| Lawrence Berkeley National Laboratory | Cat Code SU3322 | TECHNICAL NOTE | LBNL Technical Note # SU-1011-4084 | Rev A | Page 1 of 12 |
|---|---|---|---|---|---|
| Author(s) Heng Pan | | | Released By DWCHENG | Released Date Oct 4 2019 2:44:17 PM PDT | |

Title
LARP QXF
LQXF - MAGNET
**Impact of Class A Inspection on the FAD Calculations of MQXFA-03 and MQXFA-04 Shells**

## I. Introduction

The fracture analyses of MQXFA shells revealed that the critical flaw size for the cutouts is 2 mm [1], which requires a Class AA ultrasonic inspection to detect. In the case of three long (center) shells for each MQXFA-03 and MQXFA-04 structures, the material certs provided by the vendor revealed that they were only inspected to a Class A inspection criteria. Therefore the Fracture Assessment Diagram (FAD) for these shells needs to be updated with this larger critical flaw detectable by a Class A inspection, which is 3 mm.

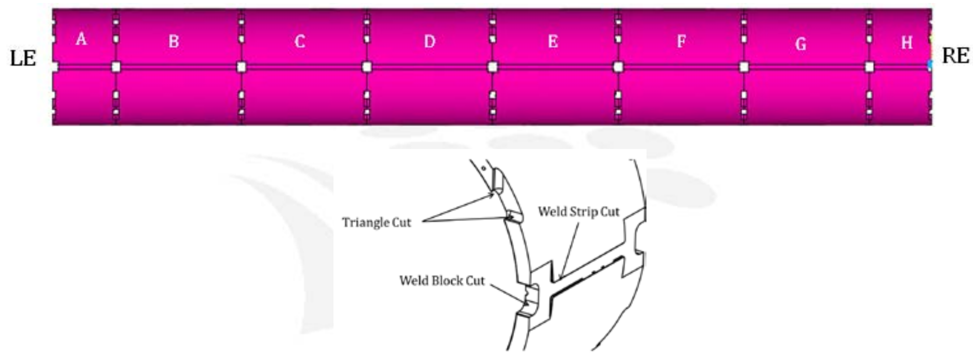


Figure 1 Shells for MQXF magnets and the cutouts on the short shells

The shells for MQXF magnets are shown in Fig. 1. All the raw forged materials of MQXF shells require ultrasonic inspections to detect flaws prior to further machining. Detection limits for ultrasonic methods in wrought aluminum (and most other standards) are described in ASTM B594 [2], and the limits for linear discontinuity is shown in Fig. 2.

| Class | Single Discontinuity Response in. (mm)$^{A,B}$ | Multiple Discontinuities in. (mm)$^{C,B}$ | Linear Discontinuity Length–Response in. (mm)$^{D}$ | Loss of Back Reflection (%)$^{E}$ | Noise in. (mm)$^{F}$ |
|---|---|---|---|---|---|
| AAA | 1/64 (0.40) or 25 % of 3/64 (1.19) response | 10 % of 3/64 (1.19) response | 0.12 (3.0)–10 % of 3/64 (1.19) response | 50 | 10 % of 3/64 (1.19) response |
| AA | 3/64 (1.19) | 2/64 (0.79) | 0.5 (12.7)–2/64 (0.79) response | 50 | alarm level |
| A | 5/64 (1.98) | 3/64 (1.19) | 1.0 (25.4)–3/64 (1.19) response | 50 | alarm level |
| B | 8/64 (3.18) | 5/64 (1.98) | 1.0 (25.4)–5/64 (1.98) | 50 | alarm level |
| C | 8/64 (3.18) | Not applicable | Not applicable | 50 | alarm level |

Figure 2 Inspection limits specified in ASTM B594-13

However, the standard does not specify the minimal detection limit or resolution explicitly; it is assumed that the calibrated flaw size represents the 95% Confidence Limit of detection.

The analyses according the specification of "MQXFA Structural Design Criteria" [3] assumes that a crack is semi-elliptical, as shown in Fig. 3, and it may grow from a characteristic size, to ratios of either $a/c = 1$ or $a/c = 0.8$ upon initial loading, but may still remain sub-critical afterward.

