RECOMMENDATIONS FOR AVOIDANCE OF SUSTAINED LOAD CRACKING OF ALUMINIUM ALLOY CYINDERS

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Prepared by WG-2 Gas cylinders and pressure vessels

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Amendments from 57/11

Section	Change
	Editorial to align style with EIGA Style Manual
1	Section updated
3.1	Addition of Publication terminology
9	Addition of new Section 9 References

Note: Technical changes from the previous edition are underlined

1 Introduction

This publication was prepared at the end of the 1990s and revised in 2004 and then, in 2011. During the 2011 revision, the following information was added:

- Aluminium alloys, (AA) 6351 and 6082 are no longer used for the manufacture of aluminium alloy cylinders;
- AA5283 cylinders, initially proposed as an alternative (see 5.2) for the above cylinders are no longer manufactured; and
- Recommendations made for the use of the existing AA6351 and AA6082 cylinders are still valid.

This edition includes updated standards references.

2 Scope and purpose

This publication gives recommendations for the purchase of new aluminium alloy cylinders and the manner of treating those already in service.

The principal aim of this publication is to avoid and/or detect sustained load cracking (SLC) of cylinders manufactured from aluminium alloys 6351 and 6082, see Appendix 1, though relevant features may be used for other aluminium alloys as appropriate. Previously documented stress-corrosion cracking aspects associated with other aluminium alloy cylinder materials are not the subject of this publication, nor are the ageing aspects of a number of heat treatable aluminium alloy cylinders. To date, the vast majority of the cracking phenomenon has been observed in the neck/shoulder areas of the cylinders though some cracks in the cylindrical part have also been recently reported.

3 Definitions

3.1 Publication terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

4 Background

Gas cylinders manufactured from aluminium alloys are widely used for the transportation of a variety of gases in a number of applications. This EIGA publication deals with ways of tackling a metallurgical mechanism found in a number of aluminium alloy cylinders, manufactured from aluminium alloys 6351 and 6082, see Appendix 1, which is sustained load cracking.

In aluminium alloy cylinders this SLC mechanism first became apparent around 1983 when a number of hoop-wound, fibre-wrapped aluminium alloy cylinders burst in USA whilst in use. The cylinders had been manufactured from AA 6351 and were in service for about a year at a pressure of 4500 psi (approximately 310 bar). The cylinders' shells (liners) were manufactured from a billet of aluminium alloy which had been cast in a re-melt facility. Although compositionally within specification, the lead content was approximately 400 ppm, against less than 30 ppm associated with a billet originating from a smelter facility, where only virgin metal and hardeners are normally combined. Re-melt facilities incorporate scrap aluminium alloy in furnace charges and the lead is believed to have come from free machining aluminium alloy scrap. Consequently, all cylinders in USA made from high lead containing casts, were recalled and destroyed upon receipt [1][1].

The preliminary conclusions into the failure mode of these cylinders, based on the high lead content were reassessed in the light of a further rupture in February 1984, also of a hoop-wound cylinder, but containing a low lead level (30 ppm). This is to be borne in the light of the then existing specifications, which in the USA stipulated 500 ppm maximum content for lead. Subsequently the specification for lead in USA was lowered to 100 ppm. Even after this move by the USA, it should be noted that considerably lower values were specified in other countries at that time. In both of the examples the failures were as a result of cracks which had initiated in the shoulder area of the cylinder.

Cracks such as these were subsequently also found in the USA and other countries, from 1986 to the present time in aluminium alloy 6351 monolithic, seamless cylinders which were not fibre-wound. This shoulder cracking phenomenon and the formal documentation of yet another, but related, mode of cracking namely neck cracking, promoted discussions and activity in centres of metallurgical research in both the USA and UK. The differences between shoulder cracking and neck cracking are of great importance when assessing future actions.

It should be noted that there has been no recorded incident of a shoulder crack in aluminium alloy cylinders for industrial gases within Europe, however upon examination some diving cylinders have been found to contain such defects on the internal surface. These have at times been the result of abuse such as illegally filling the cylinder to the test pressure.

In 1999 the first example of an SLC mechanism was also reported in the cylindrical section of an aluminium alloy seamless cylinder. Several other similar cracks have been subsequently found, also in AA 6351 cylinders.

Up until now the vast majority of neck cracks have been detected prior to filled cylinders being despatched to the gas users and at the periodic inspection stage. There are no recorded examples within EIGA of neck cracks having given rise to an incident. It should be noted that whereas neck cracks are readily observed during visual examination, it takes considerable expertise to detect shoulder cracks and body cracks.

