ARL-TR-8047 • JUNE 2017

US Army Research Laboratory

Fabrication of High-Strength Lightweight Metals for Armor and Structural Applications: Large-Scale Equal Channel Angular Extrusion Processing of Aluminum 5083 Alloy

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NOTICES

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
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1. REPORT DATE *(DD-MM-YYYY)* June 2017	**2. REPORT TYPE** Technical Report		**3. DATES COVERED (From - To)** January 2013–February 2016
4. TITLE AND SUBTITLE Fabrication of High-Strength Lightweight Metals for Armor and Structural Applications: Large-Scale Equal Channel Angular Extrusion Processing of Aluminum 5083 Alloy			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Vladimir M Segal, Philip J Young, and Laszlo J Kecskes			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-WMM-F Aberdeen Proving Ground, MD 21005-5069			**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-8047
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			
13. SUPPLEMENTARY NOTES			

14. ABSTRACT

This report entails the summary of work done under a Phase II Small Business Innovation Research project, W911NF-12-C-0113, awarded to Engineered Performance Materials, Inc., Whitmore Lake, Michigan. In the report, we show for the first time the successful implementation of large-scale equal channel angular extrusion (ECAE) processing in a manufacturing environment. We describe the key features of the large-scale tooling, the pertinent steps in the ECAE process sequence, and identify the necessary operational protocols as they have been applied to 24- × 24- × 4-inch AA5083 billets. While the technology transition and feasibility of the upscaled process were demonstrated, several key issues were identified that prevented the successful demonstration of the multi-pass nature of the ECAE process. These issues include the need to maintain the tooling at isothermal conditions, reducing the time delay between successive passes, and improving the dexterity in handling the hot billet between removal and reinsertion from the tool. We conclude the report by offering potential solutions and a path forward towards the implementation of the process.

15. SUBJECT TERMS

AA5083, ECAE, severe plastic deformation, manufacturing environment, upscaled process

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Laszlo Kecskes
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	UU	54	410-306-0811

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

The US Army Research Laboratory has been interested in developing a large-scale severe plastic deformation (SPD) processing technology for several years. Of the various SPD methods, equal channel angular extrusion (ECAE) offers the simplest means for upscaling. Since its invention[1] and initial descriptions[2,3] by Prof Vladimir Segal, and with coworkers,[4,5] ECAE has found a niche in the materials science community. Over the last decade, several review articles have been written about the versatility of the SPD technique and tangible mechanical property benefits imparted to the material being processed.[6–8] As such, ECAE continues to remain a viable methodology for improving a material's strength, primarily by grain size refinement, while maintaining a reasonable level of ductility.[9–12]

About 4 years ago, results of a Small Business Innovation Research (SBIR) Phase I study, conducted by Engineered Performance Materials, Inc., (EPM) Whitmore Lake, Michigan, demonstrated the significant improvements in the mechanical properties of a commercially available armor-grade aluminum 5083 alloy (AA5083) plate material that was subjected to 4 passes of ECAE, via the Bc (D) route, followed by cold and warm rolling. The results from that prior work have been described by Whelchel,[13] Whelchel et al.,[14] and Hammond et al.[15]

The objectives of this report are to describe the efforts of the follow-on Phase II SBIR project that resulted, in part, based on the preliminary Phase I SBIR effort. The 2-year Phase II SBIR Project, under Contract W911NF-12-C-0113, was awarded in 2012. Funding was started in the first quarter of 2013. However, in 2015, due to a series of unexpected delays, the contract was extended to the end of 2015. The project was completed in February 2016.

Specifically, in accordance with the original EPM Proposal, the technical goals of the Phase II project were the following:

- Identifying the demonstration material and appropriate billet size.
- Designing and optimizing a large-scale ECAE tooling die for plate-shaped billets with a maximum allowable size within the constraints of a fixed-program budget.
- Fabricating the industrial-scale die and required auxiliary equipment.
- Tool testing, adjustment, and repair in a production environment.
- Demonstrating a multi-pass ECAE of large-scale, plate-shaped AA5083 billets.

- Rolling plate billets to a 1-inch thickness for further material evaluation.

2. Material and Billet Selection

One of the most often used lightweight armor materials is the nonheat treatable aluminum alloy (AA) 5083 (nominal composition of Al-4.4Mg-0.7Mn-0.15Cr). Because this alloy can be strain hardened via cold and hot working, it is commonly used in many structural applications. In Phase I of this project, it was demonstrated that 3–4 ECAE passes at a temperature of 250 °C, followed by rolling at a temperature of 160 °C, increases the ultimate tensile strength to as high as 450–500 MPa, thereby resulting in superior ballistic performance.[15] Such a processing sequence also resulted in excellent characteristics for high-strain rate super-plasticity during hot sheet, bulk, and precision forming. Therefore, it was determined to use the same AA5083 for the Phase II part of the project.

Previously, it has been extensively documented that multi-pass ECAE is an effective technique for structural refinement.[3,9,11] However, ECAE, when operated in batch mode, is time and labor intensive resulting in high-product costs. Despite these limitations, there are a few ways for transforming ECAE into a lower cost production operation. To this end, there are several aspects that must be addressed. First, the number of passes must be minimized by combining ECAE with other forming operations such as rolling or extrusion to produce the products with a greater variety of shapes. Second, the material reshaping step (e.g., end cutting, trimming, machining) that usually is necessary between successive ECAE passes must be eliminated. This is especially important for warm ECAE because typically, after each pass, it is necessary for the material to cool before machining, after which it has to be reheated. Third, multi-pass ECAE operations should be performed with a considerable level of automation. This requires repeatability of orienting the billet into the appropriate configurations and the high-functional reliability of the ECAE die and other related equipment. Finally, a significant cost reduction per pound of the ECAE-processed materials may be obtained by using larger-scale billets. Because the labor and processing times are essentially independent of billet size, increasing the billet dimensions will result in a cost savings (per unit weight) in proportion to the ratio of $(A/a)^n$, where A and a are the length of the large and small billets, respectively.

However, there are restrictions on the processing of large-scale billets. Typically, these are factors associated with the cost of the press and the ECAE tool. When the billet size increases from (a) to (A), the required press capacity must increase by $(A/a)^2$ times and the die cost increases on the order of $(A/a)^3$ times. Hydraulic load frames or presses with capacities larger than 15,000 tons are uncommon, custom made, and expensive. Practical data on the cost of large-scale ECAE tooling dies for plate-shaped billets with different dimensions are shown in Table 1.

Table 1 ECAE tooling die cost depending on billet size

Billet size (inches)	Die cost US $	Source
6 × 6 × 1.25	22,000	EPM
15 × 15 × 3.25	130,000	Honeywell
24 × 24 × 4	305,000[a]	EPM (current project)

[a] This price excludes the isothermal heating system.

EPM – Engineered Performance Materials, Inc., Whitmore Lake, Michigan.