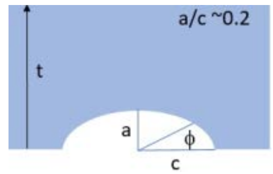


Figure 3 Part-Through crack geometries with definitions of a, c, and φ

Based on the typical loading conditions that are experienced in MQXF magnets, the critical flaw size of the cutouts of the aluminum shells is determined as 2 mm, where $K_I$ approaches a “critical” characteristic assessment value e.g. $K_{Ic}$. This critical flaw size is used to both determine inspection limits and rejection criteria for components.

In order to make use of the calibrated flaw sizes listed in the standard (Fig. 2) with the assumed geometry in the analyses, one should tie the two by the area of an elliptic flaw. The area of an elliptic flaw is $A = \pi ac$; and the area is $A = \pi(D/2)^2$ for a circular flaw, where $D$ is defined as the detection limit for the various inspection grades.

Therefore, for a flaw with $a/c$ = 0.2, i.e. $c = 5a$ the area is:

$$A = \pi \text{ac} = \pi\left(\frac{D}{2}\right)^2$$

$$a = \frac{D}{2\sqrt{5}}, 2c = D\sqrt{5}$$

A detected flaw with this geometry will start with a characteristic length of $a$, with $2c = 10a$ as showed in Fig. 3. So, the inspection limit for a given grade of inspection should yield a flaw with a width of 2.24 $D$, as shown in Table 1:

Table 1 Flaw sizes correlated to Inspection Grades for Aluminum Forgings

| Inspection Class | Calibration Block | Allowable Critical Flaw Size |
|---|---|---|
| AAA | 0.40 mm | > 0.90 mm |
| AA | 0.79 mm | > 1.77 mm |
| A | 1.19 mm | > 2.67 mm |
| B | 1.98 mm | > 4.44 mm |

According to Table 1, if a critical flaw is 3 mm, a Class "A" inspection is sufficient to detect a critical flaw, whereas critical flaw of 2 mm requires a Class of "AA" inspection for proper detection.

## II. FAD Calculations with Class A Inspection

Since the Class A inspection can only detect a ~3 mm size flaw, the FAD for these shells must be updated with the increased flaw size. Fig. 4 indicates the FAD of different cutouts after cooldown. With larger critical flaw size, the load factor increases for the triangle cutout and weld block cutout; however, the load factor decreases for the weld strip cutout, which reduces the safety margin. A flaw with a load factor of 1.2 is considered acceptable. The load factors of the different cutouts are listed in Table 2, which are applicable to the two shorter end shells.

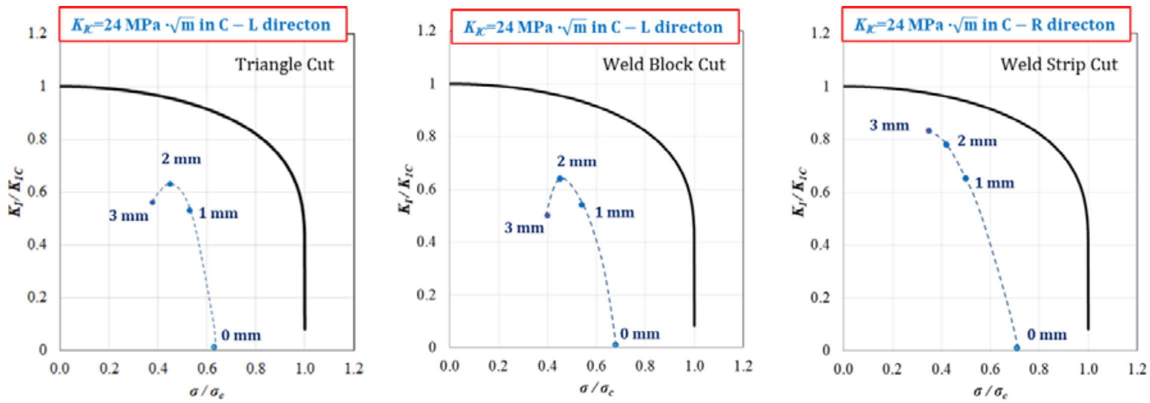


Figure 4 FAD calculations of the three cutouts on the end shell after cooldown

For the six "long" center shells, the trends of load factor vs. crack size are similar, but the margin still seems to be safe because the end effects are smaller on the center shells.