All forms of cracking, that is the neck, shoulder and body cracking referred to in Section 2, are as a result of the microstructure within the cylinder being exposed to high stresses for extended periods of time. The resultant cracking is intergranular in nature, occurring on grain boundaries, with no evidence of stress corrosion or fatigue. Apart from an early publication [2] little information existed prior to about 1984, after which time considerable resources have been devoted to establishing the causes of the failures.

Neck and shoulder cracks are shown in Appendix 2 and Appendix 3 and appear to be a function of whether the cylinder's neck threads are of a parallel or taper configuration respectively. Hence, the magnitude and manner of the applied stress from the associated valving arrangement are of

[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

paramount importance. Cracking associated with the cylindrical part has, to date, only been seen in taper threaded cylinders, but could equally occur in parallel threaded cylinders. Thereafter, micro structural deficiencies within the alloy have an accelerating effect on any eventual failure. Two areas to consider are lead content and manufacturing defects, see 5.1 and 5.3.

5 Metallurgical understanding

5.1 Lead content

An important factor which increases the cracking incidence and hence decreases the time to failure, is the presence of a high lead content. The earlier work by Guttman et al [2] indicated the association of the lead with intermetallic inclusions in the aluminium alloy. Any cracking at the inclusion/grain boundary interface is accelerated, permitting the associated lead globules to diffuse further along the grain boundary, thus enabling intergranular cracking to proceed. This follows on from the fact that lead diffuses at a high velocity along grain boundaries even at room temperature, on account of its low melting point, since room temperature in degrees Kelvin is almost 50% of the melting temperature for lead when one considers the absolute temperature scale.

5.2 Alloy composition

The quantity and distribution of manganese and silicon based intermetallic precipitates have also been studied and found to affect the cracking propensity (3). In theory, modified 6351 alloys with chromium additions are thought to be beneficial, though the overall effects in this category are probably of a secondary nature. Based on data from a cylinder manufacturer [3] cylinders from AA 6061, see Appendix 1, which contain a balanced magnesium/silicon ratio forming Mg_2Si, have shown to exhibit good resistance to SLC. This was proven by accelerated testing involving severe, artificially induced damage and over-pressurisation during bunker testing. Cylinders made from AA 6061 have been in used in the USA since 1986, in Europe since 1991 and in Australia since 1994, all with good service experience. However, aluminium alloys 5283 and 7060, see Appendix 1, have given extremely good results in both SLC laboratory testing and many years of industrial cylinder use.

5.3 Manufacturing defects

Manufacturing defects, when present on the internal surfaces of a cylinder, such as folds in the shoulder regions, have been shown to be harmful, particularly for parallel threaded cylinders. Hence folding of the alloy during the heading stage of fabrication is to be avoided, since such areas resulting from their high local stress concentrations are a source of crack initiation.

5.4 Grain size

At first it was believed that the potential for crack initiation and growth involving SLC was enhanced

by a coarse grain structure in the alloy. Consequently, the attainment of a fine grain structure was advocated to provide resistance to SLC. However, other factors, see Section 4, are now believed to play a more important role in influencing the SLC mechanism.

Though many of these metallurgical enhancements outlined in 5.1, 5.2 and 5.3 can be incorporated for new cylinder purchases, they cannot be applied for existing cylinders. However, other operational features see 6.3 and Section 7, which have come to light during the course of the research and development work in this field can be applied to existing aluminium alloy cylinders.

6 Recommendations for new cylinders

The metallurgical and manufacturing aspects described in Section 4 form the technical basis for future cylinder purchases. Additional features which reflect the use of cylinders and may also be the integrity of the aluminium alloy cylinder are also considered below.

6.1 Lead content

The level of lead in the alloy shall be kept to a minimum. The acceptable maximum limit of lead is 30 ppm. In commercially obtainable grades, it is possible to achieve less than 30 ppm of lead in the billet, provided the source of the alloy is a non-recycled product. It is recommended that the alloy shall be from a primary aluminium smelter. It is to be noted, that measuring lead concentrations at these levels, is an exacting procedure and needs to be performed critically by competent laboratories/organisations. There is a suspicion that bismuth can also contribute to SLC and for that reason a maximum level of 30 ppm of bismuth is also stipulated in the latest EN and ISO standards for manufacturing seamless aluminium alloy cylinders and liners used for the manufacture of composite cylinders.

