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Microstructure evolution of carbon steel by hot equal channel angular extrusion

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Abstract

An equal channel angular extrusion (ECAE) process equipment which enable a repetitive hot ECAE process without ejecting workpiece with route A and C are developed. This equipment has T-shape 3 actuator axis in horizontal plane and is capable of simulating the formation of fine grained steels in the transformation route. Each actuator (mechanical servo press unit) can be controlled by both position and load with programed motion. The outline of the developed ECAE equipment and the results of preliminary application of the ECAE equipment at an elevated temperature at various pressing speeds ranging from 2 to 32 mm/s for a Nb alloyed steel are present. 2 passes via route C at ram speed 16mm/s are also conducted. The ferrite grain size of about 2μm steel is obtained throughout the workpiece at ram speed of 32 mm/s, preheated temperature 960°C.

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Keywords: Hot ECAE; Fhase trasformation; Ultra fine grain

1. Introduction

Microstructure evolution or crystal structure after severe plastic deformation (SPD) is important to understand mechanism of production of the bulk nanostructured metals. Shear deformation is known to effective to produce ultra fine grain. The research of grain refinement by phase transformation after severe shear deformation for low

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carbon steel was limited in a torsion test. Beladi et al. (2004) reported that a polygonal ferrite with a grain size of less than 1μm was produced by dynamic strain-induced transformation (DSIT) using hot torsion tests of a C-Mn-V steel. The DIST ferrite growth occurred during post deformation cooling, the mean ferrite grain size increases to 2.5 μm with increasing ferrite transformed volume fraction. Recently, a new physical simulation method for evaluating shear deformation on the evolution of microstructure was proposed by Yanagimoto et al. (2012). The method was based on shearing and named 'Interrupt shearing test'. The large shear deformation reproduced by the method could produce ultra fine grained Nb alloyed steels with a grain size around 2 μm. On the other hand, the research for a hot equal channel angular extrusion (ECAE) in the range of 500-900 °C for SUS 304L austenitic stainless steel was reported by Huang et al. (2008). The single pass ECAE process was achieved. Because a repetitive hot ECAE process and rapid ejecting the workpiece from die is difficult for 1 axis press. Nishida et al. (2001) developed a rotary-die ECAP which consists of a die containing two channels with the same cross-sections intersecting at the center with a right angle in order to remove the limitation in the conventional ECAP, i.e. the sample must be removed from the die and reinserted again in each step. At first, the sample is inserted into the die with the plunger as shown in Fig. 1(a), and after pressing the sample as Fig. 1(b), the die is then rotated by 90°, and the sample is pressed again as Fig. 1(c). Rotary-die ECAP allow the ECAP time reduce more than 75% compared to conventional ECAE, however, the pressing mode is fixed to route A(Furukawa et al., 1998) and enable to apply back pressure. The research of phase transformation after hot ECAE process has not been conducted. Then, we developed an ECAE process equipment which enable the repetitive hot ECAE process without ejecting workpiece with both route A and C with backpressure. The outline of the developed ECAE equipment and the results of preliminary application of the ECAE equipment at an elevated temperature at various pressing speeds ranging from 2 to 32 mm/s are present in this paper.

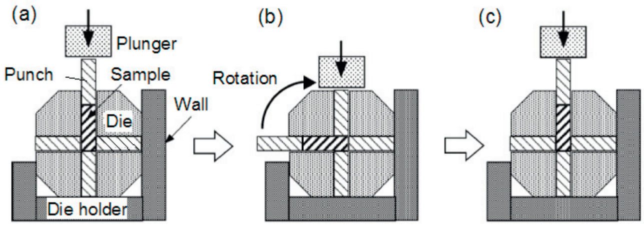


Fig. 1. Equal channel angular pressing (ECAP) process using rotary-die: (a) initial state, (b) after one pass and (c) after 90° die rotation (Nishida et al., 2001).

