billets, the strain associated with a total of N pressings through the die having a round-cornered channel, epsilon n, is given by the following relationship:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi\cos ec\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] \qquad (2.3)$$

Therefore, it is possible to press the same billet through the die a number of times in order to achieve a high total strain because the cross-section of the pressed billet is not changed after pressing.

When no friction effect is also considered, on the other hand, the total strain after N pressings through a die having a sharp-cornered channel is given by the following equation:

$$\varepsilon_N = \frac{2}{\sqrt{3}} N \cot\left(\frac{\phi}{2}\right) \qquad (2.4)$$

It is evident from the above equations that the total strain accumulated in the pressed billet is only a function of the number of passes and the angles of a die. These theoretical relationships were verified experimentally [47, 48]. It was concluded that the above relationships can be directly applied to the canter of the billets but they may not valid at areas away from the center of the billets due to friction.

2.5.3 Versions of ECA pressing

During ECAP, the direction and number of billet passes through the channels are very important for microstructure refinement. In papers, the following routes of billets were considered as shown in figure 2.7 and 2.8 below [32].

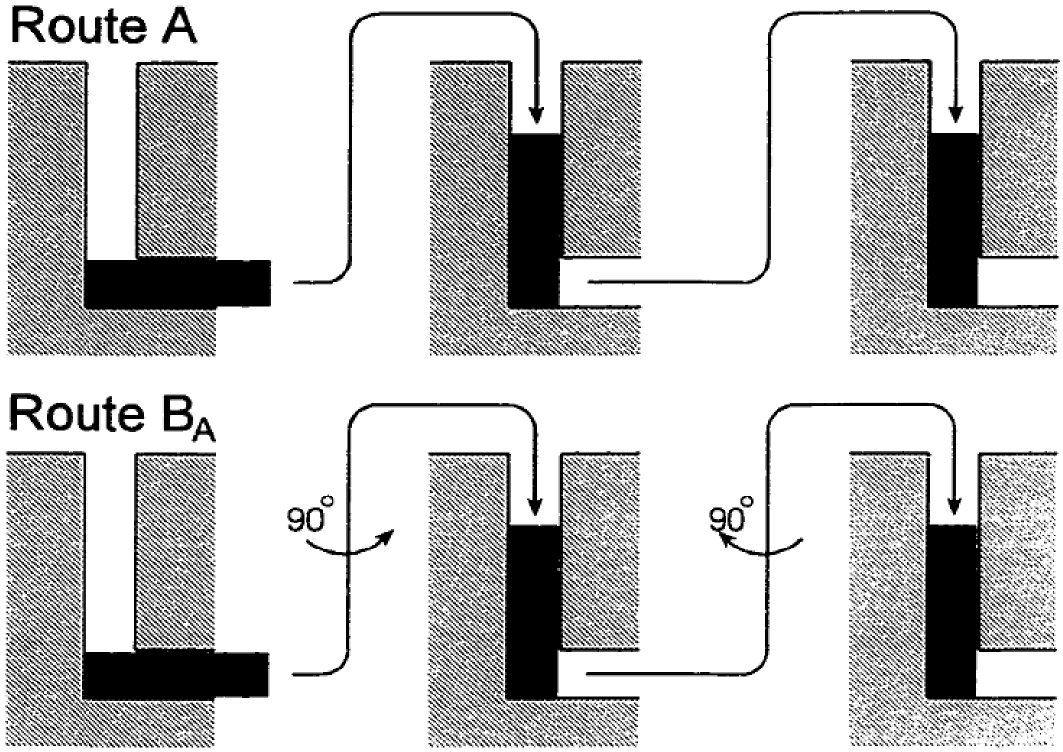

Figure 2.7 – Schematic illustration of route A and route B_A (Valiev, 2000).

As seen in the figure 2.7, in route A, the orientation of a billet is not changed at each pass while in route B_A, after each pass a billet is rotated 90^O clock-wise and 90^O counter clock-wise alternatively.

