Manufacturability Evaluation of Large Volume Seamless Gas Cylinder Pipe Based on TPS

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Abstract: The thesis analyzes the requirements to material and performances of cylinder according to DOT-3AAX and ISO11120. Chemical composition, mechanical performance and wall thickness are presented as the main indexes to evaluate the Manufacturability of gas cylinder pipe, and frequency statistics to satisfy with the evaluation indexes range is put forward by analyzing quantity producing cylinder pipes. In order to estimate feasibility of mass production of cylinder pipes meeting the evaluation indexes, the theory of polychromatic sets have been used. The present of evaluation indexes explores a higher requirements to make gas cylinder pipes lighter.

Keywords: Theory of Polychromatic Sets; cylinder pipe; Manufacturability evaluation

1. Introduction

The production and usage amount of industry gas especially as natural gas and hydrogen increased rapidly in recent years. Also the demand of tube trailer for gas transportation and storing and cylinder bundle for refueling station was growing. The major diameter seamless gas cylinder which was the critical component for the equipments needed more lightweight and volume larger to decrease cost and to improve efficiency[1]. Medium filled in cylinders mostly are combustible, explosive and corrosive, and cylinders bear repeated loads because of repeated filling. Therefore, the requirements for seamless steel pipe for high-pressure cylinders are very high. In order to guarantee safety and reliability for cylinder application, it requires seamless steel pipe for cylinder to have higher strength, plasticity and toughness.

In coping with developing trend of big diameter and light type of cylinders, SHINENETGY TECHNOLOGIES, Inc. associated with Tianjin Pipe Corporation (TPCO) and University of Science and Technology Beijing (USTB) exploited seamless hot finished tubes for gas cylinder by rotary expanding technology. The outer diameter is ø559mm~ø720mm, and the length is less than or equal to 12500mm. The Manufacturability of ø559mm tube using theory of polychromatic sets was evaluated by indexes obtained according to DOT-3AAX and ISO11120. Chemical composition, mechanical performance and wall thickness are presented as the main indexes, and frequency statistics to satisfy with the evaluation indexes range is put forward by analyzing quantity producing cylinder pipes.

2. The propose of evaluation index

The main method to lightweight of the large diameter seamless cylinder was to reduce wall thickness which depended on property and wall thickness homogeneity directly. So weight reduce could be true if a good property and homogeneity wall tube was produced. The chemical compositions and technology for heating processing decided the property, and homogeneity of wall thickness was realized by controlling the rolling technology. Therefore, chemical composition, mechanical performance and wall thickness were presented as the main evaluation indexes.

2.1. Chemical composition indexes

The purity of steel need to be improved to insure the mechanical property of the steel pipe after heat treatment, such as reducing of content of sulfur and phosphorus. The content of sulfur should be controlled in 0.01% and phosphorus in 0.02% which has achieved the level of high-grade quality alloy steel according to the specification of ISO11120. Therefore, the index of the content of sulfur and phosphorus for evaluation needs to match with the level and the total content of both should be controlled below 0.025%. The strength reserve should be improved as far as possible to guarantee the safety of cylinder on the premise that high plasticity and toughness.

The result shows that the strength and hardness increases, the toughness and ductility decrease with the increase of carbon content. The strength, hardness, toughness and quenching degree increases with the increase of manganese content, but tendency to quenching crack increases obviously if manganese
content is too much. So the lower limit of carbon content was improved 0.03% and the manganese was improved 0.3% based on grade steel 4130X. The upper limit was the same as 4130X considering the requirement of plasticity and toughness. The content of Cr can improve the tensile strength, elongation and quenching degree of steel. The content of Mo can make the grains of the alloy finer and improve its yield strength, quenching degree and temper brittleness. So we adjusted the lower limit of Cr and Mo considering the manufacture and use for quenching and corrosion resistance. The evaluation index of chemical composition was given in table 1 which met the need of DOT-3AAX and ISO11120 [2-3].

| Table 1 chemical compositions, wt% |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Grade                   | C               | Si              | Mn              | P               | S               | Cr              | Mo              |
| 4130X*                  | 0.25~0.35      | 0.15~0.35      | 0.40~0.90       | ≤0.020          | ≤0.010          | 0.80~1.10       | 0.15~0.25       |
| Group II**              | 0.25~0.40      | 0.10~0.45      | 0.40~1.00       | ≤0.020          | ≤0.010          | 0.80~1.20       | 0.15~0.35       |
| Evaluation index        | 0.28~0.34      | 0.17~0.35      | 0.70~0.90       | ≤0.020          | ≤0.010          | 0.90~1.10       | 0.19~0.25       |