6.2 Neck folds

Though not thought to be a major concern for aluminium alloy cylinders with taper threads, fabrication defects on the internal surfaces of the cylinders (folds) in the shoulder region, should not be present. The exact level of the defects is difficult to quantify and the acceptable detection levels will vary from one inspection body to another.

The usual method of detecting such defects is after a visual and tactile inspection of the area, immediately beneath the internal neck threads. Any coarse protrusions are subject to either a rejection or a suitable machining operation.

6.3 Stresses in the cylinder

6.3.1 Neck stresses

Stresses in the neck can be influenced by four main factors. These are:

- valving torques (see 6.3.1.1);
- mismatch tolerances between cylinder neck and valve stem (see 6.3.1.2);
- shrunk-on neck rings (Neck ring reinforcement) (see 6.3.1.3); and
- use of parallel threads (see 6.3.1.4).

6.3.1.1 Valving torques

The lowest possible torque for taper threads consistent with gas tightness and operational parameters must be used at all times. The exact level of the torque will be influenced by the nature and quantity of lubricant or the thread sealant used. As a guide, the torque levels for new taper threaded aluminium alloy cylinders are outlined in Table 1. For additional information, details see EN ISO 13341: *Gas cylinders. Fitting of valves to gas cylinders* [4].

Table 1 Valve torques

	Minimum (Nm)	Maximum (Nm)	
Cylinder thread size		**Without neck ring reinforcement**	**With neck ring reinforcement**
17E*	75	95	140
25E**	95	110	180
M18	85	100	
M25/M30	95	130	

*Torque values recommended for taper 17E may be used for taper diameters of 17 to 19 mm

** Torque valves recommended for taper 25E may be used for taper diameters of 24 to 28 mm

6.3.1.2 Cylinder neck/valve stem tolerances

Cylinder necks and valve stems shall be checked to ensure that both are within specification, see EN ISO 11363-1 *Gas cylinders. 17E and 25E taper threads for connection of valves to gas cylinders. Specifications* [5] and EN ISO 11363-2 *Gas cylinders. 17E and 25E taper threads for connection of valves to gas cylinders. Inspection gauges* (6)). The cylinder neck angle and valve taper shall be gauged, such that any mismatch is kept to a minimum, see EN ISO 11363-2 [6].

6.3.1.3 Shrunk-on neck rings

One possible way of reducing tensile stresses in the neck is to fit a shrunk-on neck ring, that is a neck reinforcement which will put the neck into compression. The material for the neck ring shall be chosen to ensure compatibility with the aluminium alloy cylinder material, for example to avoid galvanic corrosion. This method of reducing local tensile stresses can give rise to high stresses in other parts of the cylinder, for example cylinder shoulders, with subsequent defects difficult to detect.

If shrunk on neck rings are fitted, the fitting should be performed by the manufacturer of the cylinder or according to their approved specification.

6.3.1.4 Parallel threads

Aluminium alloy cylinders with parallel threads were first introduced to avoid damage of the taper thread through incorrect valving procedures including, for example, overtorquing, poor thread profile, and inadequate structure of the alloy.

Though suppressing neck cracks, parallel threads cannot prevent shoulder cracking because of stresses from the gas pressure acting on the folds which are present in the shoulder region.

The use of parallel threads can be recommended for liquefied gases, with a normally low working pressure. For example, carbon dioxide at between 50 to 70 bar, compared to the maximum working pressure or test pressure of the cylinder, and then only for gases which are not dangerous to the atmosphere or to the public, that is not for flammable, corrosive, toxic, pyrophoric. This is because the gas tightness of this system cannot be guaranteed under all operating conditions. Parallel threads are forbidden by regulations for toxic gases in many countries.

6.3.2 Other stresses

It is now also accepted that externally induced damage which gives rise to stress raisers, can also induce an SLC mechanism initiating starting at the root of the damaged area.

6.3.3 Other features

The out of roundness of the cylinder’s neck and the need for any thread tapping, are additional features which may need to be specified to reduce local neck stresses. Exact guidelines for these are difficult to specify in this publication and will depend on the individual company’s operational procedures.

7 Recommendations for existing cylinders

The most critical points to minimise the onset of SLC are outlined in 7.1. It is possible that certain operational/gas service conditions in some cases can also have to be included in order to form a complete set of criteria. In particular, points specific to parallel threaded cylinders are highlighted in 7.2.2.