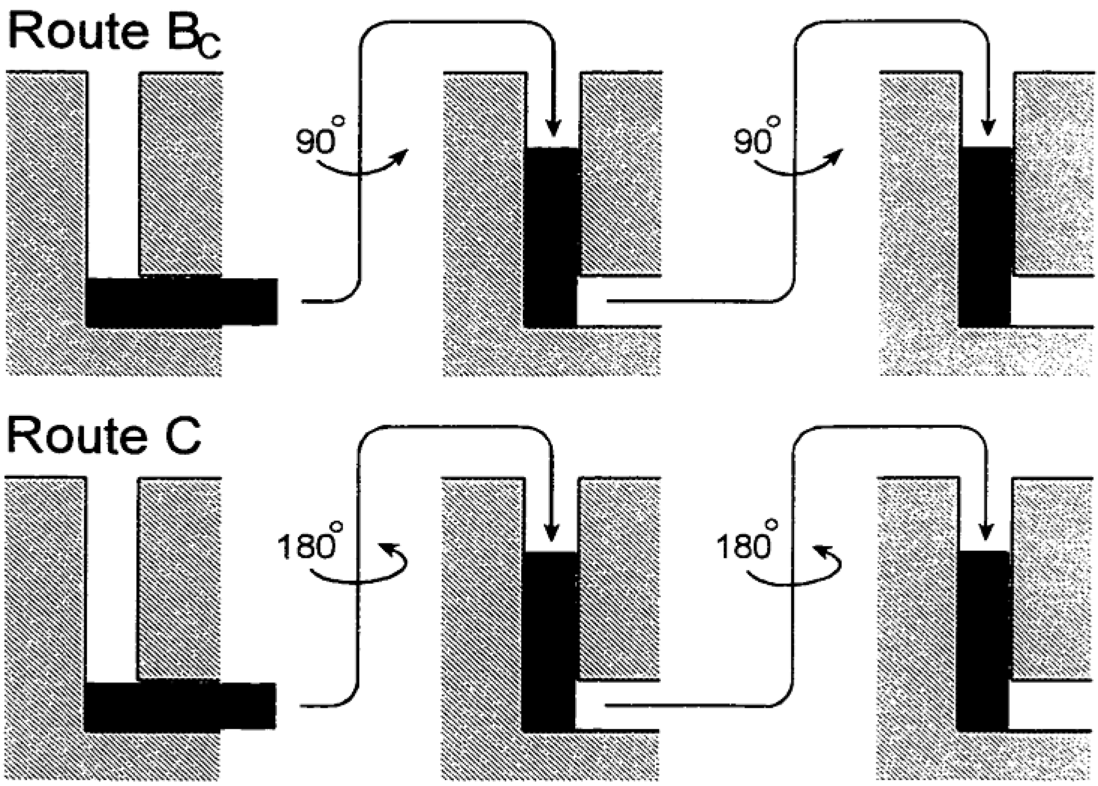

Figure 2.8 -Schematic illustration of route B_C and route C (Valiev, 2000).

In route B_C, after each pass, the billet is rotated 90^O clock-wise while in route C, the billet is rotated 180^O.

The given routes are distinguished in their shear direction at repetitive passes of a billet through intersecting channels. Due to that, during ECAP a change in s spherical cell within a billet body occurs as schematically described in figure 2.9.