At the beginning of the Phase II project, only data for billet sizes (6 × 6 × 1.25 inches) and (15 × 15 × 3.25 inches) were available. These data follow n ≈ 2. As our intent was to use the largest possible billet dimensions, initial cost estimates for billet sizes of 32 × 32 × 5 inches; 28 × 28 × 4.75 inches; and 24 × 24 × 4 inches resulted in a cost of $591,000, $453,000, and $333,000, respectively. (In these cost estimates, no provisions for an active heating system have been made.) An approximate design for each of the cases showed that only a billet size of 24 × 24 × 4 inches, equivalent to a AA5083 billet weight of 102 kg, could be practically realized under the limitations of the fixed budget of the Phase II SBIR project.

3. Brief Description of the New ECAE Tooling Die Concept

Over the past 15 years, Segal and others have described the issues and complexity associated with the transition from laboratory-scale ECAE research tooling to that required in a manufacturing environment in which the tooling must be significantly larger, more robust, and able to meet production quotas determined by economic factors.[16–19]

Presently, known industrial ECAE dies (Fig. 1) for plate-shaped billets[18,19] are comprised of a vertical channel (2) formed in a solid block (1) and a horizontal channel (3) formed between the block (1) and a movable horizontal slider (5). The block (1) is attached to a second block (4) that is mounted onto a bottom baseplate (9). A hydraulic cylinder (7) operates the horizontal slider (5). Figure 1a shows the position of the various components before the beginning of the extrusion cycle, when a billet material (8) is inserted into the vertical input channel (2). During the working stroke, a punch (6) acts on the billet (8) and, once against the horizontal slider (5), the stroke action forces the billet (8) to be extruded into the horizontal channel (3). Friction between slider (5) and the material (8) moves the slider along the extrusion direction. Figure 1b depicts the end of the working stroke. Subsequently, the cylinder (7) retracts the slider to the left until the billet (8) is fully released (Fig. 1c). Next, the punch (6) moves slightly downward and thus releases the billet from the horizontal channel (3); (Fig. 1d). Finally, the punch (6) and slider (5) return to their initial positions and the ejected billet (8) can be removed from the lower part of the die (4) (Fig. 1e).

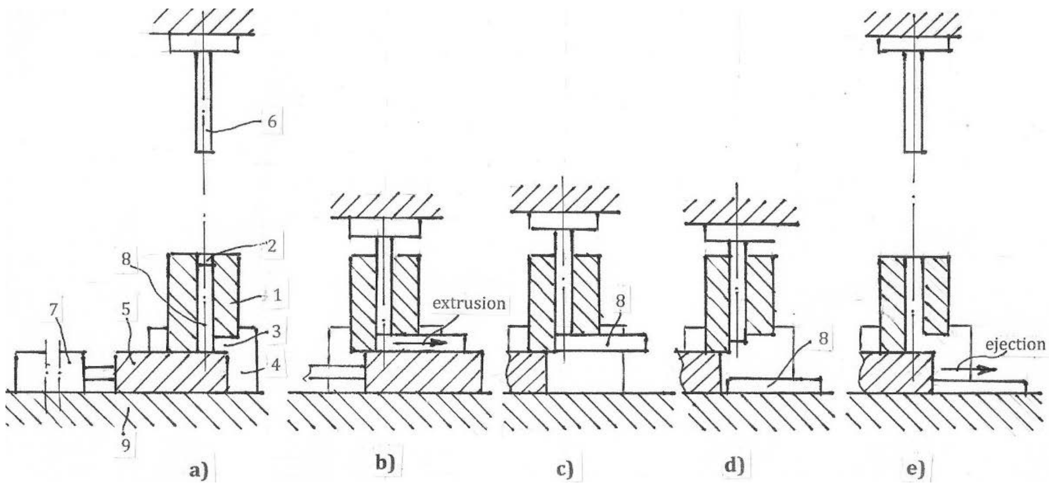

Fig. 1 Key processing steps in typical ECAE tooling die operations for plate-shaped billets

The traditional ECAE die design has several disadvantages. As the front of the billet is stress free during extrusion, it acquires a strong distortion and bowing (Fig. 2). To be able to reinsert the billet into the channel with a 90° rotation, it will have to be cut to the dimension A such that the front face is parallel to the back face. Another problem is the flash B located on the top billet surface. The flash is created at the end of the down stroke as the deforming billet fills the clearance gap between the punch and the 2 intersecting channels. Of course, it is necessary that the massive flash material is machined or trimmed after each pass. Furthermore, to eliminate billet bending during ECAE and surface cracks on top of the billet, the inner corner where the channels intersect must be imparted with a radius, R. Finally, the last major problem is that a movable slider reduces but does not entirely eliminate the friction along the bottom billet surface. If not mitigated, this friction increases the extrusion load and induces strain non-uniformity.

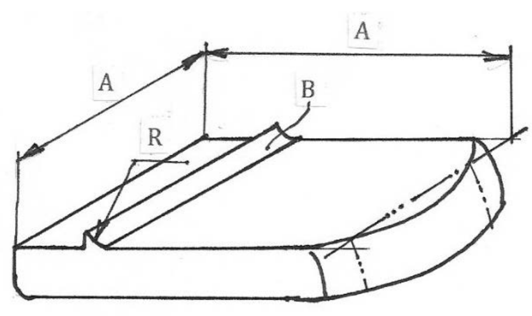

Fig. 2 Billet shape after ECAE in typical dies

To meet the scaling aspects of this effort, a new concept design for the ECAE die was developed by EPM. Figures 3 and 4 show that the new design resolves many of the aforementioned problems. The tool design was also intended to demonstrate the feasibility of transiting the ECAE technology to a semi-continuous operational environment.

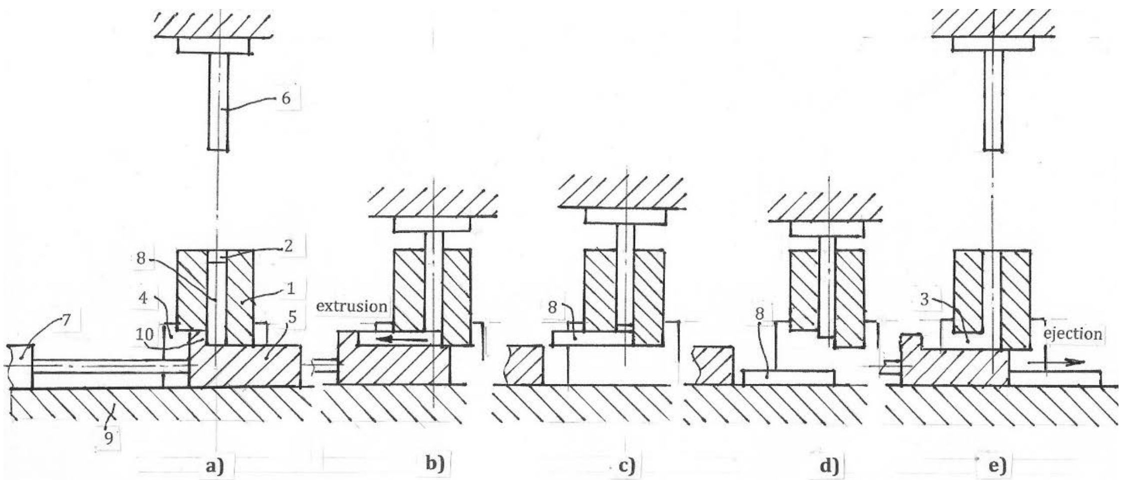

Fig. 3 Key processing steps in the new ECAE tooling die design for plate-shaped billets