7.1 Compositional checks

This may be performed from reviewing the cylinders’ test certificates. In particular, the lead level of the aluminium alloy has to be checked. The level of the lead indicated shall be lower than 100 ppm

(0.01%) though it is likely that the actual value is close to 30 ppm. For cylinders manufactured after 1988 the 30 ppm level will not be found to be exceeded.

Certificates issued prior to 1988 may not include an analysis value for bismuth. However, for metal supplied by a primary smelter, as opposed to a re-melt operation, it is unlikely that the bismuth level would exceed 30 ppm. Cylinders known to contain lead in excess of 100 ppm shall be scrapped.

7.2 Inspection for cracks

This shall be carried out at the time of filling and during the periodic inspection and testing of the cylinder.

7.2.1 Filling inspection

Each cylinder shall be checked for freedom of leakage as a result of cracks. One suggested way could be by filling the cylinder for the intended gas service and then performing a leakage test at the junction of the valve stem and cylinder neck.

Care shall be taken to avoid interference from the test date ring, when fitted at the cylinder's neck.

For cylinders containing toxic, corrosive, pyrophoric or flammable gases, before filling it shall be checked, for example, by reference to the cylinder's markings, that the procedures described in 7.2.2 and 7.3, particularly dealing with the presence of cracks and valve fitting, have been performed at the time of manufacture.

Whenever cylinders have to be specially prepared prior to filling, involving removal of the valve, the opportunity shall be taken to visually inspect the cylinder's top face and neck threads, for freedom of defects. Finally, to prevent SLC failures from the body, an inspection of the external surfaces shall be undertaken to reject cylinders with harmful defects, see EN 1802, ISO 10461 or ISO/DIS 18119 [7].

7.2.2 Periodic inspection

Upon removal of the valve, all loose joining medium in the neck threads shall be carefully removed without damage to neck threads to permit a thorough visual inspection of the neck. Similarly, where the cylinder's top face has been contaminated/soiled, this shall be cleaned by using a suitable abrasive medium enabling a careful inspection for cracks to be performed. Care shall be taken so as not to confuse tap marks in the neck threads, with genuine cracks.

The region beneath the neck threads and around the cylinder's shoulder shall be inspected with the use of an endoscope, a dentist's mirror arrangement or other suitable equipment. If significant folds are found, the cylinder should be scrapped. In some cases, if regulations permit, and there is a safe procedure, recommended by the manufacturer, which will not endanger the future service of the cylinder, light folding may be removed by machining by a competent person. Subsequently such cylinders should not be used for toxic gases. Additionally, a visual inspection of the entire internal neck area (threaded and unthreaded) shall not exhibit any signs of cracking.

Also, a thorough examination of the external surface shall be made in particular for defects associated with physical damage, including dents, gauges and cuts. All such cylinders shall be rejected. Final assessments shall be made using a non-destructive examination method such as ultrasonic testing.

Attention shall be paid during the hydraulic test for any signs of leakage particularly for parallel threaded cylinders, since this could be indicative of a shoulder crack.

7.3 Cylinder valve considerations

All valves shall be free of burrs and free of a sharp edge on the leading thread so that cylinder neck thread damage/stripping is avoided. Valve torques for taper threads should be in accordance with the values stated in 6.3.1.1. Values near the maxima may be appropriate in view of some damage which invariably occurs to aluminium alloy cylinder neck threads on account of the material's lower tensile properties compared to conventional valve materials. The cylinder neck/valve stem tolerances shall be in accordance with 6.3.1.2. The fitting of a shrunk-on neck ring to minimise stresses is a possibility on used cylinders, see 6.3.1.3.

7.4 Damaged neck threads

When damaged taper threads, through incorrect valving are found, checks should be carried out using non-destructive testing methods, for example, eddy current testing, to see whether neck-cracks can be found. If no cracks are found, it has to be decided whether the cylinder thread can be changed to a parallel configuration, see 6.3.1.4, or the cylinder scrapped.

8 Recommendations

This EIGA publication recommends solutions for combating sustained load cracking for aluminium alloy gas cylinders. Recommendations for both new (future) and existing cylinders are offered in the light of research and development work, which has been performed to establish an understanding of the metallurgical mechanisms relevant to SLC. Also, the experiences of EIGA member companies, which are predominantly with taper threaded cylinders, are included.

It is essential that aluminium alloy cylinder manufacturers continue their efforts to consider the various points raised in this publication. Improved post-filling and periodic inspection procedures will also increase the safety of aluminium alloy cylinders.

The optimum choice of an aluminium alloy enables a taper thread to be recommended because the consequences of shoulder cracks associated with parallel threads are thought to be more hazardous than those of neck cracks associated with taper threads.