Table 2 Load factors of different cases

| | End of the End shell | | | End of the Center shell |
|---|---|---|---|---|
| | Triangle Cut | Weld block | Weld strip | Weld strip |
| 2 mm | 1.4 | 1.4 | 1.24 | 1.34 |
| 3 mm | 1.5 | 1.7 | 1.16 | 1.26 |

The load factors vs. crack sizes for Class A inspection grade are shown in Fig. 5.

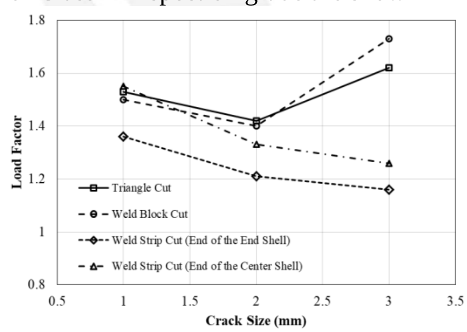


Figure 5 Load factors vs. crack sizes (the least load factor of 1.2 is specified in [3])

## III. FAD Calculations with Class A Inspection for a Buried Flaw

In addition to the UT inspections on the raw forgings, a dye penetrant test is also performed on the shells after machining is complete. The dye penetrant tests performed on these long shells came back negative, meaning no surface flaws were detected (See Appendices). The dye penetration inspection can capture surface flaws as analyzed above; but cannot detect buried flaws. Ultrasonic inspection has no limits on this aspect. Therefore, a similar analysis has been performed for a buried flaw if dye penetration is used for the inspection, shown below.

A buried flaw typically has smaller *a/c* value because it tries to grow to be round. A reasonable value of *a/c* for an elliptical buried flaw could be 0.2 based on the range given in [4].

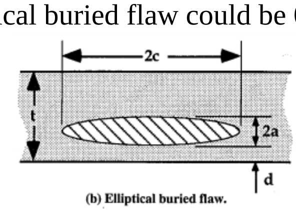

Figure 6 Elliptical buried flaw

In the analysis, the formula for a buried flaw is same as that for a surface flaw, but the influence coefficients $G_j$ of flaw geometry [3] will be changed accordingly.

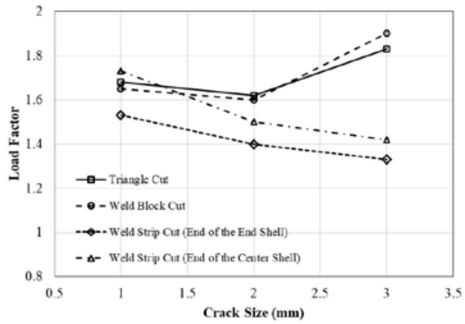


Figure 7 Load factors vs. crack sizes (buried flaw, the least load factor of 1.2 is specified in [3])

The calculated load factor vs. crack size of a buried flaw is shown in Fig. 7. The load factor of a buried flaw is ~20 % higher (safer) compared to the load factor of same size surface flaw.

## IV. Conclusion

In summary, the above analyses show that the detectable flaw size of the Class A UT inspection limits does not impact the safety margin significantly in the FAD for long MQXFA shells under the same loading conditions. Note this result, however, does not apply to the shorter end shells, but these were, in fact, inspected to Class AA UT. Additionally, dye penetrant tests performed on all shells passed; therefore, a worst-case scenario that a buried flaw of Class A size may exist. Fortunately, however, such a condition does not detrimentally affect the FAD of either the long or short shells. These results indicate that the long (center) shells of MQXFA-03 and MQXFA-04 inspected to Class A standard still meet the structure design criteria guidelines.

## V. Appendices

STEEL INDUSTRIES INC.
an AFGlobal Company

**Quality Certification**

Heat Code: 376102

Steel Industries Inc.
An AFGlobal Company
12600 Beech Daly Rd. Redford, MI 48239-2455
Phone: (313) 535-8505 Fax: (313) 534-2165

METALEX MANUFACTUR ME5500
5750 CORNELL RD
CINCINNATI, OH 45242-2010

PO: 27344-BL-2623 Item# | Sales Order: 159609 | Line: 1
Item Code: 2/3 | Qty Shipped: 6
Item Desc: Rings
Supplier Heat: 376102