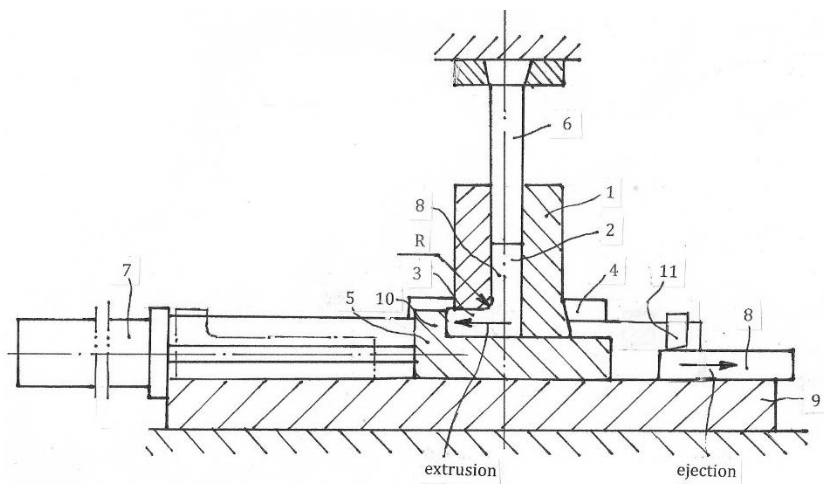

Fig. 4 Detailed schematic drawing of the new ECAE processing and tooling die design

In general, the die is identical to that was shown in Fig. 1, except that the billet extrusion and ejection are performed in opposite directions. This modification allows one to use a slider (5) with an added protrusion (10) overlapping the horizontal channel (3) during the billet extrusion step. Further, this rearrangement allows a trimming knife (not shown in the figure) to activate during the billet ejection step. In the original position (Fig. 3a), the protrusion works as an extension of the vertical channel (2). Then, the punch (6) extrudes the material along the direction of the cylinder (7), which typically does not provide a resistance to the material flow. Figure 3b shows the completion of the extruding step. At the next step (shown in Fig. 3c), the cylinder (7) moves the slider (5) along the extrusion direction until the billet (8) is fully released. In turn, the punch (6) then can eject the billet (8) from the channel (3) (Fig. 3d). In the last step (Fig. 3e), as the cylinder (7) returns the slider (5) to its original position, its action ejects the billet (8) from the die and, at the same time, it trims the flash.

The trimming knife (11) and other components of the new die design can be seen more clearly in the more detailed schematic in Fig. 4. In addition to the components already identified in Fig. 3, the latter figure also reveals a radius R on the front end of the tooling block (1). The function of this radius is to ease the deformation of the billet around this corner; it also serves to minimize or eliminate cracking of the billet.

In comparison to known or existing ECAE tooling die designs, the new die provides several advantages:

- Corrected rectangular billet shape after completion of each pass
- Flat billet surfaces and uniform thickness
- Zero friction along the bottom billet surface
- Stable billet ejection
- Trimming of the flash
- Automatic application of backpressure for billet confinement
- Semi-continuous extrusion pass-by-pass without the need for billet reshaping, cleaning, and cooling/preheating between passes.

The billet shape after ECAE processing using the new die is shown in Fig. 5. After processing the billet now is square-shaped and the flashing (B) is detached as it has been sheared off by the trimming knife.

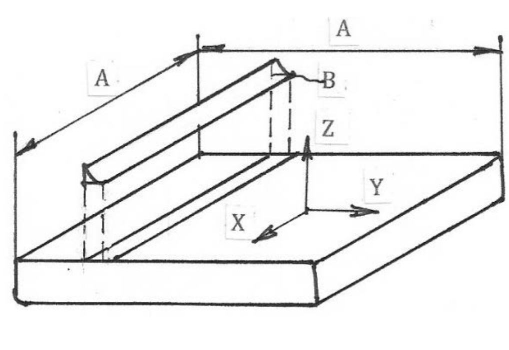

Fig. 5 Billet shape after ECAE processing using the new tooling die design

4. Implementation of the New ECAE Tooling Die Design

The bottom part of the new die comprises 2 main subassemblies: the ring assembly and the bottom assembly. The ring assembly consists of a retaining ring and 4 inserts that have been machined. The 2 inner inserts form the rectangular vertical channel of the die, while the other 2 spacer inserts ensure a tight fit in the retaining ring. During assembly, the 4 inserts together are pressed into the retaining ring. A horizontal slot cut into the ring assembly forms the top and side walls of the horizontal channel. The inner inserts are machined from FX (Finkl & Sons, Chicago, IL) die steel (HRC = 32–35) and have been imparted with a nitrided surface coating. Other parts of the die are machined from conventional as-received 4130 steel (HRC = 28–33).

The bottom assembly includes the plate assembly, with support blocks, slider assembly, column with cylinder plate, cylinder, trimming knife, and billet stopper assembly. Two billet stoppers secure the billet position before ejection by the punch.

The ring assembly is attached to the bottom assembly using a series of container clamps to form the container assembly. This assembly also includes a stopper that secures the bottom punch position and billet guides for billet orientation during insertion into the vertical channel.

The top part of the tooling die includes the punch and punch plate; these components are external and attached to the forging press. As the punch is the most heavily stressed/loaded part of the die, it was machined from H13 tool steel and heat-treated to a hardness of HRC = 53.

The die was designed by EPM for operation in any type of large-scale forging press. As such, a sufficiently large enough capacity, 11,000-ton hydraulic forging press at Ellwood Texas Forge, Inc. (ETF), Houston, Texas, was selected to prove out its functions. This company provided the lowest rental costs and good customer service. The sequence of processing steps was programmed into and operated from the computer numerical control (CNC) system of the press. Within the funding limitations of the Phase II program, and as a cost saving measure, the large-scale tool did not include a self-contained heating system. Instead, for this massive tool and the processed billets, it was expected that external heating by a portable gas heater or in an industrial oven would be adequate.

Improvements in the design were also done to optimize costs and ease the eventual transition into a manufacturing environment. Owing to the careful design of all of the parts using the Solid Works computer software code, the final die cost was reduced to $305,000 (Table 1 for die cost comparisons).

5. Manufacturing of the ECAE Tooling Die and Auxiliary Equipment

The ring assembly with the punch and bottom assembly were manufactured separately by 2 companies in the Houston, Texas, area under EPM's close supervision. A special technology was developed to provide a tight tolerance and the required clearances between the punch, bottom slider, and related channels. Final die assembly was performed in the forging shop at ETF by company personnel in October 2015. During this time, only a few manufacturing mistakes were detected, which were promptly corrected at the ETF machine shop.

Additionally, a special hydraulic power unit (40 kW) was designed and built to operate the die cylinder independently from the press power system. Also, a furnace with air recirculation and a reinforced bottom suitable for heating of the heavy AA5083 plates was purchased. All of the equipment was delivered to ETF, preliminarily tested, and put into operation in October 2015.

