Specifying the allowed remained bottom thickness after milling in CNG steel cylinders by FEM analysis and experimentation

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Abstract

In CNG steel cylinders produced by the hot spinning method from seamless tubes, homogeneity of the material in the closed-end region is a significant factor. Therefore, in the production process, the produced cups are immediately under a hot heavy press, and in addition to forming the bottom shape, the heterogeneous area is driven out, finally, this region is eliminated via machining. Ideally, the depth of this milled area should be to the extent that the heterogeneous region is completely removed, also according to the designing standards, the minimum bottom thickness shall be more than that of wall thickness. However, the problem is that controlling this parameter is impossible in the machining process, and in some cases, it may become more than the specified limit. In this research, the minimum allowed remained thickness after bottom milling has been obtained by analysis and also compared with real results acquired from static and fatigue tests. Deducing the results of the FEM analysis, it can be seen that the remained bottom thickness up to 6mm has no limitation for the endurance hydrostatic pressure, and that was supported by experimental burst tests. Considering this amount for the bottom thickness, the percentage of rejected products declined considerably from 4% to 2% in the factory.

Keywords: CNG steel cylinders, Hot spinning, Heterogeneous region machining, FE analysis

1- Introduction

Today in different industries, especially automotive production, using of CNG fuel has extensively increased as a substitute for oil fuels, because of its less damage to nature and lower prices. As storing this gas should be under high pressure, sufficient strength in the storage vessels is an important factor. One of the different types of CNG storing vessels is a full steel cylinder. These cylinders are usually thin-walled and made of seamless tubes or deep-drawn sheets [1].

Generally, in the production process of cylinders made of seamless tubes, firstly tubes are cut in the appropriate sizes, then the ends of the tubes are closed by hot spinning method, then after threading the valve mounting place and passing the

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specified tests, they are painted and carried for sale.

Some standards such as ISO9809-1 [2] and ISO 11439 [3] have set laws to design, manufacture, and test processes for different kinds of cylinders. These standards have specified the important parameters for cylinder design such as material, strength, geometrical dimension, and safety tests. Also, some researchers have presented different design methods based on static and fatigue stress analysis for cylindrical seamless vessels [4, 5]. Working on fatigue crack growth behavior in cylinders wall has also attracted the attention of some researchers to minimize the fatigue failure probability in pressure vessels [6].

Moreover, many researchers have done analytical and experimental works on the production process of cylindrical seamless vessels. Zoghi, Huang, Lexian, and many other researchers simulated the hot spinning forming by the finite element method [7-9]. They have optimized the time and energy used in forming process. Also, some other research and optimizations have been done on the effect of different strategies and tools on the quality of formed dome in the neck spinning process [10-11].

The objective of this research is to clarify the amount of one of the important parameters in the production process of cylindrical seamless vessels utilizing FEM stress analysis and the verification by experimental results. This analysis could extend the product safety borders and lead the manufacturers to ensure some of their products that have yet been unreliable, hence, they would save expenses, energy, and time.

2- Problem explanation

As shown in Figs. 1 and 2, in the bottom closing step, materials may be heterogeneous in the closed region and there may be a rather big conical crack called 'channel' which may cause leakage. To eliminate this region, the bottom side of the cylinder is put under the hot pressing immediately after spinning to form the bottom shape; in addition, this process extrudes the created channel out through the material flow. After this step the extruded area is milled and eliminated [12].

To prevent the fatigue phenomenon and crack growth through cycle loading, the amount of this machining must be as enough as the heterogeneous region is completely removed and there is no sign of cracks and cavities which are created in the previous process. It's important to mention that, in some cases, after machining, the leakage of the cylinders in the milled region is checked by doing a pneumatic test under 200 bar pressure for one minute.