Spec: AMS 4126C, Grade 7075, Condition T6 ✓

| Element | (%wt) | Ladle | Product | EPCRA | CAS# |
|---|---|---|---|---|---|
| Mn | Manganese | 0.01 | | ✓ | 7439-96-5 |
| Si | Silicon | 0.06 | | | |
| Cu | Copper | 1.6 | | ✓ | 7440-50-8 |
| Cr | Chromium | 0.20 | | ✓ | 7440-47-3 |
| Ti | Titanium | 0.03 | | ✓ | 7440-02-0 |
| Al | Aluminum | | | | |
| Fe | Iron | 0.015 | | | |
| Zn | Zinc | 5.8 | | | |
| Mg | Magnesium | 2.5 | | | |

**Mechanical Testing**

| | |
|---|---|
| Tensile - Longitudinal (KSI) | 79.0 ✓ |
| Yield Strength - Longitudinal (KSI) | 67.0 ✓ |
| Elongation% - Longitudinal | 11 ✓ |
| ROA% - Longitudinal | 21 |
| Tensile - Long trans (KSI) | 73.5 ✓ |
| Yield Strength -Long trans (KSI) | 61.5 ✓ |
| Elongation% - Long trans | 9.7 ✓ |
| ROA% - Long trans (KSI) | 18 |
| Tensile - Short trans (KSI) | 75.0 ✓ |
| Yield Strength - Short trans (KSI) | 62.5 ✓ |
| Elongation% - Short trans | 7.6 ✓ |
| ROA% - Short trans | 14 |

**Other**

Stock used 15" Ingot

Job # 2623
PART# SU-1010-1073
P.O# 27344-BL
S/N: 001, 002, 003, 004, 005, 006
6 PCS TOTAL

LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3

METALEX Q.A. DEPT ACCEPTED
DATE 11/26/18
BY KKS

The recording of false, fictitious, or fraudulent statement or entries on this document may be punishable as a felony under federal statute.

EPCRA Supplier Notification: This product may contain one or more toxic chemicals subject to the reporting requirements of Section 313 of the Emergency Planning and Community Right-to-Know Act (Title III of the Superfund Amendments and Reauthorization Act of 1986) and 40 C.F.R. Part 372. Potentially reportable chemicals are indicated with a checkmark in the "EPCRA" column and a Chemical Abstract Services (CAS) registry number is provided for each such chemical in addition to the percent by weight of the chemical present in this product. It is your responsibility alone to determine whether your facility is required to submit a Toxic Release Inventory Report under EPCRA Section 313.

Certification No.: 1344682
Certification Date: 9/28/2018
Issued By: Nick Kraft
This report is issued in compliance with the requirements of EN10204 3.1

Page 1 of 2

# Quality Certification

**Heat Code:** 376102

Steel Industries Inc.
An AFGlobal Company
12600 Beech Daly Rd. Redford, MI 48239-2455
Phone: (313) 535-8505 Fax: (313) 534-2165

| | | | |
|---|---|---|---|
| METALEX MANUFACTUR ME5500 | PO: 27344-BL-2623 | Sales Order: 159609 | Line: 1 |
| 5750 CORNELL RD | Item Code: | | Qty Shipped: 6 |
| CINCINNATI, OH 45242-2010 | Item Desc: Rings | | |
| | | Supplier Heat: 376102 | |
| Spec: AMS 4126C, Grade 7075, Condition T6 | | | |

Job 2623

24.17 x 21.89 ID x 25.64 (finish sizes)
P.O. Item 2 (5 pcs)
24.60 x 21.39 ID x 26.14 (approx. supplied sizes)
P.O. Item 3 (1 pc)
24.60 x 21.39 ID x 28.14 (approx. supplied sizes)
Forged
Heat treated in accordance with AMS 2772G to the T6 temper
Solution treated 890F, 4:06 hours, cold water quenched
Aged 250F, 24:08 hours, air cooled
Hardness achieved (10mm/500kg): 158/158/158/158/158/158 HBW
Rough machined
Ultrasonic inspected per ASTM B594-13, Class A: No indications detected ✓

Other Elements, each: 0.05
Other Elements, total: 0.15

P.O. Lines 2 & 3

No welding was performed on this material.
Material is free from mercury contamination.

We hereby certify that the above item(s) has been inspected and tested in accordance with the listed specifications and is in conformance with all requirements as modified by the Purchase Order and/or Steel Industries, Inc. Quote.