2. Hot ECAE process

2.1. Repetitive ECAE equipment

The ECAE process equipment which enable the repetitive hot ECAE process without ejecting workpiece is shown in Fig. 2. This equipment has T-shape 3 axis actuator in horizontal plane. Each actuator can be controlled by both position and load with a programed motion which allow for conducting the ECAE with back pressure. The schematic of repetitive ECAE process is shown in Fig. 3. As shown Fig. 3(a), at first pass the workpiece is extruded through X1 to Y1 direction, then, extruded through Y1 to X2 direction, which coincides with route A. After second pass the workpiece is moved to initial position through X2 to X1 direction. On the other hand, at second pass the workpiece is extruded through Y1 to X1 direction, which coincides with route C.

The JANOME JPU-8004 servo press units were implemented as actuator. The specification of the servo press unit is shown in Table 1. The mechanical servo press offers the flexibility of a hydraulic press (pressing speed and position control, availability of press force at any slide position) with the speed, accuracy and reliability of a mechanical press(Osakada et al., 2011). The position controlling and force controlling can be switched during a process. The forming speed and back pressure of the ECAE process can be controlled accurate in synchronization with each servo unit.

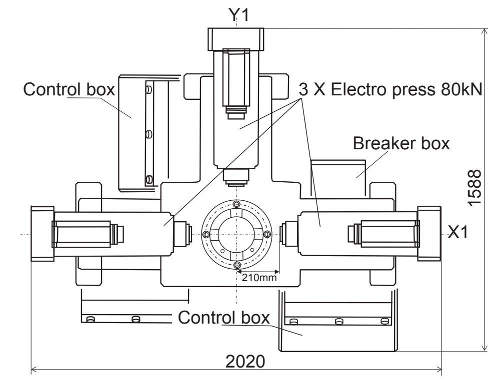


Fig. 2. Schematic illustration of repetitive ECAE equipment.

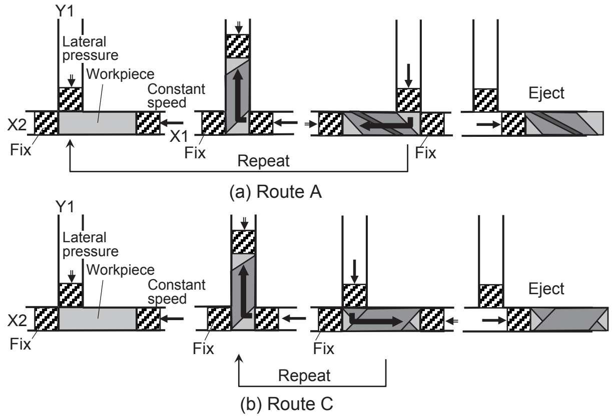


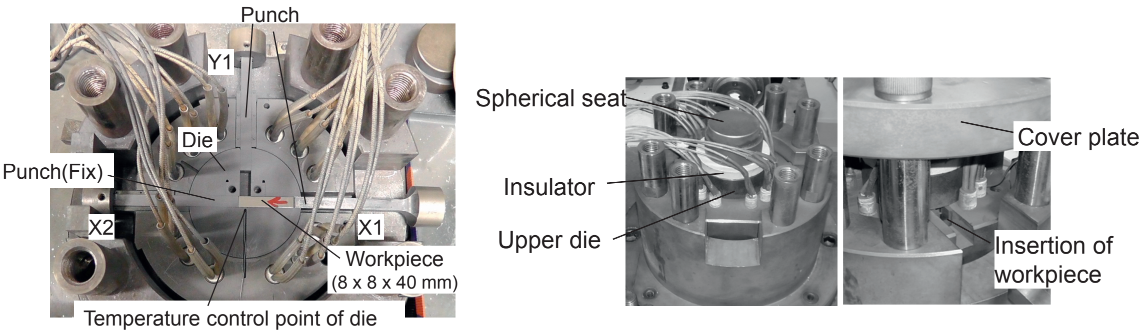
Fig. 3. Schematic illustration of repetitive ECAE process.

