ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 2, July 2012

Review Article

A REVIEW ON DEFORMATION STUDIES OF ALUMINUM ALLOYS PROCESSED THROUGH EQUAL CHANNEL ANGULAR PRESSING

R Raj Mohan[1]*, R Venkatraman[2], S Kabilan[1] and S Raghuraman[1]

Corresponding Author: **R Raj Mohan, ✉ 23.rajmohan@gmail.com*

Equal Channel Angular Pressing (ECAP) has been increasingly recognized due to the inimitable physical and mechanical properties inbuilt in various ultrafine grained materials. It is known that ECAP involves perfectly homogeneous large simple shear plastic deformation within a work piece pressed through a die containing two intersecting channels of identical cross-section. This Paper offers a brief summary of the effect of die geometry and processing route on aluminum alloys processed through ECAP which entails a deformation process on the material. Various factors have been known to affect the properties ECAPed materials like type of route, die geometry to control the properties of aluminum material. Die geometry is considered to be channel angle, corner angle and type of routes are followed in ECAP is Route A, Route BC, Route BA, Route C. These characteristics effects are to be discussed in this paper.

Keywords: Equal channel angular pressing, Corner angle, Channel angle, Type of routes

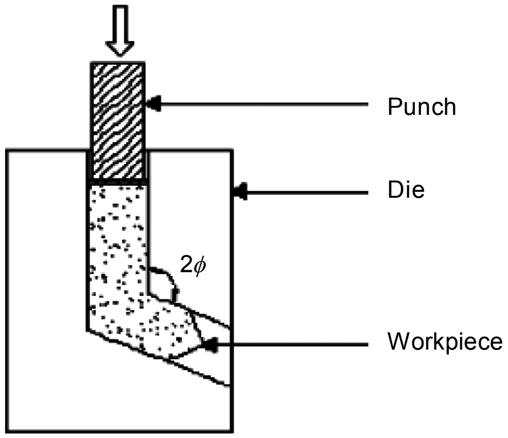
INTRODUCTION

Grain refinement is one of the techniques, which provides finer grains and hence ultra high strength and ductility combination demanded for ambient and cryogenic temperature applications. On the other hand, Severe Plastic Deformation (SPD) is an effective tool for producing bulk ultrafine grained (submicron or nanostructure) metals. Equal channel angular pressing is one of the SPD techniques developed for producing ultra fine grain structures in submicron level by introducing a large amount of shear strain into the materials without changing the billet shape or dimensions (Saravanan *et al.*, 2006). Besides that, people studied the influence of die structure and extruded materials on the effect of refining crystal, and found that the effect of extrusion was different with the die structure, especially the included angle of

[1] School of Mechanical Engineeering, SASTRA University, Thanjavur 613401, India.
[2] Shanmugha Precision Forging, Thanjavur 613401, India.

channels, ϕ, the die outer corner angle, ψ, and the radius of outer angle, *R* (Zhang *et al.*, 2008). Figure 1 Shows the Schematic Diagram of ECAP Process.

Figure 1: Schematic Diagram of ECAP Process



Source: Zhang et al. (2008)

ALUMINUM ALLOYS

Aluminum alloys are classified into two categories, wrought alloys, those that are worked to shape, and cast alloys, those that are poured in a molten state into a mould that determines their shape. The diversity of alloys and the wide range of certain properties explain the growth in applications from aeronautics to packaging.

Non-Heat Treatable Aluminum Alloys

Non-heat treatable aluminum alloys constitute a class of alloys that owe their strength mainly to elements in solid solution, but also to some types of particles. A heat-treatment of such an alloy will generally not produce any strengthening precipitates as in the heat treatable alloys (an exception is the dispersions formed in Al-Mn alloys). The strength may in fact decrease during heat treatment due to the removal of solute atoms. The alloy systems belonging to this class are the AA1xxx system (commercially pure with small amounts of mainly *Fe* and *Si*), the AA3xxx system (as AA1xxx with manganese and magnesium additions), the AA5xxx system (as AA1xxx with magnesium addition) and the AA8xxx system (as AA1xxx, but with higher alloy additions).