Steel Industries, Inc. operates a quality management system in accordance with Quality Manual, Issue 2, Revision 2 dated June 14, 2018, which conforms to the following quality programs and directives for the manufacture of open die forgings and seamless rolled rings:
1) ISO 9001:2015 and AS9100D - certified by Performance Review Institute (PRI)
2) NADCAP (National Aerospace Accreditation Program) for heat treating - certified by Performance Review Institute (PRI)
3) PED (Pressure Equipment Directive) 2014/68/EU Annex 1 Para 4.3 - certified by Bureau Veritas
4) CFR Part 21 - Unauthorized Shipment of Defective Material applies

LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3

METALEX
Q.A. DEPT
ACCEPTED
DATE 11/26/18
BY KKS

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EPCRA Supplier Notification: This product may contain one or more toxic chemicals subject to the reporting requirements of Section 313 of the Emergency Planning and Community Right-to-Know Act (Title III of the Superfund Amendments and Reauthorization Act of 1986) and 40 C.F.R. Part 372. Potentially reportable chemicals are indicated with a checkmark in the "EPCRA" column and a Chemical Abstract Services (CAS) registry number is provided for each such chemical in addition to the percent by weight of the chemical present in this product. It is your responsibility alone to determine whether your facility is required to submit a Toxic Release Inventory Report under EPCRA Section 313.

Certification No.: 1344682
Certification Date: 9/28/2018
Issued By: Nick Kraft

Nicholas Kraft - Q.C. Certification Specialist

This report is issued in compliance with the requirements of EN10204 3.1

Page 2 of 2

# Certified Inspection Report

ARCONIC

ARCONIC FORGING AND EXTRUSIONS
Pimalco Inc
6833 West Willis Road
Chandler, AZ
85226

Pimalco, Inc., a subsidiary of Arconic Inc.

**Invoice To Customer**
STEEL INDUSTRIES INC DIP
12607 BEECH DALY RD
ATTN: ACCOUNTS PAYABLE
REDFORD, MI - 48239

**Ship To Customer**
STEEL INDUSTRIES INC DIP
12600 Norborne
Redford, MI - 48239-2553

| Sales Order Number | Line No. | Customer P/O | Cert Number | Page |
|---|---|---|---|---|
| | | | AEP1761634 | 1/2 |
| | | | | Cert Print Date |
| 1001016192 | 1.1 | 27329-001 | 06-JUL-18 | 06-JUL-18 |

| Quantity Shipped | Date Shipped | Item Description |
|---|---|---|
| 4572 LB | 06-JUL-18 | SCALPED ALUMINUM INGOT<br>19.5 IN DIA<br>7175 W/F 361.962<br>AMS-A-22771 REV C<br>AMS-QQ-A-367 REV E<br>AMS4149 REV E<br>AMS4179 REV D<br>BMS7-186 REV M<br>BMS7-214 REV U<br>AMS4148 REV E<br>ASTMB247 REV 15<br>AMS4126 REV C<br>AMS4131 REV D<br>AMS4147 REV D<br>AMS4310 REV E<br>AMS4311 REV E<br>AMS4323 REV C<br>F7.4.1.1 REV 4 |
| B/L: 2377944 | Item No.: G03343621 | |
| Delivery ID: 11793318 | Item No. Rev | |
| Customer Part No | | |

**Notes**

Cast # Log Length Weight 376100 5 162.250 4920 376100 1 162.250 4922 376101 5 157.000 4524 376101 3 152.375 4616 376100 4 161.625 4900 376100 2 151.000 4574 376101 2 159.750 4614 376099 5 151.125 4576 376102 3 150.875 4566 376102 5 150.875 4572
CERT NOTE: MEETS THE CHEMISTRY REQUIREMENTS OF BOTH 7175 AND 7075 ALLOYS.
Current version of AFE Quality Manual is June 15, 2012. This material was not welded while being processed. The material is free of radioactive contamination. Homogenization Practice: 860-890 for 20 hrs. Melt and cast using Induction and Aloca R825 process.
CLARIFICATION: Specifications apply for chemical composition only.
CLARIFICATION: When forged, extruded or rolled mill products, produced from Arconic ingot by Arconic customers, are ultrasonically inspected before being placed into service and indications are found which exceed the applicable USI limits, Arconic will provide replacement ingot. Arconic will accept no incidental or consequential damage claims arising from the fabrication or use of products from such ingots, the customer's exclusive remedy being the above stated replacement ingot. Unless the product fabricated from Arconic ingot is ultrasonically inspected prior to being placed into service, Arconic does not make the warranty stated herein.
COMPOSITION NOTE: The values for 'Others Each' and 'Others Total' have met the limits as shown on this certified inspection report. Remainder is Aluminum.
CAST/JOB NUMBER : 376099/25562107 376100/25562107 376101/25562107 376102/25562107