Table 1. Specification of servo press unit.

Load	Max 80kN
Ram speed	Max 35 mm/s (loading) Max 200 mm/s (run up)
Control range	0 - 200mm (stroke control) 800N -80kN (load control)
Setting range	0.001 mm (stroke control) 10 N (load control)

2.2. Experimental setup of hot ECAE process

The experimental setup of the hot ECAE process is shown in Fig. 4. The dies material was SKD61 steel (X40CrMoV5-1). The die temperature can be heated up to 400 ◦C by the 12 cartridge heaters (200W) with control unit and the temperature control point of the die is 1 mm from channel as shown in Fig. 4(a). The die is covered by upper flat die, the insulator, the spherical sheet and the cover plate. The cover plate was fasten by eight M20 screws with fastening power of 80 N·m. The workpieces were heated up to the deformation temperature in the furnace. To reduce the decreasing of temperature of workpiece during transfer from the furnace, the workpiece is heated within the container block and insert to the die through insertion with the container as shown Fig. 4(c). The material of the container block is SUS 310 stainless steel.



(a) Overview of die and punches. (b) Layout of upper die (c) Insertion of workpiece

Fig. 4. Experimental setup of hot ECAE process. (a) Overview of die and punches. (b) Layout of upper die. (c) Insertion of workpiece.

3. Experimental conditions

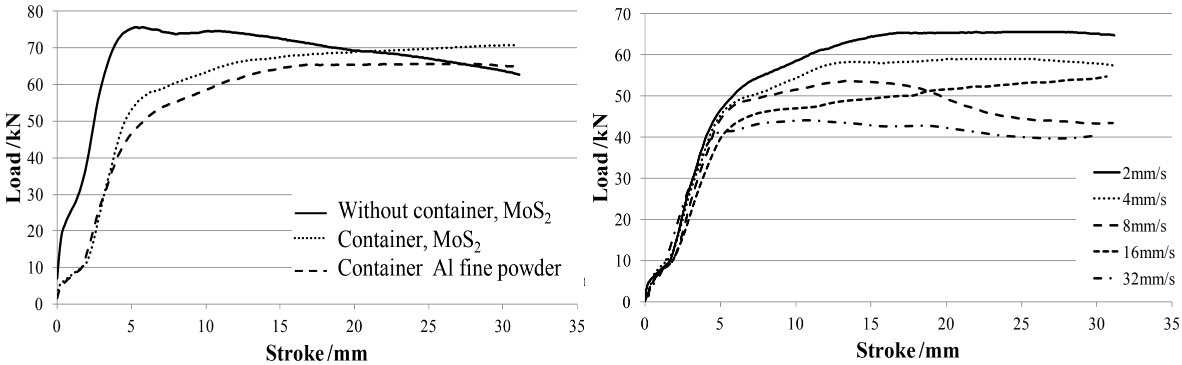
A Nb microalloyed steel (0.16% C, 1.41% Mn, 0.030% Nb) is used in the experiment aiming at utilizing the pinning effect to obtain austenite with a high accumulated dislocation density before transformation and to keep super cooled austenite longer during ECAE process. The Ae3 temperature of this steel is about 820°C. The workpieces were machined in the longitudinal direction to dimensions of 8 mm square and 40 mm length.

The workpieces were heated up to the 960°C in the furnace for 10 min within the container block or without the container. Before extrusion, the die was preheated to 400 ◦C. A MoS_2 is used for lubricant between the die and the punches. The MoS_2 and an Al fine powder are used for the lubricants for between workpiece and die to investigate the effect of lubricant. The pressing speeds are 2, 4, 8, 16 and 32 mm/s and stroke is 32 mm. The back pressure is not applied during ECAE process. The workpiece is ejected from the die at a speed of 5 mm/s, followed by natural cooling. 2 passes via route C are also conducted at a speed of 16 mm/s, the inter-pass time is about 4 sec.