More than twenty years have passed since this publication was first issued by EIGA and its usefulness is summarised below. During that period in Europe and elsewhere there have been many thousands of AA6351 and AA6082 cylinders rejected due to neck cracks, through SLC in various gas services. These defects in taper threaded cylinders were mainly detected during pre- filling checks and at periodic retest and inspection. However, there has been a rejection of a few cylinders through shoulder racks. No serious incidents have occurred, demonstrating that an awareness of SLC and diligence in checking, brought about by this publication and subsequent revisions have contributed to the problem being managed.

The recommendations in this EIGA publication will continue to significantly reduce and hopefully eliminate the likelihood of neck, shoulder and body cracks in aluminium alloy cylinders as referred to in this publication, from causing an incident in the gases industry.

9 References

Unless otherwise specified the latest edition shall apply.

[1] DOT Federal Register, (1987) Vol.52, No 132, July 10th pages .26027-26030 www.loc.gov

[2] Intergranular creep embrittlement by non-soluble impurity: Pb in precipitation hardened Al–Mg–Si alloys M Guttman et al, Metal Science, Vol 17 (1983) p.123-140

[3] Effects of Pb on Sustained Load Cracking of Al-Mg-Si Alloys at Ambient Temperatures N. J. H. Holroyd, J. J. Lewandowski and V. Kohler, Mat. Sci. Eng., Dec.1987 p.185-195

[4] EN ISO 13341 *Gas cylinders. Fitting of valves to gas cylinders* www.cen.eu

[5] EN ISO 11363-1 *Gas Cylinders. 17E and 25 E taper threads for connection of valves to gas cylinders. Specifications* www.cen.eu

[6] EN ISO 11363-2 *Gas Cylinders. 17E and 25 E taper threads for connection of valves to gas cylinders. Inspection gauges* www.cen.eu

[7] EN 1802 Transportable *Gas Cylinders – Periodic Inspection and Testing of seamless aluminium alloy gas cylinders* www.cen.eu

ISO 10461 *Gas cylinders – Seamless aluminium-alloy gas cylinders – Periodic inspection and testing* www.iso.org

ISO/DIS 18119 *Gas cylinders – Seamless steel and seamless aluminium-alloy gas cylinders and tubes – Periodic inspection and testing* www.iso.org

NOTE The three standards listed under [7] will be combined in EN ISO 18119 by 2019.

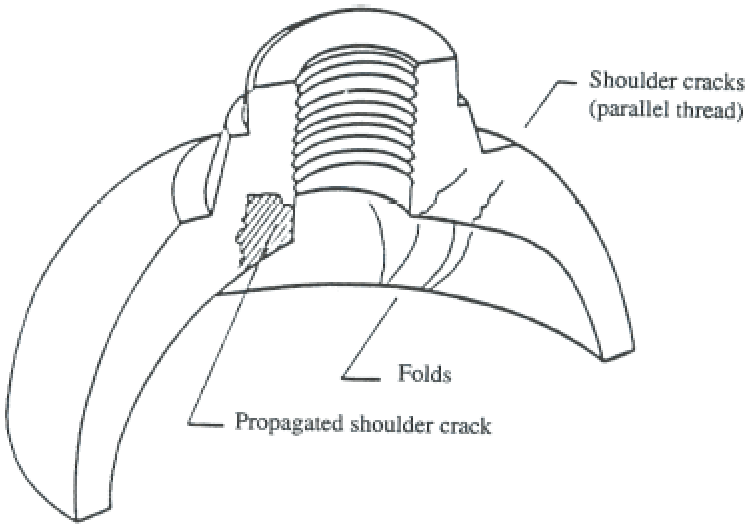
Appendix 1 - Chemical composition of various aluminium alloys

	Material Code				
Element (wt. %)	**Alloy 6082†**	**Alloy 6351†**	**Alloy 6061**	**Alloy 5283**	**Alloy 7060**
Silicon	0.7-1.3	0.7-1.3	0.4-0.8	Max 0.30	Max 0.15
Iron	Max 0.50	Max 0.50	Max 0.70	Max 0.30	Max 0.20
Copper	Max 0.10	Max 0.10	0.15-0.40	Max 0.03	1.8 – 2.6
Manganese	0.40-1.0	0.40-0.80	Max 0.15	0.5 – 1.0	Max 0.20
Magnesium	0.6—1.2	0.40-0.80	0.8-1.2	4.5 – 5.1	1.3 – 2.1
Chromium	Max 0.25		0.04-0.35	Max 0.05	0.15 – 0.25
Zinc	Max 0.20	Max 0.20	Max 0.25	Max 0.10	6.1 – 7.5
Titanium	Max 0.10	Max 0.20	Max 0.15	Max 0.03	Max 0.05
Others each*	Max 0.05	Max 0.05	Max 0.05	Max 0.05	Max 0.05
Others total	Max 0.15	Max 0.15	Max 0.15	Max 0.15	Max 0.15
Aluminium	Remainder	Remainder	Remainder	Remainder	Remainder

*In addition to this limit it is necessary to restrict lead and bismuth to 0.003% max.