According to designing standards, the minimum bottom thickness shall not be less than wall thickness [1], so in the production process, the maximum milling depth is supposed as the remained thickness exceeds the wall thickness. On the other hand, in some cases due to the deep channel, the machining depth needs to be increased more than the allowed amount.
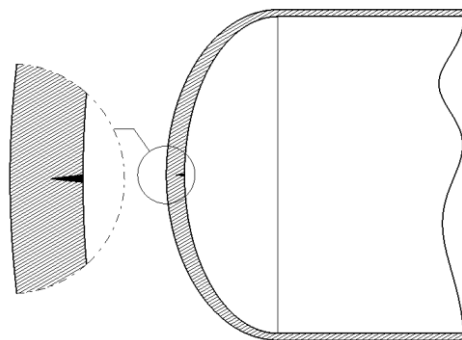

Fig. 1 The heterogeneous region which is created in the bottom of the cup in the spinning process

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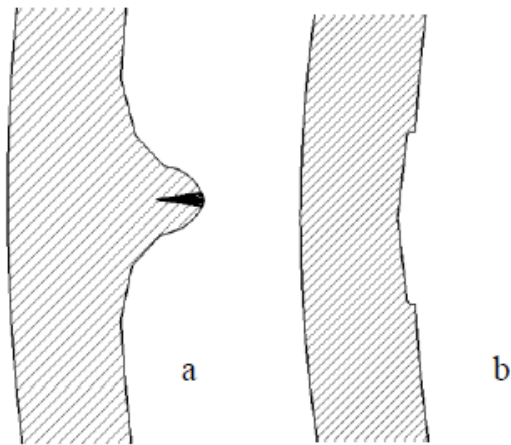
Fig. 2 The heterogeneous region in the cup center
(a) After pressing, (b) After milling

In addition, machine and operator errors are the other important factors of this problem. The amount of critical remained thickness after machining has always been significantly one of the indeterminate factors for designers and manufacturers of this product, which in this research, it is tried to obtain that. For instance, according to the statistics of the production department of Pars MCS factory, on average, 4% of products are rejected due to this problem.

In the following, firstly the specifications and input conditions for the experiment and analysis will be given. Next, after the experimental procedure, the results of the analysis will be brought in Von Mises stress contours and stress contribution on the bottom thickness, and then the results of the burst test and pressure cycling test will be given. Finally, by comparing these results, the allowable range of this thickness will be obtained.

3- General Specification

In the following, all of the needed parameters of cylinders that would influence the experiment and analysis are illustrated .

The 62-liter steel cylinder is one of the frequently produced products of the factory, so as an appropriate sample it was chosen for the test. The important Geometrical dimensions of this cylinder are according to Fig. 3.

The material of these cylinders is steel 34CrMo4 [2], and its chemical composition can be seen in Table 1.
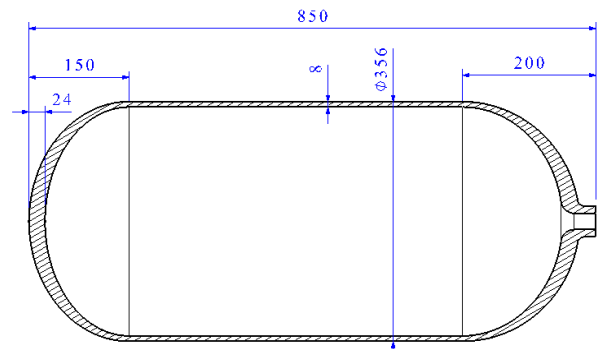

Fig. 3 Dimensional specifications of considered cylinders (mm)

Table 1: The chemical composition of the material of the cylinder

C	Si	Mn	P	S	Cr	Mo
0.30-0.37	0.10-0.40	0.60 - 0.90	≤0.020	≤0.010	0.90 - 1.20	0.15 - 0.30
			S + P ≤0.025			

The mechanical properties of this material after heat treatment were acquired according to Table 2.