4. Result and discussion

4.1. Load –stroke curve

Fig. 5 shows load – stroke curves of the hot ECAE. In Fig. 5(a), the result without the container block, or directly inserted only the workpiece is also included. From Fig .5(a), the pressing load with the container block is smaller than without that one. It means the container block is effective to reduce the decreasing of temperature of workpiece before pressing. The pressing load under lubricated Al fine powder is smaller than that of MoS_2. Al fine powder is more effective lubrication than MoS_2 under this experimental condition. The later experiments (various pressing speed) are conducted under Al fine powder lubricant. Fig. 5(b) shows load – stroke curves employed at several pressing speed. From Fig. 5(b) the pressing load decreases with increasing pressing speed. This means that the workpiece is extruded at elevated temperature at a high pressing speed condition, in other word the temperature of workpiece decreases to around 400 °C, which is the temperature of die, during ECAE process at low speed pressing.



(a) At pressing speed 2mm/s. (b) At various pressing speed, lubricated with Al fine powder.

Fig. 5. Load – stroke curves of hot ECAE. (a) Pressing speed of 2mm/s, (b) various pressing speed, lubricated with Al fine powder.

4.2. Hardness and microstructure

Fig. 6 shows photograph of the workpiece after the hot ECAE process. The head and tail parts of the workpiece is not flat. The outer contact angle between the two channels of the die were around 15°, an effective strain is 1.07 assuming simple shear model proposed by Segal 1995. The workpieces have been cut longitudinally at the center of the transverse direction.

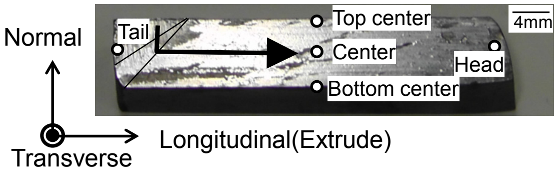


Fig.6. Overview of workpiece after ECAE process.

Vickers microhardness, Hv, was taken on the polished cross-section from the tail to head of the workpiece, as illustrated in Fig. 6. A load of 1kgf was applied for a dwell time of 15s. Fig. 7 shows the hardness distributions from the tail to head of the workpieces. The tail edge of after second pass was coordinated with the head edge of 1st pass. From Fig. 7 the hardness in the head part of the workpiece is low and increases closing toward the tail part with pressing speed of 2mm/s. The microstructure at position within 20mm from the tail edge is assumed work hardened bainite, which are transformed before deformation due to the decrease of temperature of the tail part of workpiece during waiting time, following ECAE deformation. The hardness distribution with pressing speed of 32 mm/s is constant around 240Hv through the tail to head of the workpiece. The hardness of 2 passes ECAE processed with pressing speed 16mm/s is constant around 280Hv, the value is intermediate between single pass with 2mm/s and 32mm/s at zone of within 20mm from the tail edge. The microstructures at longitudinal plane at the center of the transverse direction are observed. Fig. 8 shows optical microstructures in the transverse plane (in Fig. 6) parallel to the extruded direction of the workpiece after hot ECAE with pressing speed of 2 and 32 mm/s. From Fig. 8(a), the microstructure of the center part of workpiece is severely elongated along the direction of about 30° inclined to its longitudinal axis with pressing speed of 2 mm/s. From Fig.8(b) the microstructure with pressing speed of 32 mm/s is consist of pearlite band which about 30° inclined to its longitudinal axis and fine equiaxial ferrite grains about 2μm. The fine grain is obtained by hot shear deformation in the austenite region and subsequent transformation. At the head tail of the workpiece, plastic deformation did not occur, bainite was formed chilling by the die which temperature is 400°C. From Fig. 8(c) the for 2 passes with pressing speed of 16mm/s, elongated ferrite is observed and it is also assumed by the hardness of about 280Hv in Fig. 7. Ferrite transformation will occur during 4 sec inter-pass time, because of accelerate transformation by accumulated strain energy by severe shear deformation.