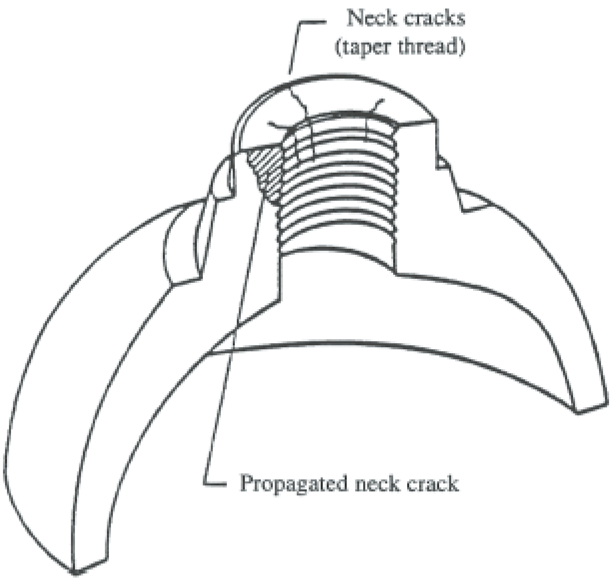
† Alloy 6351 is essentially within the limit of alloy 6082

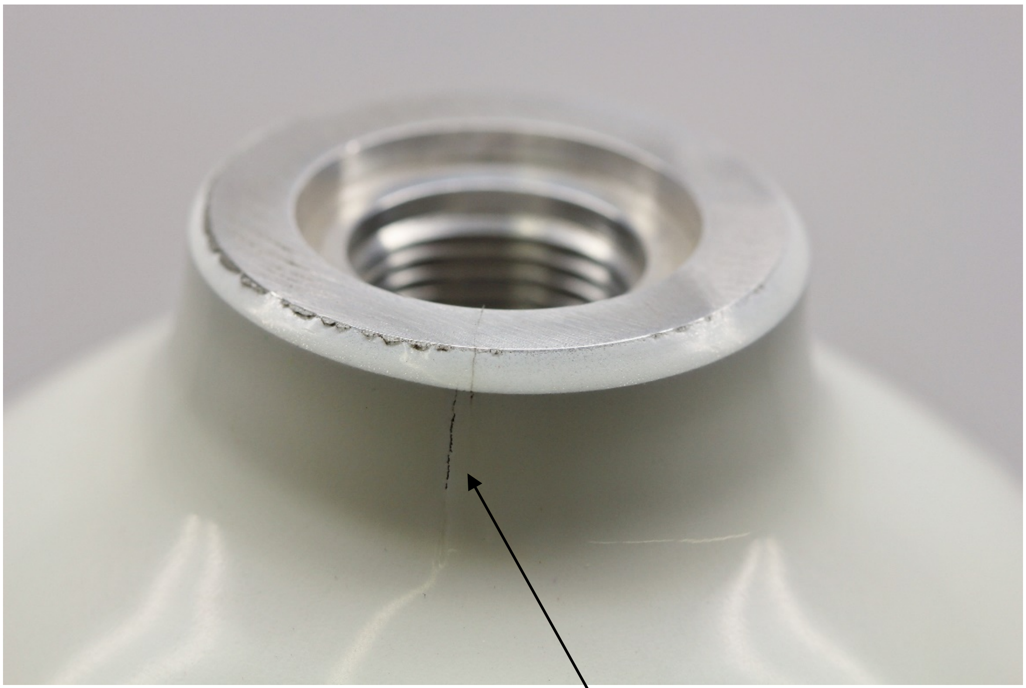
Appendix 2 – Schematic of shoulder cracks of an aluminium alloy cylinder (view from inside)



Shoulder cracks viewed from the inside

Appendix 3 Schematic and photograph of shoulder cracks of an aluminium alloy cylinder (new cracks on the top)





Propagated neck crack