Table 2: Mechanical properties of the material of the cylinder

El	ν	E	Sut	Sy
14.5 %	0.3	200 GPa	1018 MPa	938 MPa

The Milled profile in the internal bottom of the cylinders and also the relevant tool is shown in Fig. 4. To avoid deep milling for eliminating heterogeneous regions, machining was done by a taper tool that contained two face milling inserts and one filleting insert.
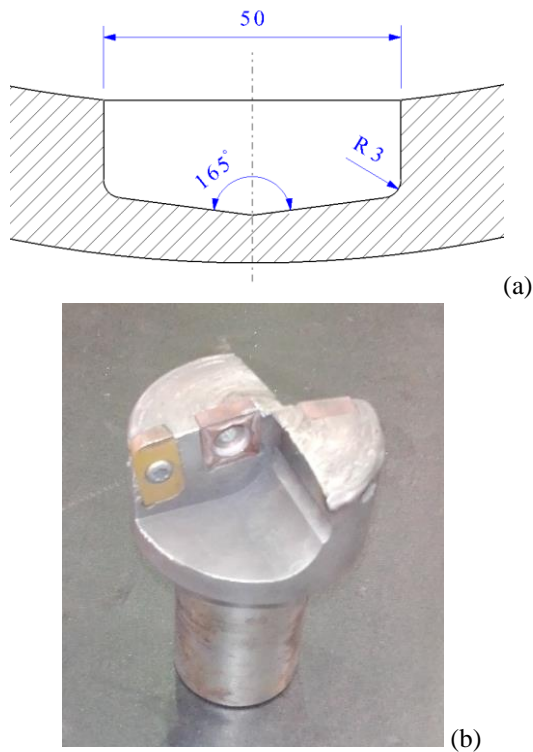
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(a)

(b)

Fig. 4 (a) Dimension of milled profile (b) Bottom milling tool

4- Experimental Procedure

To confirm and validate the obtained results from FEM analysis, and investigate the fatigue effects and crack growth, 6 normal cylinders consisting of three pairs of samples by the different depths of milled bottom according to Table 3 were used for burst and pressure cycling test. Considering the maximum machining error and operator, the remained thickness cannot become less than 6mm. So, these vessels were produced with low to high critical bottom thicknesses of 16, 10, and 6 millimeters of remained thickness respectively. Samples 1 to 3 were chosen for the burst test and samples 4 to 6 were taken under a pressure cycling test. The results are given in the next sections.

The machining depth and remained thickness in created profile in the three different types of test samples are shown in Fig. 5.

Table 3: Dimension of milled area in specimens

Specimen Number	test	Machining depth (mm)	Remained thickness (mm)
1	Burst test	8	16
2		14	10
3		18	6
4	Pressure cycling test	8	16
5		14	10
6		18	6

4-1- Burst test

To validate the analysis results and to compare them with the real condition, three cylinders according to the specified dimensions of the milled bottom were taken under the burst test. This test aimed to recognize the critical region (torn area). In other words, to find out whether the cylinders fail from the milled area or the cylindrical wall? It is important to say that these tests were done considering all of the requirements of the related standards, for all three vessels [1-2].
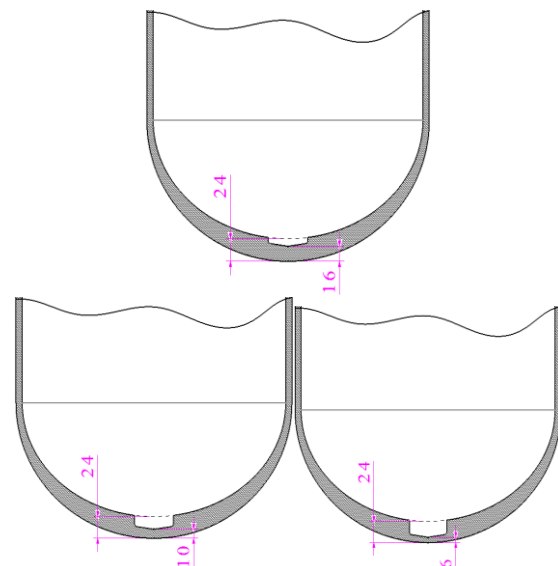

Fig. 5 Milled profile in the three different types of specimens

In this test, the cylinder is filled with water and then put in a 2.5-meter depth borehole

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of water. Next, the internal pressure of the cylinder is gradually increased by a high-pressure pump, until it bursts. Finally, the maximum recorded pressure by the gages on the device is recorded as the burst pressure.

4-2- Pressure cycling test

After demonstrating the safety of the milled area by static strength assessment, three other vessels, with the same considered condition, were used for the cycle pressure test to ensure resistance to the effects of fatigue and crack growth. In the process of this test, firstly, the cylinder is filled with the hydraulic oil and after mounting the connections, it will be under the periodic cycling pressure between 30 and 300 bar while the number of cycles is recorded. It should be said that, according to the related standard [1-2], vehicle cylinders must pass at least 15000 cycles of filling and emptying without any leakage. The pressure cycling test device is shown in Fig. 6.