*Chemical compositions of 4130X steel refers DOT-3AAX; **Chemical compositions of Group II steel refers ISO11120

2.2 Performance property index
The strength range of material was not specified in DOT-3AAX, but the wall stress of cylinder under hydraulic test pressure was not exceeding 67% of minimum tensile strength. The value was not exceeding 70000psi also for DOT-3AAX cylinder. For cylinders filled with tendency to stress corrosion as nature gas and hydrogen, some specifications were given in DOT-SP8009 as the tensile strength less than or equal to 869MPa, yield ratio 86%, upper hardness limit HB269, elongation equal or greater than 20%. They were specified by ISO11120 that the tensile strength was less than or equal to 1100MPa and yield ratio 90%. For cylinders filled with hydrogen brittleness medium, specifications were also given as the tensile strength less than or equal to 950MPa, yield ratio 90%. The elongation was equal or greater than 16%. The single impact value was greater than 40J and the average value was greater than 50J.

The pipe should meet the requirements of DOT-3AAX and ISO11120 cylinder standard. So the evaluation index of mechanical property was given in table 2.

<table>
<thead>
<tr>
<th>Table 2 evaluation index of mechanical property</th>
</tr>
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<tbody>
<tr>
<td>Performance index</td>
</tr>
<tr>
<td>DOT-3AAX</td>
</tr>
<tr>
<td>ISO11120</td>
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<tr>
<td>Evaluation index</td>
</tr>
</tbody>
</table>

2.3 Wall thickness homogeneity index
The homogeneity of wall thickness of pipe has big influence on weight and usage of cylinder. Advanced rolling equipment provided guarantee to homogeneity. The deviation of wall thickness was 0~22.5% specified in GB18248, and it was too big. So we adjusted it into 0~15% to get a more uniform wall. The minimum design wall of 559mm cylinder calculated according to DOT-3AAX was 16.5mm, and the range was 16.5mm~19mm considering the allowance.

3 Batch statistic analyses
3.1 Frequency statistic of chemical composition
The chemical composition of different batch about 122 furnace number cylinder pipe was statistic as table 3. The result showed the composition was stable and fluctuation was small. While the content of C, Mn, Cr and Mo met the need of DOT-3AAX and ISO11120, but the min value was lower than the evaluation index given in table 1.

<table>
<thead>
<tr>
<th>Table 3 statistic analysis of chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>element</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>Si</td>
</tr>
<tr>
<td>Element</td>
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</tbody>
</table>

The frequency of four elements which met the evaluation index as table 1 was statistic and the histogram was given as Fig.1~4. Take C for example, the furnaces of content 0.28% was 68, 0.28%~0.29% was 28, 0.29%~0.30% was 8, 0.30%~0.31% was 2, 0.31%~0.32% was 3, 0.32%~0.33% was 1, and the total was 122. Therefore, the content of 0.28%~0.34% was 90% of all the statistic number. Also the content of Mn was 80%, the content of Cr was 90% and Mo was 80%.

![Fig.1 statistical histogram of C frequency](image)
![Fig.2 statistical histogram of Mn frequency](image)
![Fig.3 statistical histogram of Cr frequency](image)
![Fig.4 statistical histogram of Mo frequency](image)

### 3.2 Frequency statistic of mechanical property

The mechanical property of same batch about 143 furnace number cylinder pipe was statistic as table 4. The results showed that the index could meet the requirement of ISO standard, and individual exceeded DOT standard. But the fluctuation was small.

<table>
<thead>
<tr>
<th>Performance index</th>
<th>min</th>
<th>max</th>
<th>average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength/MPa</td>
<td>720</td>
<td>950</td>
<td>835</td>
<td>47</td>
</tr>
<tr>
<td>Yield strength/MPa</td>
<td>600</td>
<td>810</td>
<td>715</td>
<td>41</td>
</tr>
<tr>
<td>Elongation/%</td>
<td>16.5</td>
<td>24</td>
<td>20.5</td>
<td>1.6</td>
</tr>
<tr>
<td>-50°C impact value/J</td>
<td>55</td>
<td>143</td>
<td>100</td>
<td>22</td>
</tr>
</tbody>
</table>

Performance index of frequency which met the requirement of table 2 was statistic, and histograms were also given as Fig.5~8. It showed that the tensile strength was 70%, yield strength was 75%, elongation was 80% and impact value was 75%.
3.3 Frequency statistic of wall thickness