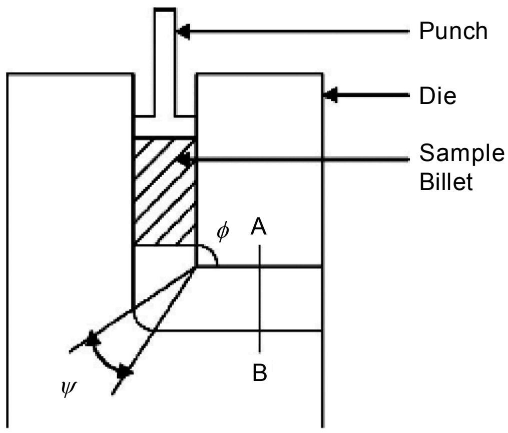
Heat-Treatable Aluminum Alloys

The heat-treatable aluminum alloys get their strength mainly from precipitate particles, and collect the AA2xxx, AA6xxx and AA7xxx alloy systems. These alloys are heated to the single phase area of the phase diagram where alloying elements are more or less dissolved into solid solution.

CHARACTERISTICS OF DIE GEOMETRY

The Channel angle will vary from 60° to 150°, this will influence strain homogeneity on the material. The greater strain homogeneity obtained in an angle closer to 90° compared

Figure 2: ECAP with Channel Angle 'ϕ' 90°



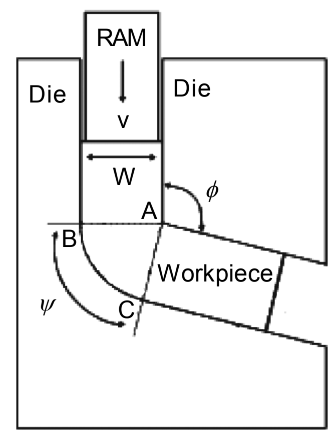
Source: Nagasekhar et al. (2007)

to all other channel angle while keeping the outer corner angle as 10° (Nagasekhar *et al.*, 2007). Figure 2 illustrates the above condition.

It can be understood that the deformation behavior is more complicated with acute channel angles ϕ < 90°, and becomes smooth with obtuse channel angles ϕ > 90°. Lack of free flow of the sample caused strain heterogeneity with acute channel angles. Large corner gap formation and inadequate length of plastic zone caused the strain heterogeneity with obtuse channel angles. Figure 3 shows ECAP with Channel Angle 'ϕ' greater than 90°.

The die corner angle ø was varied as 0°, 6°, 13°, 20°, 37° and 90°. It should be noted that the corner angles ψ = 0° and 90° are the minimum and the maximum values obtainable under the channel angle ϕ = 90° condition.

Figure 3: ECAP with Channel Angle 'ϕ' Greater than 90°



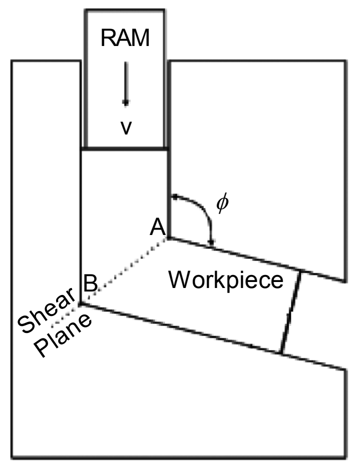
Source: Yoon et al. (2007)

The less sheared zones are formed in non-strain hardening materials of the round corner die conditions and in strain hardening materials. In the strain hardening materials, the deformed geometry was predicted to be almost independent of the die corner angle. The optimum die corner angle among the conditions in this study is ψ is equal to 3°, which may enhance the homogeneity of strain of severely plastic deformed work pieces during ECAP.

As the corner angle ψ increases to 45° and to the maximum value 90° under ϕ = 90°, the lesser sheared zone in the bottom region of the work pieces increase.

When the die corner angle is zero, strain rate is relatively homogeneous within the deforming zones along the line AB compared to the cases of the round corner dies, in which the strain rates are locally high in the inner corner region (near A) and gradually decrease with the distance from the inner corner point A towards the point B. Figure 4 shows ECAP with Corner Angle 'ψ' is 0°.

Figure 4: ECAP with Corner Angle 'ψ' is 0°



Source: Yoon et al. (2007)

This expanded less sheared zone is the characteristics of the round corner die ECAP process due to the shorter length of the die outer part in ψ > 0° than in the case of sharp corner (ψ = 0°). It should also be noted that the round die corner not only reduces the overall shear deformation but also intensify the strain inhomogeneity (Yoon *et al.*, 2007).