6. Industrial Trials of the Large-Scale ECAE Tooling Die

Operation of the tool and press required the services of a shift of about 10 individuals at ETF. All processing steps including billet loading/unloading to/from the oven, delivery to the forging press, loading into the tooling die, handling and rotation between passes by ETF's large-scale GLAMA rail-bound mechanized forging manipulator, (GLAMA Maschinenbau GmbH, Gladbeck, Germany), and die/billet lubrication were reviewed and carefully discussed with the press crew. In response to the large number of processing steps and coordination between crew members, ETF developed an operational protocol consisting of a sequence of steps for ECAE operations for the 11,000-ton press. See Appendix A for a listing of these operating protocols. Also, see Appendix B for a pictorial account of the extrusion operations.

The first extrusion trial and requisite adjustments at the press were performed November 5–6, 2015. Subsequently, a second trial was completed February 24–27, 2016. All die systems—billet insertion, extrusion, ejection, and trimming—worked properly from the first trial onward. Figure 6 shows the large-scale ECAE tooling die in the 11,000-ton press with the auxiliary hydraulic power unit on the right.

Fig. 6 Large-scale ECAE tooling die at the ETF 11,000-ton forging press with the auxiliary power unit on the right

Experience with the forging runs detected several problems related to die preheating. It was known from Phase I that processing of the AA5083 billets required that the die temperature should be within a range of 175 °C–250 °C; otherwise, surface cracks in the billet would be possible. Also, operation of the ECAE die requires a small clearance between the punch and the die channel. Periodic preheating by gas or in an oven does not maintain uniform temperatures in each as the punch heats up much faster than the die. Thus, an interference fit between the punch and the channel could result and cause scratches.

7. ECAE of Large-Scale AA5083 Billets

During the first forging run with an extrusion speed of 40 inches/min, one billet was processed at a temperature of 235 °C and a die temperature of 150 °C preheated by a gas heater. The first pass was successful (Fig. 7); however, on the second pass, the billet developed deep edge cracks at an angle of 45° (Fig. 8). The next billet was extruded at a temperature of 250 °C and a slightly cooled die (135 °C) with similar results. As a consequence, it was decided to increase the die temperature to 175 °C by the external gas heater, but forging was aborted because the inadvertent overheating of the punch led to scratches on the vertical channel wall.

Fig. 7 Appearance of the ECAE processed billet after the first pass

Fig. 8 Appearance of the ECAE processed billet after the second pass

For the second forging run, to avoid the differential cooling of the die and punch, the die was preheated in an oven to a temperature of 250 °C together with the punch. The billet temperature was increased to 265 °C and extrusion speed was reduced to 12 inches/min. The first pass was completed with good results, but edge cracks were observed again after the second pass. In all cases, the second pass was performed semi-continuously without reshaping and preheating. However, the large ETF manipulator destined for heavy steel billets could not provide the necessary precision and accuracy for billet handling, rotation, and insertion into the ECAE die. Therefore, the time between passes was about 2 mins. It is believed that this delay caused significant material cooling around sharp edges that probably led to cracking. Attempts to use additional gas preheating of the die and the billet material before the next ECAE pass resulted again in a poor interference fit between the punch and the die, and further processing was stopped.

8. Conclusions

Under this Phase II SBIR Project, a large-scale ECAE die was designed, fabricated, and tested in a production environment. It was shown to be functional. This new die design implements a new extrusion concept, eliminating disadvantages of known industrial ECAE dies.

During extrusion trials, the first ECAE pass was consistently successful for each of the billets processed at temperatures of 235 °C and 265 °C, and extrusion speeds of 40 inches/min and 12 inches/min, respectively. All billets after extrusion had a rectangular shape, correct and uniform thickness, and were free from flash and other macro-scale defects.

In all cases, the second pass was performed semi-continuously without the need for billet cooling, reshaping, and machining.

The most probable reason for edge cracks during the second pass was flow localization caused by material overcooling in particular parts of the billet due to extended handling time and low die temperature.

9. Prognosis

The aforementioned results demonstrate that most of the technical objectives of the Phase II project were completed. Furthermore, lessons learned in the industrial extrusion trials indicate that many of the necessary improvements and modifications are tangible and could be done with relative ease. However, due to the inability to process 4-pass ECAE billets and subsequently roll them into 1-inch-thick plate, the earlier processing protocols identified in the Phase I program could not be fully validated at a larger scale. Key modifications identified include the following:

An internal electrical heating system for the die with a feedback-enabled automatic temperature control to maintain a uniform material temperature and clearance between the punch and the channel.

A more precise billet manipulator, rotation table, and guide system for handling of the large-scale plate-shaped billets is necessary.

An automated forge line with a conveyer furnace and a CNC manipulator would provide a more optimal arrangement for the industrial ECAE manufacturing of large plates.

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Appendix A. Extrusion Operations Protocol

This appendix appears in its original form, without editorial change.

The ETF team approached the large-scale ECAE trials with great professionalism. To ensure this, the team lead, Mr. Louis Adolph, developed a generic check list for the operation of the EPM tool in the 11,000-ton press environment. Prior to extrusions, these procedures were reviewed and practiced to ensure compliance and smoothness of operations.

This checklist is enclosed herein. It consists of a list of steps that were identified after the first extrusion trials (October 2015), which were then reviewed and subsequently modified for the second trials (February 2016). As the sequence of steps indicate, the procedure was complex and required many preliminary steps to ensure that the extrusions proceeded as planned.

Briefly, assuming that the hydraulic power unit was already set up and all the assemblies installed, the nominal ECAE sequence entailed several key steps.

1. Preheat billets to 518 ± 10 F for minimum of 2 hours
2. Pre-heat ECAE tool, including the punch
3. Lubricate all moving surfaces
4. Align the GLAMA forging manipulator (GLAMA Maschinenbau GmbH, Gladbeck, Germany) for efficient movement
5. Load billet into the tooling die cavity
6. Forge stage 1
    a. press operator push billet through vertical channel
    b. hydraulic control operator pushes billet through horizontal channel.
7. Forge stage 2
    a. billet ejection; bottom slider fully retracted
    b. punch retracted
8. Forge stage 3
    a. index punch for cleaning
    b. re-lubricate die cavity, slider, and clean knife
9. Using the GLAMA, rotate billet and reinsert it into die cavity

However, due to limitations in the availability and operation of some of the equipment, (i.e., the GLAMA Manipulator) resulted in less than desired efficiency in the ECAE process. In particular, this large-scale manipulator is designed for grabbing and moving hot metal during forging operations. It has a single mandible grip that can be extended from a large stand-off distance for safely conducting operations. Obviously, it was not specifically designed or modified to pick up the much smaller ECAE plates and move them with dexterity and ease. As such, the times that it took to extract, pick up, and transfer the billets between successive passes were, typically, much longer than desired, exacerbating the cooling process within.

The enclosed list and the accompanying series of photos in Appendix B illustrate the many facets and stages of the procedure.

ETF
ELLWOOD TEXAS FORGE

FORGE PROCEDURE: FP-EPM, REV. B

GENERAL INFORMATION

DESCRIPTION:	24” ALUMINUM BILLETS
MATERIAL:	ALUMINUM ALLOY (AA5083)
STOCK SIZE:	24” × 23” × 4”
CW RANGE:	216 LBS (Density: 0.0975-lbs/in^3)
TOOLING SETUPS:	D-EPM-110K ASSEMBLY
11K RECIPES:	EPM LATEST REV.