SIT Appvd SP 7-11-18

METALEX
Q.A. DEPT
ACCEPTED
DATE 11/26/18
BY KKS

LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3

**Legal Statement**

We hereby certify that, unless otherwise indicated, the material covered by this report has been manufactured, inspected, and tested in accordance with, and has been found to meet, the applicable requirements described herein, including any specifications forming a part of the description and that samples representative of the material met the composition. Also, note that mercury is not a normal contaminant in aluminum alloys and neither it nor any of its compounds are used in the manufacture of our product. This certification is not to be reproduced in partial form without prior written approval of our Quality Assurance Dept.

**Signature And Title**

Conesia P. Watson (signature)
Conesia Watson 06-JUL-18
Quality Assurance Manager

**Quantities per Lot / Packages**

| Package Number | Lot Number | Quantity | UOM | Weight Gross | Weight Net |
|---|---|---|---|---|---|
| G16-PKG669377 | 25562107 | 1 | PCS | 4602 | 4572 |

# Certified Inspection Report

ARCONIC

ARCONIC FORGING AND EXTRUSIONS
Pimalco Inc
6833 West Willis Road
Chandler, AZ
85226

| Sales Order Number | Line No. | Customer P/O | Cert Number AEP1761634 | Page 2/2 Cert Print Date |
|---|---|---|---|---|
| 1001016192 | 1.1 | 27329-001 | 06-JUL-18 | 06-JUL-18 |

**Composition Limits**

| Alloy | Wt % | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|---|
| 7175 | Min | --- | --- | 1.2 | --- | 2.1 | 0.18 | 5.1 | --- |
| | Max | 0.15 | 0.20 | 2.0 | 0.10 | 2.9 | 0.28 | 6.1 | 0.10 |

| Alloy | Wt % | Others Each | Others Total |
|---|---|---|---|
| 7175 | Min | --- | --- |
| | Max | 0.05 | 0.15 |

**Composition Results**

| Heat / Cast / Lot Number | Si ✓ | Fe ✓ | Cu ✓ | Mn ✓ | Mg ✓ | Cr ✓ | Zn ✓ | Ti ✓ |
|---|---|---|---|---|---|---|---|---|
| 376099 | 0.07 | 0.16 | 1.6 | 0.02 | 2.5 | 0.21 | 5.8 | 0.02 |
| 376100 | 0.06 | 0.15 | 1.6 | 0.01 | 2.6 | 0.21 | 5.8 | 0.02 |
| 376101 | 0.06 | 0.15 | 1.6 | 0.01 | 2.5 | 0.20 | 5.7 | 0.03 |
| 376102 | 0.06 | 0.15 | 1.6 | 0.01 | 2.5 | 0.20 | 5.8 | 0.03 |