Channel has an inner angle of 120° and an outer angle of 60°. This design makes it easy to extrude the sample material through this channel and a large imposed plastic strain in each pass can be obtained. During ECAP, the deformation of sample is non-uniform. The deformation mode in the middle area of the sample is close to pure shear and the remainder areas are not subjected to pure shear (Zhang *et al.*, 2009).

For different outer corner radii in equal channel angular pressing with 105° channel angle. The radius of the outer corner of the die had an important role on strain distribution in the work piece. Strain inhomogeneity was found to be high for both sharp and large outer corner dies, with a minimum in between which could be regarded as optimal shape for outer corner (Basavaraj *et al.*, 2010).

With a fillet for the outer corner but no fillet for the inner corner reduces the stress concentration at the intersecting corner (Hu Banghong, 2002).

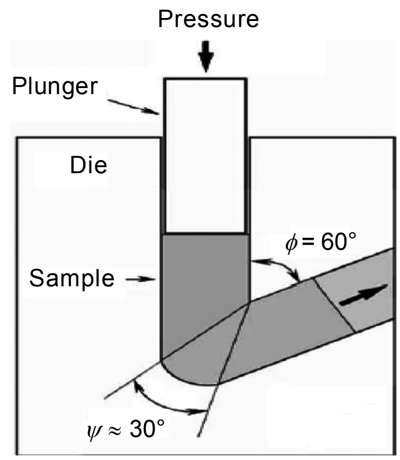
Both the largest and uniform accumulative effective plastic strain increased with the decrease of the radius of the corner die (Melichera, 2009).

The larger ψ, the lower is the pressing force. Although this is a practical advantage, both deformation level and deformation homogeneity decrease; therefore, a compromise must be found. The best relationship between pressing force and deformation homogeneity, was observed when the combination of radii gave ψ = 32°, that is r = 0 mm (sharp corner); R = 8 mm (Anibal *et al.*, 2011).

Despite the efficiency of ECAP dies with channel angles of ϕ = 90°, it is important to recognize that it is experimentally easier to press billets when using dies with angles that are larger than 90°. For some very hard materials or with materials having low ductility.

Since the strain imposed in ECAP increases with decreasing channel angle, it may be advantageous to perform the pressings using channel angles which are ϕ less than 90°. Where, High pressures are required to successfully produce billets without the introduction of any cracking (Ruslan *et al.*, 2006). Figure 5 shows ECAP with Channel Angle 'ϕ' less than 90°.

Figure 5: ECAP with Channel Angle 'ϕ' Less Than 90°



Source: Ruslan et al. (2006)

With an increase in strain rate sensitivity, the workpiece processed through the round corner die showed increased bending and strain heterogeneity in comparison to the sharp corner die. The optimal ways to reduce the bending of strain rate sensitive materials in round corner dies are reducing the processing speed and increasing the length of the die exit channel (Seung *et al.*, 2009).

The microhardness increases slightly up to 8 passes in both dies, when using the die with ϕ = 120°, and by with ϕ = 90° is used (Ali and Nurulakmal, 2010).