MATERIAL HEATING INSTRUCTIONS

1. BILLETS SHALL BE HEATED TO 518F(+/-10F):
   a. 2.0HRS MIN (Minimum soak time begins after oven reaches set point)
   b. Verify all billets are serialized on one side of the 23” x 4” faces (not both)
   c. Lube all faces of billets using anti-seize lubricant
   d. Orient with serial numbers facing NORTH
   e. Stack on racks (3 high – one billet/rack)
   f. Once removed from oven, billet must be re-heated if it stands idle for more than 5min at any time

DIE HEATING INSTRUCTIONS

1. RING ASSEMBLY SHALL BE PREHEATED IN BROODER TO 500F:
   a. Pre-heat overnight (with punch pre-inserted in die cavity)
   b. DO NOT pre-heat reaming tooling in brooder
   c. Always keep dies closed when not in use

2. SLIDER SHALL BE PREHEATED USING RING BURNER TO 400F-500F:
   a. 2.0HRS MIN

HYDRAULIC POWER UNIT – SET UP & OPERATIONAL CHECKLIST

1. FILL RESERVOIR WITH HYDRAULIC OIL PROVIDED BY EPM

2. WIRE ELECTRIC MOTOR AND VALVES UP CORRECTLY. BUMP ELECTRIC MOTOR AND CHECK CORRECT ROTATION

3. **RUN SYSTEM AND ALLOW THE AIR TO BE FLUSHED OUT OF THE SYSTEM BY OPERATING VALVES**

4. **SET RELIEF VALVE DOWN TO LOW PRESSURE, SHIFT THE DIRECTIONAL CONTROL VALVE WHILE RUNNING PUMP AND SLOWLY INCREASE PRESSURE ON THE RELIEF VALVE UP TO NORMAL OPERATING PRESSURE. DO NOT OVER PRESSURE**

5. **REFILL RESERVOIR WITH OIL, BRINGING LEVELS BACK TO FULL**

6. **SYSTEM READY TO RUN**

MOBILE OVEN CHECKLIST

1. **PLACE OVEN EAST SIDE OF TRACKS, SOUTH OF 11K PRESS**

2. **PLUG IN POWER CORD, TURN OVEN ON, AND SET OPERATING PARAMETERS**

3. **TURN ON HEATER AND TEST OVEN TO ENSURE OPERATING TEMP IS SUSTAINABLE**

PRE-FORGE CHECKLIST

1. **FINAL ASSEMBLIES:**
   a. Assembly hydraulic cylinder to plate subassembly
   b. Connect cylinder to power station and test operation, as required
   c. Adjust cylinder stroke and advance position, as required
   d. Attach protector to slider
   e. Check punch alignment, furnace temp, die cavity temp, and lube all die forging surfaces with anti-seize lubricant prior to opening furnace

2. **RECORD TRANSFER TIME: Target 60 seconds max**
   a. Start when oven door opens
   b. Stop after billet drops into die cavity

3. **RECORD RE-LOAD TIME: Target 60 seconds max**
   a. Start when cylinder is fully extended, at ejection
   b. Stop after billet drops into cavity

4. **RECORD BILLET & DIE CAVITY TEMPERATURES USING INFRARED GUN:**
   a. DO NOT slow down or impede transfer or re-load time progress
   b. Check #1: check billet (as it exits oven)
   c. Check #2: check die cavity & billet (just prior to dropping into cavity)

d. Check #3: check billet (as it exists die, after it has been re-lubed)
e. Check #4: check die cavity & billet (just prior to dropping into cavity)
f. Check #5 & #6: repeat checks #3 & #4 (prior to 3rd pass)
g. Check #7 & #8: repeat checks #3 & #4 (prior to 4th and final pass)

5. RE-LUBE SLIDER, BILLET, DIE CAVITY BEWTWEEN EACH PASS:

a. Re-lube top face of slider (after cylinder is fully retracted)
b. Re-lube top face of billet (as cylinder is being extended to eject part)
c. Re-lube die cavity (after punch has been indexed out of the way)

6. ALIGN FORK TRUCK & GLAMMA (MANIPULATOR) FOR MOST EFFICIENT MOVEMENT:

a. Ensure fork truck is positioned to move straight forward & backwards only to remove billet
b. The idea is to restrict its operation to simple movements in effort to minimize transfer times
c. Ensure manipulator is positioned to rotate and index only to transfer billets
d. The idea is to restrict its operation to simple movements in effort to minimize transfer times

11000 TON PRESS – FINISH OPERATIONS

1. LOAD BILLETS INTO DIES:

a. Review all checklist prior to starting this operation

2. FORGE STAGE 1 IN AUTOMATIC MODE:

a. Tonnage set point: 5,500 tons (6,200 tons max overshoot)
b. Reference: die-to-die with 0.00” offset
c. Rapid approach to 22.00” (within 1.50” of billet)
d. Press speed: 12.00”/minute
e. Finish position: 0.13”
f. Return position: 10.00” (then auto-pause)
g. Auto-pause at the end of Stage 1 to give operator time to retract cylinder so billet drops onto protector

3. FORGE STAGE 2 IN AUTOMATIC MODE TO EJECT BILLET:

a. Fully retract cylinder so billet can drop onto protector (PRIOR TO STARTING STAGE 2)
b. Rapid approach to 1.50”
c. Press speed: 20.00”/min
d. Finish position: 0.00”
e. Return position: full up
f. Then fully extend cylinder to completely eject part
g. Move billet from protector to the rotator block, positioned behind press
h. Inspect part length, width, thickness & trimmed edges (1st PASS ONLY)
i. Adjust thickness via shims under sliding pad and knife, as necessary

4. FORGE STAGE 3 INDEXES PUNCH FOR CLEANING & RE-LUBING DIE CAVITY

5. CLEAN DIE CAVITY, SLIDER, & KNIFE:

a. Flash, trim rag, or any excess material left in die will cause billets to jam in die and prevent election
b. Remove any excess flash or trim rag from billet

6. ROTATE BILLET 90degrees CLOCKWISE

7. REPEAT STEPS 1-6 ABOVE, UNTIL BILLET PASSES THROUGH DIE FOUR (4) TIMES

8. BILLETS SHALL BE COOLED IN STILL AIR

REVISION HISTORY:

REV	DATE	BY	DESCRIPTION
A	10-30-15	BW	NEW RELEASE
B	02-25-16	LA	UPDATE

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Appendix B. Pictorial Account of the Extrusion Trials

Fig. B-1   A stack of 3 of the as-received 24- × 24- × 4-inch AA5083 plates

Fig. B-2   Front view of the Ellwood Texas Forge, Inc. (ETF) 11,000-ton forging press. On the right side of the press is the blue-colored auxiliary hydraulic power control unit for the ejection of the billet from the Engineered Performance Materials, Inc., (EPM) equal channel angular extrusion (ECAE) tool.

Fig. B-3 Side view of the ring and bottom assemblies of the ECAE tool being moved to the forging press by an overhead crane. The man on the right is included as a scale marker.

Fig. B-4 After loading, the ECAE tool had to be anchored to the floor of the forging press. During these adjustments, the punch is pulled out of the input channel.