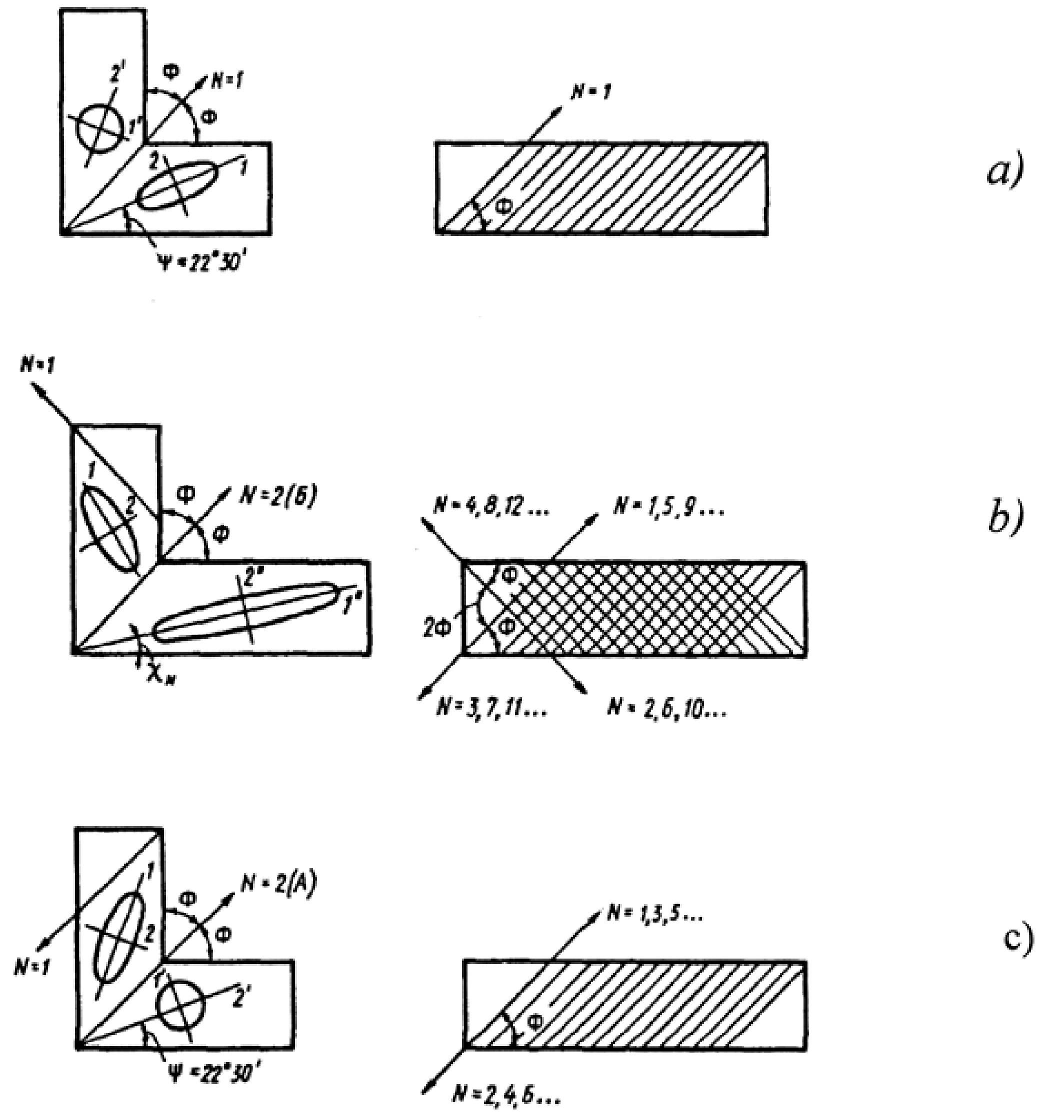

Figure 2.9 – Regimes of simple shear during ECAP: (a) one cycle deforming; (b) route A; (c) route C (Valiev, 2000).

During ECAP in a place of intersection of channels, the cell takes a shape of an ellipsoid (Figure 2.9 (a)). This occurs after the first pass due to the pure shear.

Further, in the process of route A, the following passes results in lengthening of axis 1 and ellipsoid is elongated. At the same time, the direction of shear is turned around the axis perpendicular to the longitudinal section of channels through the angle 2Φ. This is shown in figure 2.9 (b).