CHARACTERISTICS OF PROCESSING ROUTES

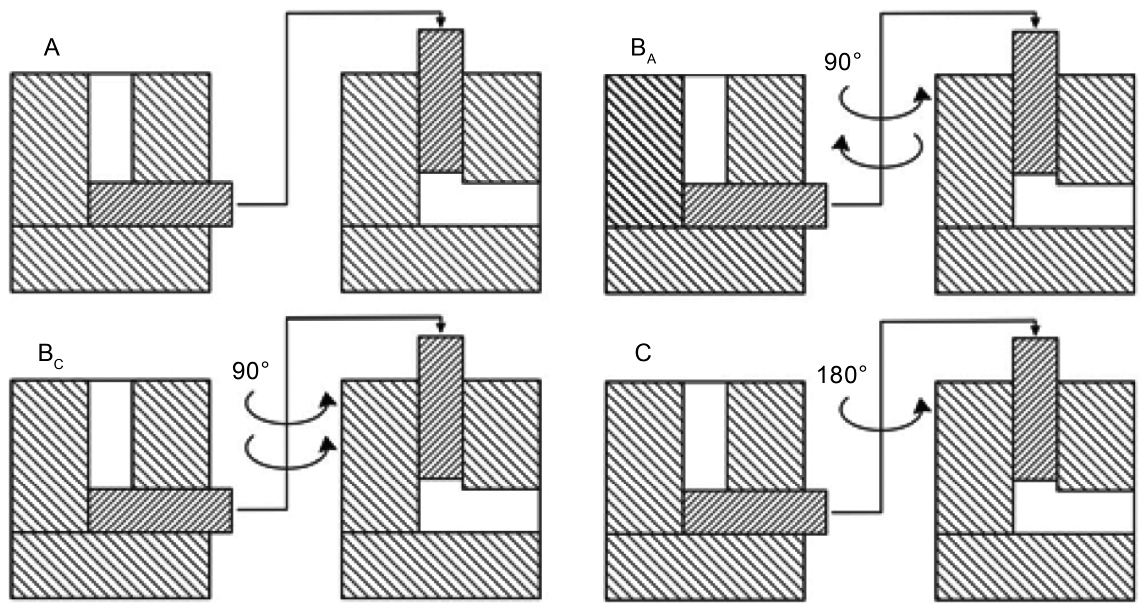
Routes mean the directions followed by the billet or test sample. ROUTE A (0°), all passes; the billet is not rotated between successive passes. ROUTE B or B_A: (90°), N even, (270°) N odd; the billet is rotated (90°) clockwise and counterclockwise alternatively. ROUTE C: (180°), all passes; the billet is rotated (180°). ROUTE D or B_C: (90°), all passes; the billet is rotated (90°) clockwise (Samuel, 2011).

The given routes are distinguished in their shear directions at repeat passes of a billet through intersecting channels.

Route C and B_C are termed a redundant strain processes and the strain is restored after every even number of passes. By disparity, routes A and B_A are not redundant strain processes and there are two separate shearing planes intersecting at an angle of 90° in route A and four dissimilar shearing planes intersecting at angles of 120° in route B_A. In routes A and B_A, there is a collective upsurge of additional strain on each separate pass.

By using the route, B_C (the rotation of 90° in the same direction between passes), up to 8 passes at room temperature, which is the preferred route for achieving equiaxed grains. Route B_C leads to the rapid development into a collection of high-angle grain boundaries. Figure 6 shows that Processing Routes in ECAP.

Figure 6: Processing Routes in ECAP



Source: Samuel (2011)

For Al6082 alloy processed through route C, The dislocation density and the subgrain size reached their maximum and minimum values, respectively, even after 1 pass. The yield strength increased monotonously even after the saturation of the dislocation density and the grain size indicating that the more equilibrated high angle grain boundaries have higher strengthening effect than the non-equilibrium boundary structures (Sandip *et al.*, 2008).

For Al6082 alloy processed through route A, The increase of the yield stress of the alloy by the increase of the dislocation density and grain size is decreased (Gubicza *et al.*, 2005).

A commercial 6082 aluminum alloy at pre-described conditions was subjected to ECAP at elevated temperature 150 °C using route B_C through 120° channel angle. The grain orientation distribution reached the random case of dislocation density and the subgrain size (Tomas *et al.*, 2009).

During the processing of 6082 aluminum alloy, the maximum absolute value for yield stress was reached by route B_C, the minimal value by route C.

For the area reduction after fourth pass, for route B_C the tendency to decrease and for B_A shows gain after eighth pass. For the elongation, route C tendency to increase and for B_C, B_A has tendency to decrease. The phenomenon of high ductility along with high strength was revealed for Al6082 after eight passes of ECAP for route C.

For purity Al (99.999%), Ultimate tensile strenght in dependence on ECAP passes through route C with channel angle 90°.

The annealed AA6082 alloy processes through B_C and C route. From that route C performed satisfactorily while during B_C third pass diffused shear crack has been attained (Vedani *et al.*, 2003).

Pure Aluminum processed through route C, the dead zone subtended by the work piece is independent of its geometry, whereas the load-displacement curve is dependent on the work piece geometry.

A stable and uniform plastic strain distribution in the material after every even pass can be attained.

The rate of increase in load required to extrude the work piece decreases with increasing number of ECAP passes (Kumar *et al.*, 2010).