Fig. 6 Pressure cycling test device

5- Finite Element Analysis

The aim of this research is a theoretical and experimental comparison of the stress distribution in the critical areas of the vessel at the failure pressure, so specimens were tested under the failure pressure. According to the standards of CNG cylinder design, the burst pressure in the cylinders used in vehicles is supposed to be more than 480bar [1]. Having this, specimens were analyzed under hydrostatic pressure of 480bar. ABAQUS 6.10-1 software was used to simulate the pressure applying process. To apply boundary conditions, cylinders were clamped from the neck thread. A Hexagonal type mesh structure of about 8 millimeters size was considered on the sample. To obtain more accurate results in the milled area, in a circle in this region with a 5cm radius, hexagonal elements by the approximate size of 2mm were distributed by sweep technique [13]. The meshed structure is shown in Fig. 7.

After applying the above conditions and solving the problem, the contours of Von Mises stress distribution would be according to Fig. 8. Outer surface of the vessel body, (b) Sweep mesh of the milled area.
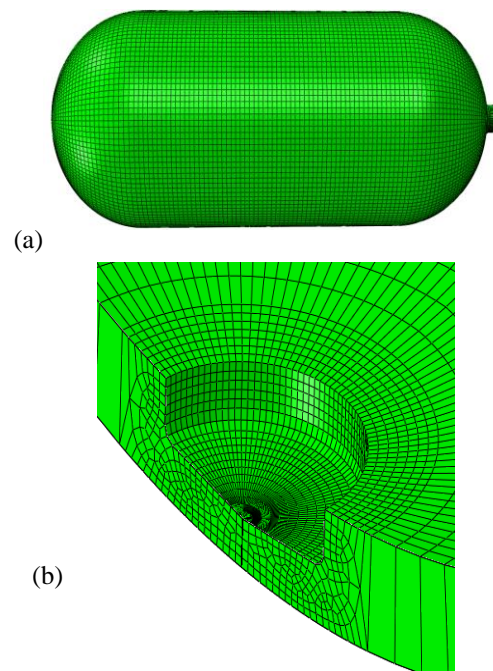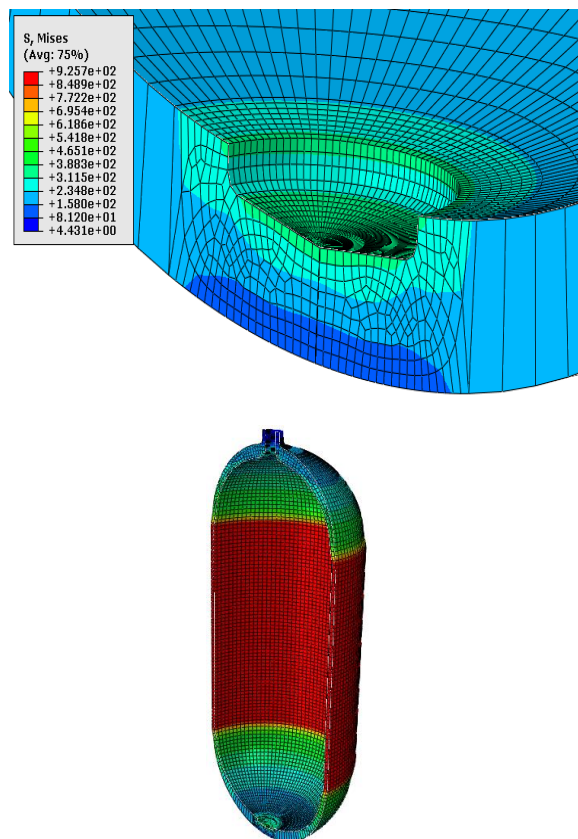

(a)

(b)

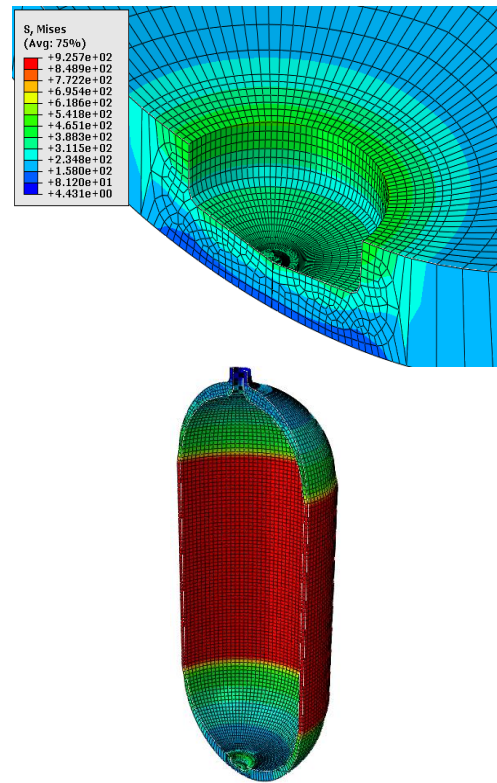Fig. 7   Meshed structure of storing vessel: (a)