Fig. B-5 Attaching the hydraulic cylinder for the application of back-pressure and billet ejection control required some work

Fig. B-6 Front end of the ECAE tool already located in the press; the round platform was used to place and ease the rotation of the hot billet between successive passes, using the GLAMA

Fig. B-7 Punch fully inserted into the ECAE tool. Both of the hydraulic hoses, driving the backpressure system are already attached to the auxiliary power unit.

Fig. B-8 Punch has been retracted from the input channel of the tool and positioned to the side during additional preheating phase of the tool

Fig. B-9 ECAE tool aligned and ready for operations

Fig. B-10 Close-up view of the hydraulic cylinder bolting arrangement attaching it to the base of the tool

Fig. B-11 Close-up view of the punch. Note the anti-seize lubricating compound on its bottom

Fig. B-12 Close-up view of the top surface of the tool showing the rectangular input channel

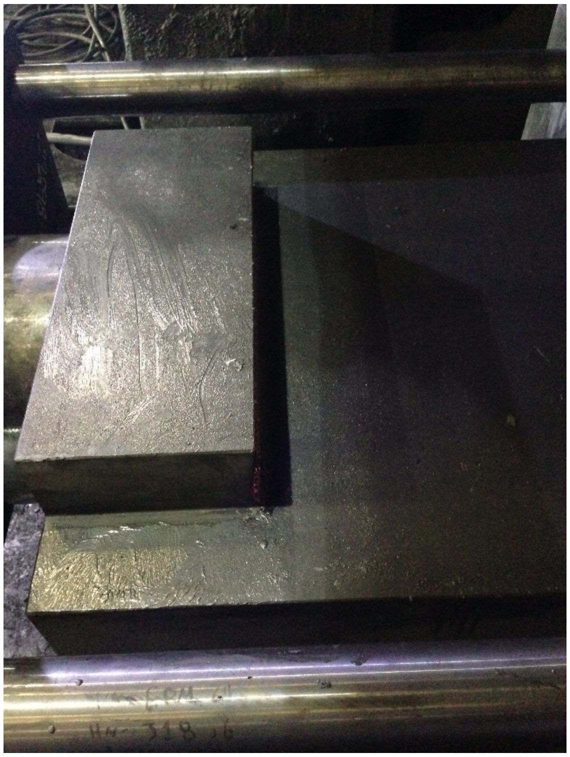

Fig. B-13 Close-up view of the rear end of the bottom slider

Fig. B-14 Close-up view of the bottom slider assembly. The bright orange light is caused by the ring heater inside the cavity.

Fig. B-15 Close-up view of the punch partially inserted into the input channel

Fig. B-16 Close-up view of the front end of the tool with the bottom slider in the forward or ejection position

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Fig. B-17 View of the 11,000-ton forging press control panel

Fig. B-18 Joystick controls for the 11,000-ton press

Fig. B-19 The 2-pass billet from Trial no. 1. Extrusion rate was 48 inches/min. Note the segmentation, periodic edge cracking, and flash attached to the bottom of the billet.

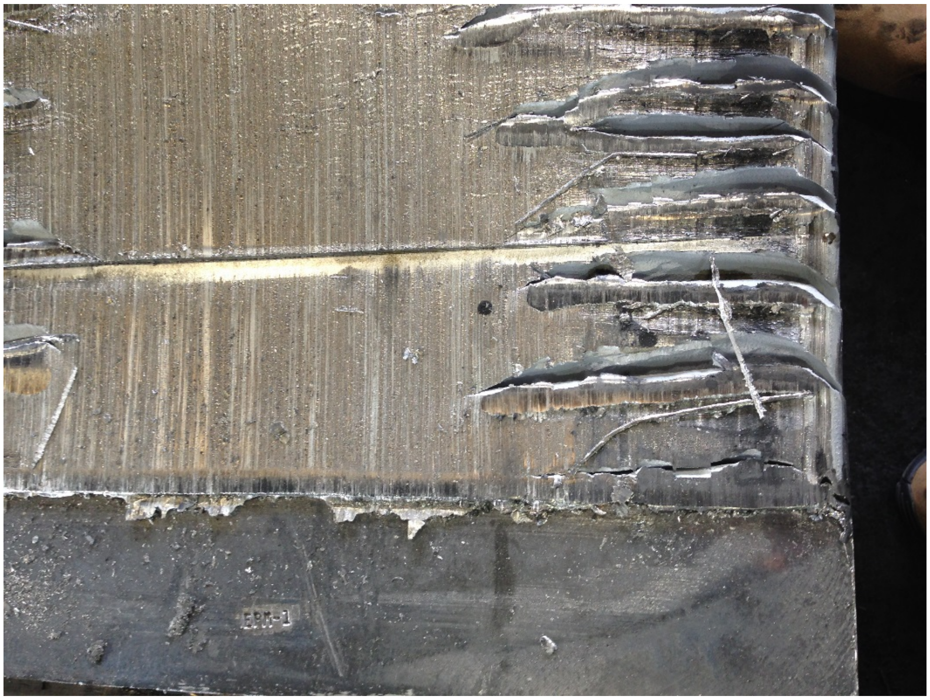

Fig. B-20 The 2-pass billet from Trial no. 1. Detail displaying the periodic lateral edge cracking in the billet; lower right-rear corner of the billet.

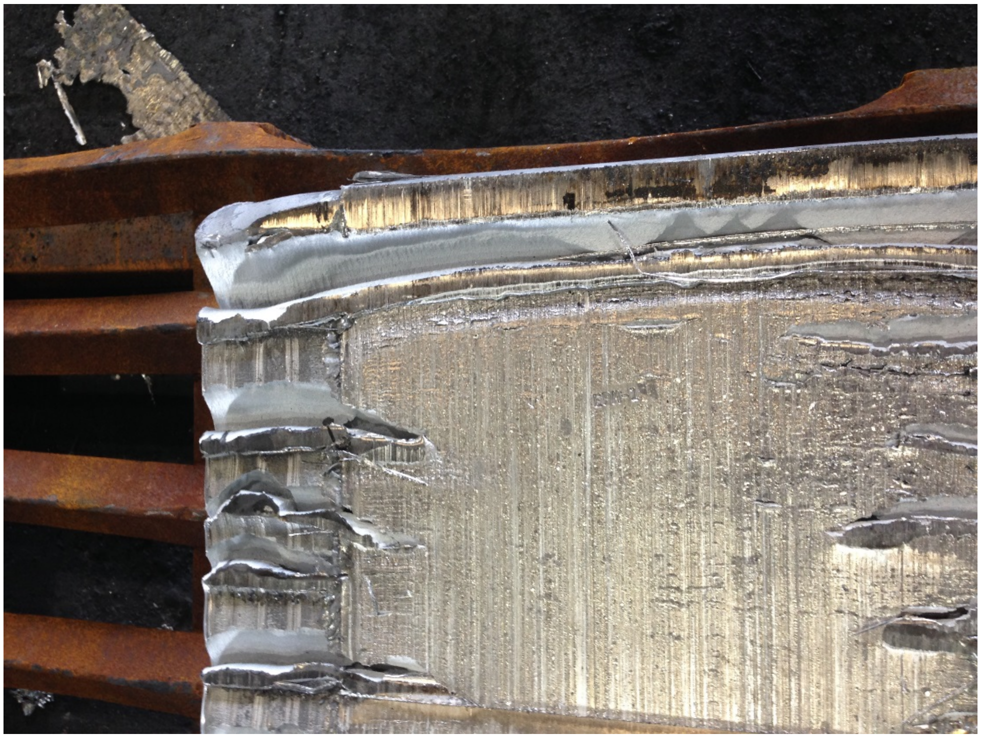

Fig. B-21 The 2-pass billet from Trial no. 1. Detail displaying the periodic lateral edge cracking and petaling; left-front edge corner of the billet.