Commercial purity aluminum 1050 processed through route B_C and C. the higher yield strength values for route B_C, though the equivalent strain achieved in both routes is the same. Route C the average grain size relatively increased and the misorientation angle relatively decreased after the compression deformation, even the percentage area with grains less than 1 μm size decreased after compression, and finally the percentage of boundaries having high angle boundaries also decreased after the compression deformation (El-Danaf *et al.*, 2007).

INFERENCE

From the above literature review, it is observed that the strain inhomogeneity was found to be high for both sharp and large outer corner dies. When ϕ is 90°, the effective strain is achieved. The punch pressure is only determined by channel angle ϕ and yield stress of the material 6_o. For a channel angle of $\phi = 90°$ shows that these boundaries have high angles of misorientation.

The channel angle ϕ is increases leads to low angle boundary. A high angle boundary leads to increase in ductility. Due to channel angle, the Strain is imposed on the material.

Strain is more sensitive to the corner angle than the channel angle. So, for aluminium the channel angle is close to 90° for attaining very high strain. But, the grain size reduction is high for channel angle 60° than 90°.

Small grains lead to high strength at ambient temperature. It indicates that grain size reinforcement is responsible for the material strengthening.

Due to corner angle, production of ultra fine grained material. Increase in the corner angle or arc of curvature leads to formation of dead zone or corner gap.

Billet is no longer remains in contact with the die walls at this outer corner. Effective corner angle is approximately 20°.

Ascendancy of the accumulated strain when using a 90° die and the ascendancy of the interaction of the shearing plane with the crystal structure and the deformation texture when using a 120° die.

Both the largest and uniform accumulative effective plastic strain increased with the decrease of the radius of the corner die.

The force required to press the workpiece through the die decreased with the increase in the radius of the corner die.

It is well established that the microhardness of ultrafine-grained materials (pressed workpieces) is higher than the microhardness of similar materials with large grain size (cast workpiece).

A microstructure of equiaxed grains separated by high angle boundaries is a requirement for achieving high tensile ductility and this is attained most readily when processing using route B_C.

Routes B_A and B_C are less effective than route A in refining grain size for $\phi = 120°$. Route B_C is the optimum ECAP processing route at least for the pressing of pure aluminum. Route A was identified as the optimum procedure in two aluminum alloys when using a die with $\phi = 120°$.

The effectiveness in terms of formation of High Angle Boundary's was A > B_C > C, in terms of reducing grain size was B_C > A > C and in terms of generating equiaxed grains was B_C > C > A.

Hardness and yield strength values for route B_C are consistently higher than those for route C, up to the eight passes.

CONCLUSION

Severe plastic deformation induced by equal channel angle pressing is capable of producing significant grain refinement.To obtain high strain rate super plasticity. Uniform and unidirectional deformations can be produced under relatively low pressure and load for massive products Production of Ultrafine-equiaxed Grained (UFG) materials has been achieved, e.g., grain size less than 1 μm. The crystallite size decreased and the dislocation density increased as a result of ECAP deformation.

The ECAPed sample illustrates severe dynamic recovery during simple compression, perhaps promoted by the developed texture during ECAP.

The higher strain hardening of the ECAPed samples during simple compression in the initial part of the deformation is due to the refined structure and the relatively high boundaries misorientation.

Achievement of Powder Compaction/ Consolidation. The relation between strain inhomogeneity and die geometry has been recognized. High strength and high ductility phenomenon can be obtained.

Loading conditions can be predicted. Significant increase in microhardness is obtained after the first pressing through the ECAP dies. Leads to minimize the development time and cost.