In Fig. 9, the graph of stress distribution in the central thickness of machined area in three specimens and direction assignment to the stress measurement.

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6. Results

Looking at the stress distribution in Figs. 8 and 9, it can be seen that in the first and second cases (remained thickness of 16 mm and 10 mm, respectively), the maximum stress on the wall (cylindrical region) by about 925 MPa is much more than that of the milled area by about 388 MPa. This issue provides an extended safety border for the milled area. In the third case (remained thickness of 6 mm), the cylindrical part is also more critical than the milled area. However, according to the graph, in these conditions, the average of Von Mises stress along the central bottom thickness is about 1.7 times more than two other specimens; so, it can increase the possibility of failure in the milled area, especially in fatigue presence.

(b)

(a)
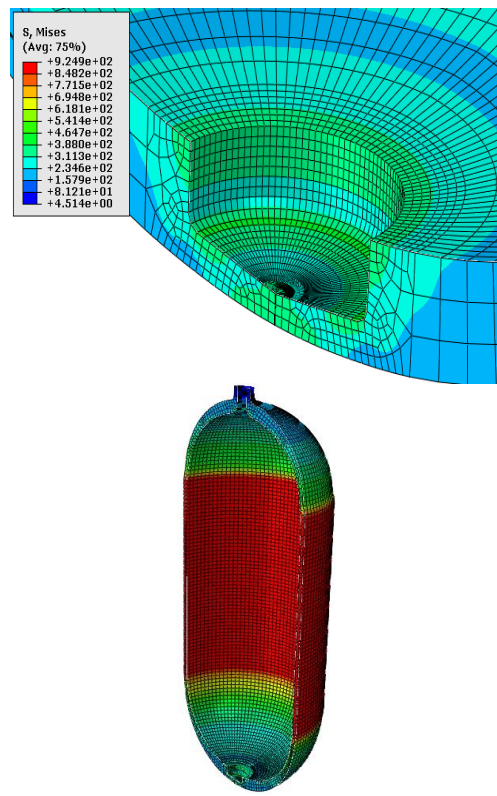
(c)

Fig. 8   Distribution of Von Mises stress, (a) remained thickness 16mm (b) remained thickness 10mm (c) remained thickness 6mm

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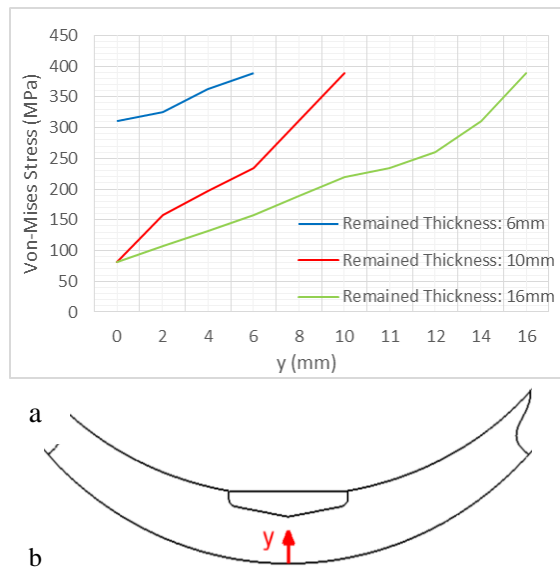
Fig. 9 (a) The graph of stress distribution in the central thickness of machined area in three specimens, (b) Direction assignment to the stress measurement.

Moreover, by comprising the stress distribution in the central thickness of the milled region (Fig. 8), it is confirmed that in all three specimens, by moving from the external surface to the internal, the Von Mises stress consistently increases to the maximum amount of around 390 MPa. It means that the internal milled surface is more critical than the external surface and failure would begin from this region. Therefore, the surface needs to be finished well to avoid creating cracks and fatigue failure [5].