**Composition Results**

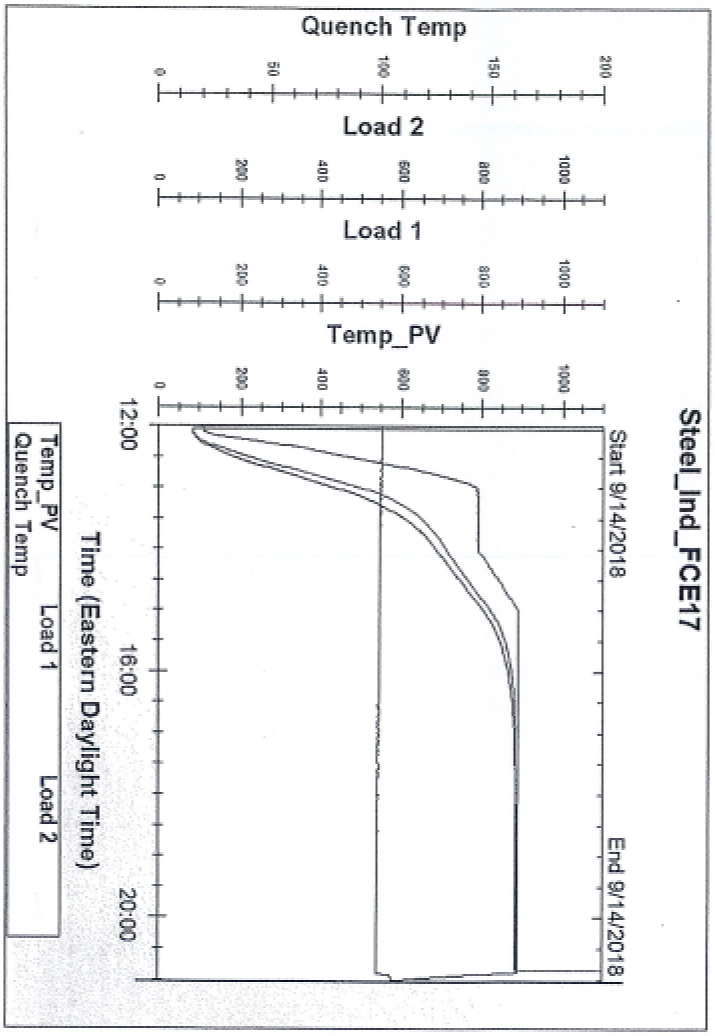
| Heat / Cast / Lot Number | Others Each | Others Total |
|---|---|---|
| 376099 | -- | -- |
| 376100 | -- | -- |
| 376101 | -- | -- |
| 376102 | -- | -- |

**Cert Notes**

Arconic - Pimalco Inc. manufactured the item described above in a plant whose quality management system is certified/registered as being in conformity with ISO9001:2008 & AS9100 Rev C by BSI Management Systems under Certificate # FM78752.
Made in USA
The test report shall not be reproduced except in full, without the written approval of the Quality Department. No alteration, addition or other change is authorized to be made to this certificate.
The recording of false, fictitious, or otherwise fraudulent statements or entries on this certificate by any recipient may be punished as a felony under applicable law.

METALEX
Q.A. DEPT
ACCEPTED
DATE 11/26/18
BY KKS

LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3



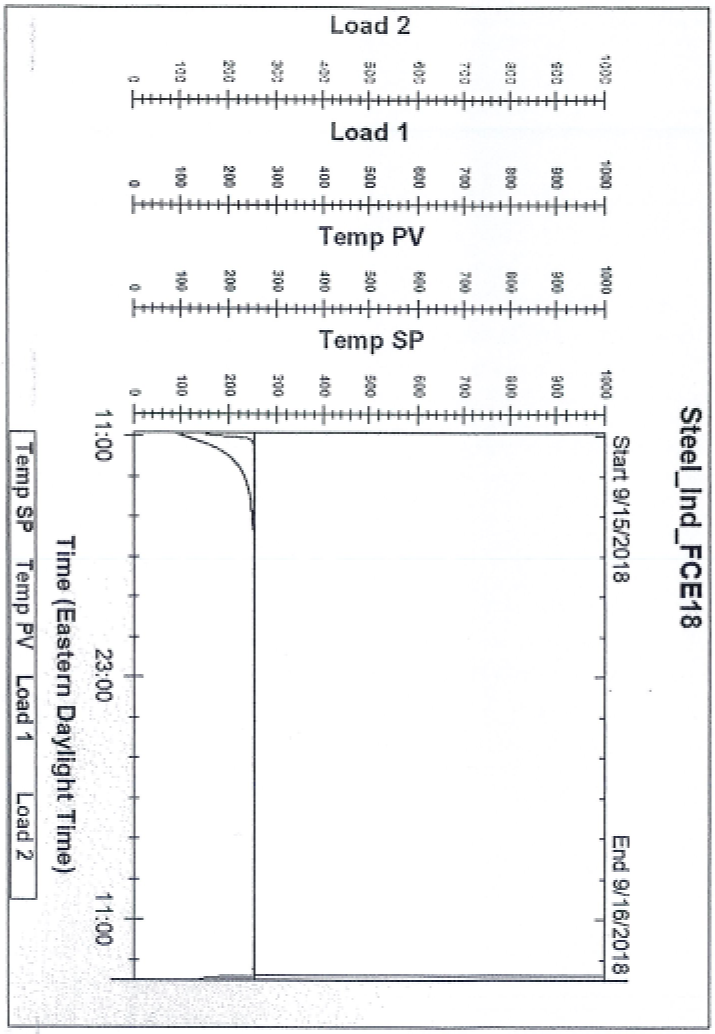

LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3

METALEX
Q.A. DEPT
ACCEPTED
DATE 11/26/18
BY KKS

STEEL INDUSTRIES INC.
SERVING AMERICAN INDUSTRY SINCE 19..