REFERENCES

1. Ali A Aljobouri and Nurulakmal Mod Sharif (2010), "Influence of Die Angles on the Microhardness of Aluminum Alloy Processed By Equal Channel Angular Pressing", *IIUM Engineering Journal*, Vol. 11, No. 2, pp. 137-149.
2. Anibal de Andrade Mendes Filho, Erika Fernanda Prados, Gustavo Trindade Valio *et al.* (2011), "Severe Plastic Deformation by Equal Channel Angular Pressing: Product Quality and Operational Details", *Materials Research*, Vol. 14, No. 3, pp. 335-339.
3. Basavaraj V Patil, Uday Chakkinga and Prasanna Kumar T S (2010), "Influence of Outer Corner Radius in Equal Channel Angular Pressing", *World Academy of Science, Engineering and Technology*, Vol. 62, pp. 714-720.
4. El-Danaf A, Soliman M S, Almajid A A and El-Rayes M M (2007), "Enhancement of Mechanical Properties and Grain Size Refinement of Commercial Purity Aluminum 1050 Processed by ECAP", *Materials Science and Engineering*, Vol. A 458, pp. 226-234.
5. Gubicza J, Gy Krállics, Schiller I and Malginm D (2005), "Evolution of the Microstructure of Al 6082 Alloy During Equal-Channel Angular Pressing", *Materials Science Forum*, Vols. 473-474, pp. 453-458.
6. Hu Banghong (2002), "Numerical Analysis in Equal Channel Angular Extrusion of Nanostructured Light Alloys", Forming Technology Group, SIMTech Technical Report PT/02/039/FT.
7. Kumar S S S, Balasundar I and Raghu T (2010), "Deformation Behaviour of Pure Aluminium During Multi-Pass Equal Channel Angular Pressing Through Route #C", *Kovove Mater.*, Vol. 48, pp. 127-135.
8. Melichera R (2009), "Numerical Simulation of Plastic Deformation of Aluminum Workpiece Induced by ECAP Technology", *Applied and Computational Mechanics*, Vol. 3, pp. 319-330.
9. Nagasekhar A V, Yip Tick-Hon and Seow H P (2007), "Deformation Behavior and Strain Homogeneity in Equal Channel Angular Extrusion/Pressing", *Journal of Materials Processing Technology*, Vols. 192-193, pp. 449-452.

10. Ruslan R, Valiev Z and Terence G Langdon (2006), "Principles of Equal-Channel Angular Pressing as a Processing Tool for Grain Refinement", *Progress in Materials Science*, Vol. 51, pp. 881-981.
11. Samuel T Adedokun (2011), "A Review on Equal Channel Angular Extrusion as a Deformation and Grain Refinement Process", *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, Vol. 2, No. 2, pp. 360-363.
12. Sandip Ghosh Chowdhury, Amit Mondala, Jeno Gubicza *et al.* (2008), "Evolution of Microstructure and Texture in an Ultrafine-Grained Al6082 Alloy During Severe Plastic Deformation", *Materials Science and Engineering*, Vol. A 490, pp. 335-342.
13. Saravanan M, Pillai R M, Pai B C *et al.* (2006), "Equal Channel Angular Pressing of Pure Aluminium—An Analysis", *Bull. Mater. Sci.*, Vol. 29, No. 7, pp. 679-684.
14. Seung Chae Yoon, Anumalasetty Venkata Nagasekhar and Hyoung Seop Kim (2009), "Finite Element Analysis of the Bending Behavior of a Workpiece in Equal Channel Angular Pressing", *Met. Mater. Int.*, Vol. 15, No. 2, pp. 215-219.
15. Tomas Kovaríka, Jozef Zrnikb and Miroslav Cieslard (2009), "Grain Refinement in Aluminium Alloy AlMgSi During ECAP at Room Temperature", *METAL*, Vol. 19, Hradec nad Moravici.
16. Vedani M, Bassani P, Cabibbo M *et al.* (2003), "Experimental Aspects Related to Equal Channel Angular Pressing of a Commerical AA6082 Alloy, *Metallurgical Science and Technolgy*, Vol. 21, No. 2 (December).
17. Yoon S C, Quang P, Hong S I and Kim H S (2007), "Die Design for Homogeneous Plastic Deformationduring Equal Channel Angular Pressing", *Journal of Materials Processing Technology*, Vols. 187-188, pp. 46-50.
18. Zhang Xiao-Hua, Luo Shou-Jing and Du Zhi-Ming (2008), "Uniformity and Continuity of Effective Strain in AZ91D Processed by Multi-Pass Equal Channel Angular Extrusion", *Trans. Nonferrous Met. Soc. China*, Vol. 18, pp. 92-98.
19. Zhang Jing, Zhang Ke-Shi, Wu Hwai-Chung and Yu Mei-Hua (2009), "Experimental and Numerical Investigation on Pure Aluminum by ECAP", *Trans. Nonferrous Met. Soc. China*, Vol. 19, pp. 1303-1311.