Obtained results of burst test can be seen in Table 4. In addition, some images of the burst cylinders and also sections of the milled region are given in the Fig. 10.

As it is obvious from Table 4 and Fig. 8, in all three specimens the failure was in the cylindrical part under the pressure of around 565 bar while the milled bottom endured this pressure and remained safe and without any signs of failure.

Table 4: The results of the burst test

Sample No.	Machining depth (mm)	Remained thickness (mm)	Burst pressure (bar)	Failure place
1	8	16	559	Cylindrical region
2	14	10	569	Cylindrical region
3	18	6	558	Cylindrical region

The results of pressure cycling tests are given in Table 5. As it can be seen, all three vessels passed 12000 cycles which is the required number for approved products. In the worst-case 6-mm remained thickness, loading had been continuously done until leakage appeared after 35260 cycles which is nearly three times more than the specified number. As it can be seen from Fig. 11, even in this case, in addition to significant resistance to fatigue failure, the leakage occurred through an about 5cm axial crack on the cylindrical part of the vessel.

7. Conclusion

In this research, three types of frequently produced CNG cylinders with different remained bottom thicknesses were taken under test. As in the bottom machining in the production process of vessels, the minimum remained intact thickness will not lessen than 6mm, so as the most critical condition in the third type, the remained bottom thickness is considered equal to 6mm to ensure its resistance to static and fatigue failure. Deducing the results of the FEM analysis, it can be seen that the remained bottom thickness up to 6mm has no limitation for the endurance hydrostatic pressure, and that was supported by experimental burst tests. In addition, to ensure the resistance to the effects of the fatigue phenomenon, cylinders were taken

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under the pressure-cycling test, and consequently, even in the most critical case, (6mm remained thickness), no leakage was detected from the milled area. Overall, according to these results and considering the probable heterogeneity of the material and also the possibility of corrosion in this region, the remained thickness of 6mm, can be supposed as the least amount of this parameter by an appropriate safety factor. Considering this amount for the bottom thickness, the percentage of rejected products declined considerably from 4% to 2% in the factory. Therefore, these results can be helpful for vessel manufacturers, designers, and other researchers who work on pressure vessels.
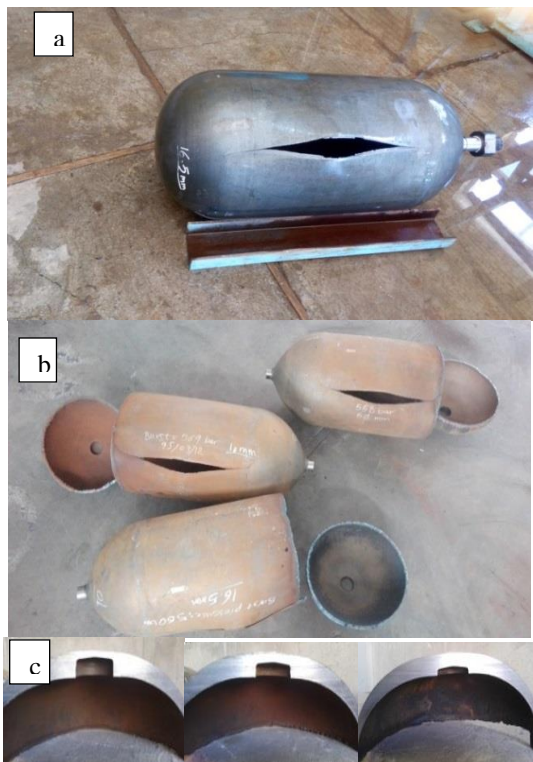
Table 5: The results of the pressure cycling test

Sample No.	Machining depth (mm)	Remained thickness (mm)	Number of cycles	Leakage area
4	8	16	15528	Without leakage
5	14	10	15528	Without leakage
6	18	6	35260	Cylindrical region

Fig. 11 (a): cylinder is leaking from the cylindrical part under test, (b): the leakage area is cut out to internal and external inspection, (c): external surface of leakage area, (d) internal surface of leakage area

Fig. 10 (a) Cylinder just after burst (b) The bottom of cylinders are cut after burst (c) the section views of bottoms for checking the milled area.

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