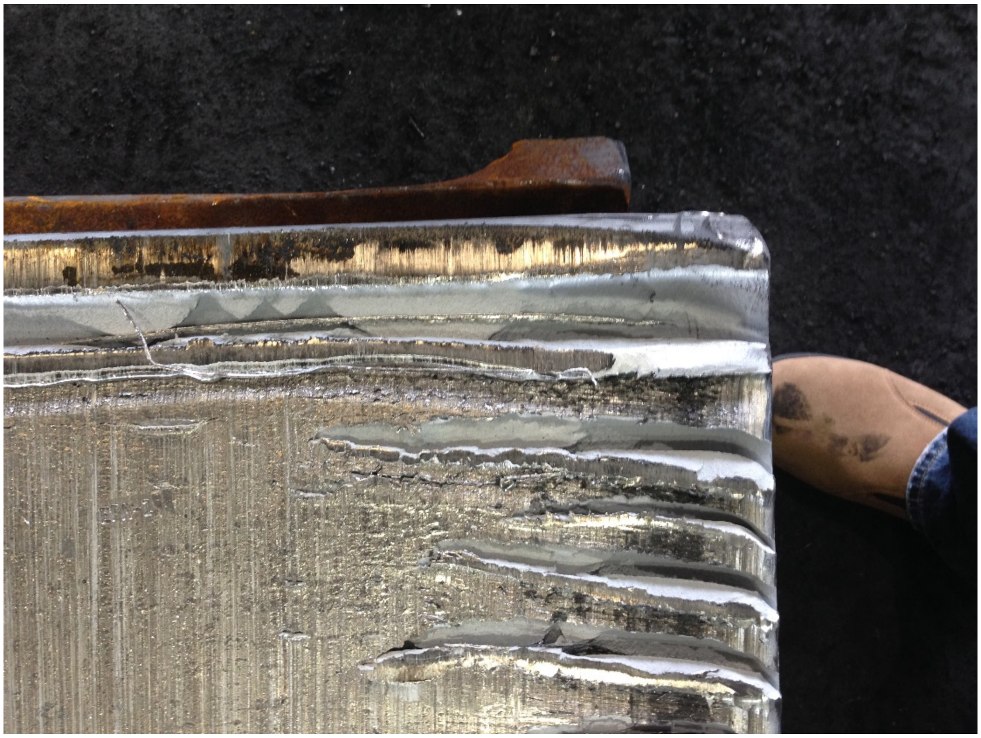

Fig. B-22 The 2-pass billet from Trial no. 1. Detail displaying the periodic lateral edge cracking and petaling; right-front edge corner of the billet.

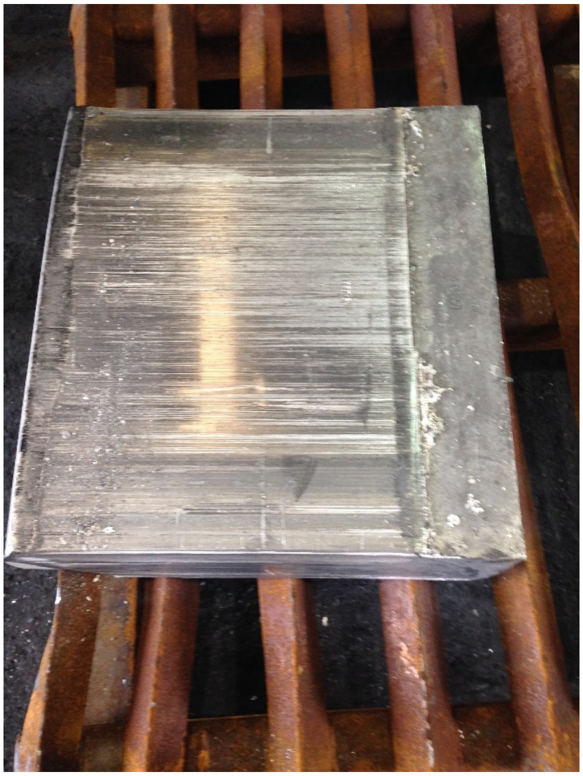

Fig. B-23 Side view of a single-pass billet from Trial no. 1

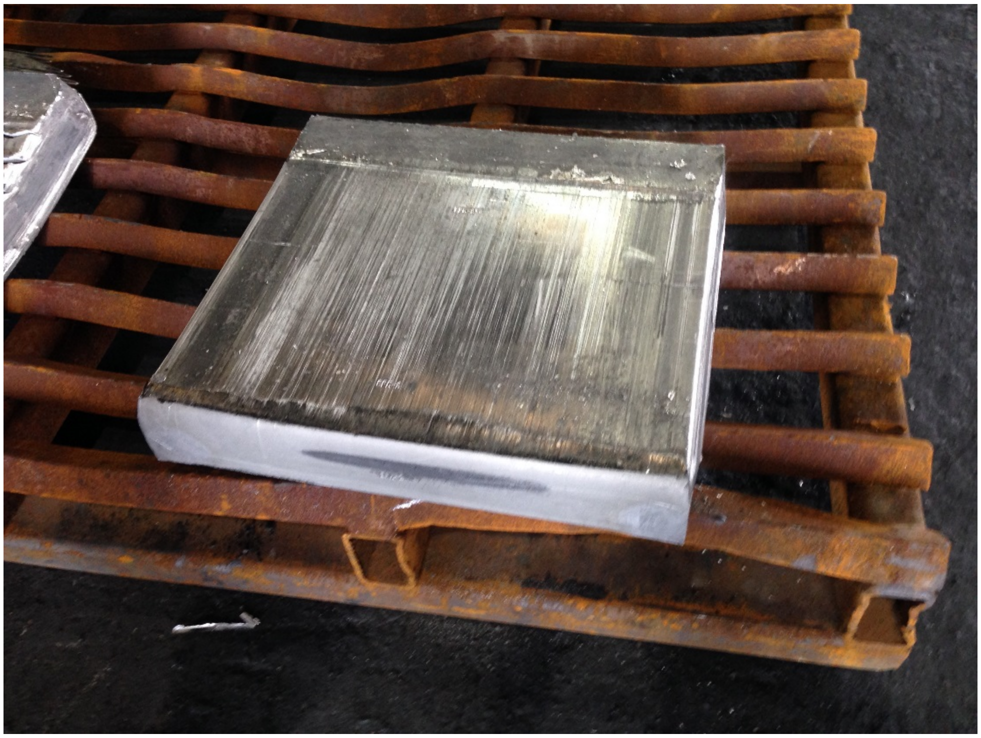

Fig. B-24 Front view of a single-pass billet from Trial no. 1

Fig. B-25 View of the GLAMA manipulator lifting up and holding a billet after the completion of the first pass

Fig. B-26 View of the box furnace used for preheating, solutionizing, and reheating the AA5083 billets

Fig. B-27 Insertion of the billet into the ECAE tool for the second pass. Note, the billet was turned on the round platform, shown in Fig. B-6, then picked up, and then lowered into the tool using the GLAMA manipulator.