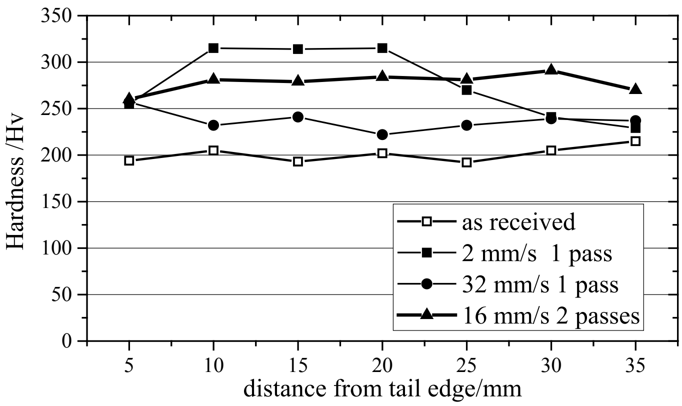
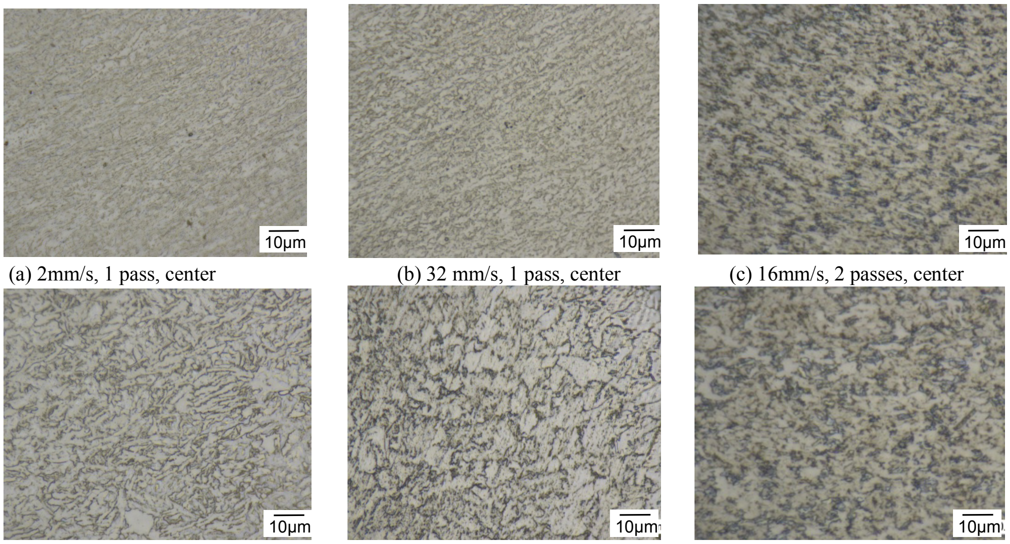


Fig.7. Hardness distributions from the tail to head of workpieces after hot ECAE at preheat workpiece temperature 960°C.



(a) 2mm/s, 1 pass, center (b) 32 mm/s, 1 pass, center (c) 16mm/s, 2 passes, center

(d) 2mm/s, 1 pass, head end (e) 32 mm/s, 1 pass, head end (f) 16mm/s, 2 passes, tail end

Fig.8. Optical microstructures in the transverse plane parallel to the extruded direction of the workpiece after single hot ECAE with pressing speed 2 and 32 mm/s and 2 passes with 16mm/s.

5. Conclusions

The repetitive ECAE equipment is developed to carry out combining hot ECAE with subsequent phase transformation. The preliminary application of the ECAE equipment is conducted at an elevated temperature with a single pass and 2 passes without a back pressure. These results indicate that the high pressing speed is necessary to obtain fine grain ferrite about 2 μm throughout the workpiece. Further investigations, such as multi-pass with the back pressure and controlled cooling to accelerate transformation are required to obtain nanostructured steel with a grain size of several hundred nanometers by the equipment.

Acknowledgements

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