SO# 159609
GRADE 7075-T6
HEAT# 376102
CUSTOMER: METALEX
PO# 27344-BL-2623
P/N
THERMAL TREATMENT:
SOLUTION ANNEAL 890 F
4 Hrs 6 min
WATER QUENCH

Leo Beverley




LBL Job#18-2623
P/N SU-1010-1073
S/N 001 thru 006
PO#27344 Item#2/3

METALEX
Q.A. DEPT
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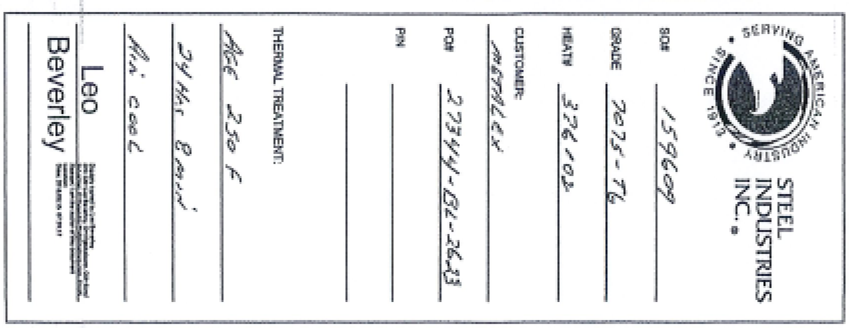

CERTIFICATE OF INSPECTION

QC Laboratories, Inc

CINCINNATI OFFICE
613 Redna Terrace, Cincinnati, Ohio. 45215-1108
Ph (513) 771-7820 Fax: (513) 771-6934
*Email qclaboratories@fuse.net*

| | |
|---|---|
| X | PENETRANT |
| | WELDING |
| | X-RAY |
| | ALKALINE TITANIUM CLEAN |
| | SWAB ACID ETCH |
| X | ACETONE CLEAN |

| | |
|---|---|
| DATE | 5/20/2019 |
| CUSTOMER | METALEX MFG. INC.<br>5750 CORNELL ROAD<br>CINCINNATI, OH 45242 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PARTS LISTED BELOW APPLY ON YOUR P.O. | 31076-CMJ-2623 | QCL INV. No. | C56258 | IDENTIFIED BY | PC | JOB No. | 9EH983 | Rev No. | |

| QUANTITY | PART NUMBER | DESCRIPTION | QUANTITY ACCEPTED | QUANTITY REJECTED/REASON |
|---|---|---|---|---|
| 3 | SU-1010-1073 REV C | LONG MAGNET SHELL S/N: 001, 002, 003 | 3 | 0 |

| | |
|---|---|
| ***THE ABOVE LISTED PARTS HAVE BEEN INSPECTED AS PER:*** | PRE ACETONE CLEAN<br>FPI PER ASTME 1417 REV 16 T1 MA L3 ACCEPTED TO NO INDICATIONS GRATER THAN 5mm CIRCULAR ALLOWED<br>POST ACETONE CLEAN |

Q.C. Laboratories,Inc. Maximum Liability for loss(es) of any kind due to interpretation, is invoice charges

**Q.C. LABORATORIES, INC**
CERTIFICATE FAA REPAIR STATION #CD4D098M

Accredited Nadcap

QCL Inspector
Pamela Combs,
L-3

Quality System AC7004

**FORM QCLCIN- 200 REV 1 7/2018**

[1] H. Pan, et al. "Failure Assessments for MQXF Magnet Support Structure with a Graded Approach", IEEE Transactions on Applied Superconductivity. Vol 29, Issue 5, 2019.
[2] ASTM B594, "Standard Practice for Ultrasonic Inspection of Aluminum-Alloy Wrought Products", 2013

[3] E. Anderssen, S. Prestemon. “US HL-LHC Accelerator Upgrade Project Structural Design Criteria”, 2018
[4] T. Anderson, “Fracture Mechanics”, Second Edition, 1994.