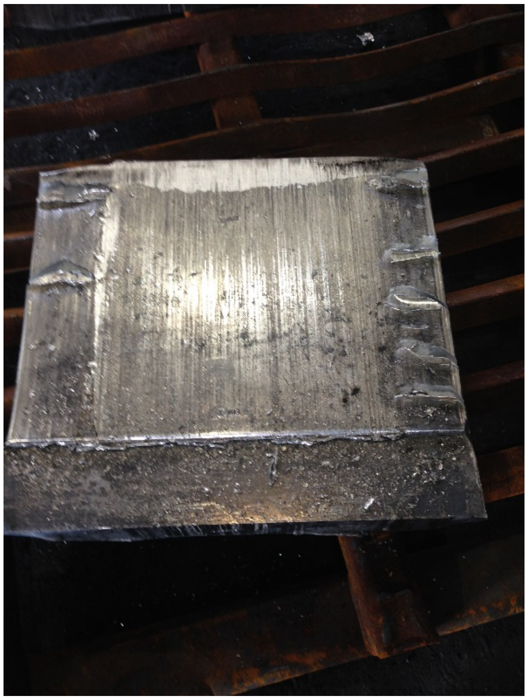

Fig. B-28 Back view of a 2-pass billet from Trial no. 2. Note, after the extrusion rate was decreased and the temperature of the billet increased, the cracking issue was somewhat reduced.

Fig. B-29 Side view of a 2-pass billet from Trial no. 2. Note the surface character of the cracks. Comparatively, these lateral cracks are fewer in number and not as deep into the billet as before.

Fig. B-30 Top view of a 2-pass billet from Trial no. 2 showing the rear end of the billet

Fig. B-31 Top view of a 2-pass billet from Trial no. 2 showing a close up view of the left-front end of the billet

Fig. B-32 View of the tracked GLAMA manipulator with its mandible grip turned sideways

Fig. B-33   Close-up view of the manipulator mandible grip showing the potential difficulties in picking up and handling a rectangular billet with smooth surfaces

Fig. B-34 GLAMA manipulator grip mandible holding the hot billet in the vertical position and moving it over the ECAE tool for insertion

Fig. B 35 Side view of the second 2-pass billet from Trial no. 2. This billet exhibited considerably deeper and higher number of lateral cracks. The formation of the lateral crack was attributed to the reduced tool temperature.

Fig. B-36 Close-up view of the left side of the rear and front ends, respectively, of the second 2-pass billet from Trial no. 2

Fig. B-37 Close-up view of the right side of the rear and front ends, respectively, of the second 2-pass billet from Trial no. 2

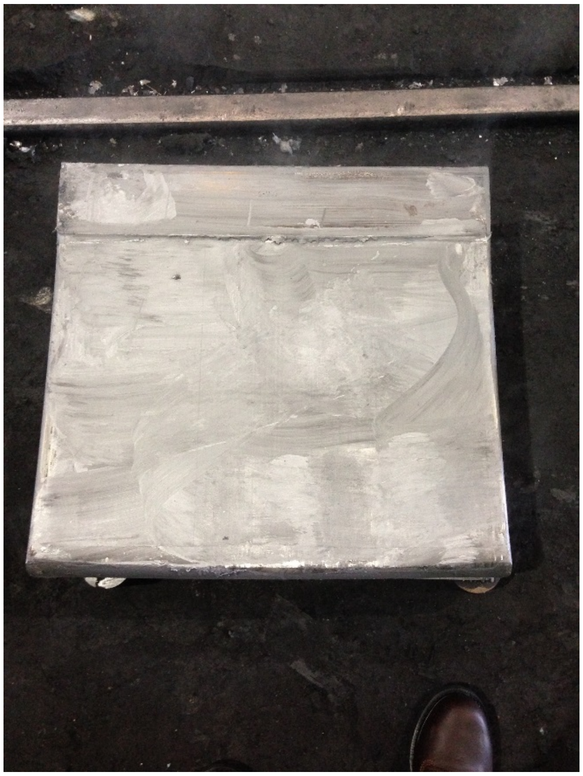

Fig. B-38 Front end view of a single-pass billet from Trial no. 2

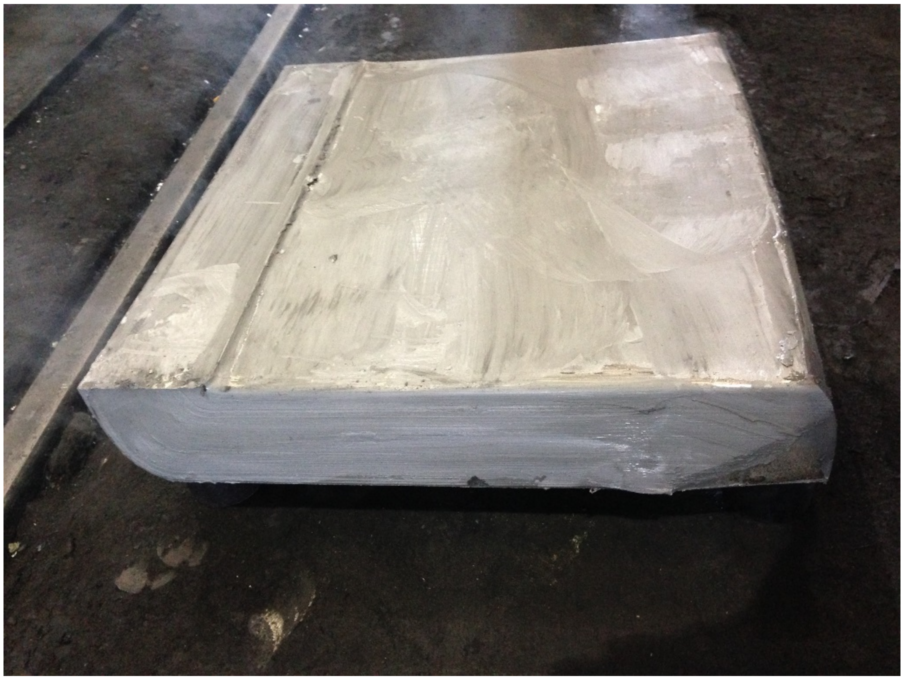

Fig. B-39   Side view of a single-pass billet from Trial no. 2

Fig. B-40   Interior arrangement of the components in the base assembly of the ECAE tool with the ring assembly removed

Fig. B-41 Top of the ring assembly showing slight damage to the input channel

Fig. B-42 Perspective view of the ring assembly removed from its base

List of Symbols, Abbreviations, and Acronyms

AA	aluminum alloy
CNC	computer numerical control
ECAE	equal channel angular extrusion
EPM	Engineered Performance Materials, Inc.
ETF	Ellwood Texas Forge, Inc.
SPD	severe plastic deformation
SBIR	Small Business Innovation Research

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