The homogeneity of wall thickness of pipe plays an important role in single pipe weight and usability. The homogeneity is expressed in uniformity coefficient which is defined the ratio of maximum deviation and average value among Orthogonal four points on the same section. The uniformity coefficient was statistic about 292 pipes manufactured in 143 furnaces. Fig.9 was the histogram of homogeneity frequency. The percentage of uniformity coefficient controlled in 6% was 95%. It showed that the cylinder pipe had a perfect uniform. Fig.10 was the statistical histogram of wall thickness frequency. The percentage of wall thickness in 16.5mm~18.5mm was 65% and it’s the evaluation index.

4 Evaluation of periodicity base on TPS

4.1 Introductions of TPS

Theory of Polychromatic Sets (TPS) was proposed by Russia professor V.V.Pavlov who was expert in aircraft design and manufacture, and he built the architecture of TPS [4-9]. Boolean matrix $[S \times F(S)]$ was used to describe the relation between character and element of object factor $A$. While $a_i$ make relation with $F_j$, the value $a_{i,j}$ was 1. Otherwise, it was 0.
While, \( A \) was collection of object; \( F(A) \) was contour collection.

### 4.2 Reasoning process base on TPS

Chemical composition, wall thickness and mechanical property are key factors influenced on cylinder pipe, and this element contains many sub-elements. For example, chemical composition includes seven sub-elements as C, Si, Mn, P, S, Cr and Mo. Wall thickness includes wall \( t \) and its homogeneity \( s \). Mechanical property includes tensile strength \( R_m \), yield strength \( R_y \), elongation \( \Delta \) and -50\(^\circ\)C impact value \( A_{k1} \). Boolean matrix was built base on parent-child relationship of manufacture influence factors.

While, \( 2^1 \) is chemical composition factor, \( 2^2 \) is wall thickness factor, \( 2^3 \) is mechanical property factor.

And \( a_1 \) is C element, \( a_2 \) is Si element, \( a_3 \) is Mn element, \( a_4 \) is P element, \( a_5 \) is S element, \( a_6 \) is Cr element, \( a_7 \) is Mo element, \( a_8 \) is wall thickness homogeneity element, \( a_9 \) is wall thickness \( t \) element, \( a_{10} \) is tensile strength element, \( a_{11} \) is yield strength element, \( a_{12} \) is elongation element and \( a_{13} \) is impact value element.

The weighting coefficient of every element in contour matrix was set according to the important degree to the manufacture of cylinder pipe. Weightiness reflects the objective information of element and is leaded by the subjective judgment of decision maker. Weighting coefficient can be determined by statistic result and the expert scoring methods. The difficulty level to reach the requirement was wall thickness, mechanical property and chemical composition in turn by the statistic results. The weighting coefficient of factors was given by the statistic analysis of reject ratio of pipe and the experience of technicians and workers in situ. The more difficult it is to achieve, the higher the weight value.

\[
\mathbf{C}_{ij}^{AF(A)} = [A \times F(A)] = \begin{bmatrix}
F_1 & \cdots & F_j & \cdots & F_m \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{i(1)} & \cdots & a_{i(j)} & \cdots & a_{i(m)} \\
\vdots & \cdots & \cdots & \cdots & \cdots \\
\vdots & \cdots & \cdots & \cdots & \cdots \\
a_{n(1)} & \cdots & a_{n(j)} & \cdots & a_{n(m)}
\end{bmatrix}
\]

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While, \( F_1^2 \) is chemical composition factor, \( F_2^2 \) is wall thickness factor, \( F_3^2 \) is mechanical property factor. And \( a_1 \) is C element, \( a_2 \) is Si element, \( a_3 \) is Mn element, \( a_4 \) is P element, \( a_5 \) is S element, \( a_6 \) is Cr element, \( a_7 \) is Mo element, \( a_8 \) is wall thickness homogeneity element, \( a_9 \) is wall thickness \( t \) element, \( a_{10} \) is tensile strength element, \( a_{11} \) is yield strength element, \( a_{12} \) is elongation element and \( a_{13} \) is impact value element.

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\[
F^* = (F_1^2, F_2^2, F_3^2) = (0.5,1,0,0.8)\\nF_1^2 = (a_1, a_2, a_3, a_4, a_5, a_6, a_7) = (1,0,0.5,1,0,0.8,0.8,1,0,1,0)\\nF_2^2 = (a_8, a_9) = (0.8,1,0)\\
\]
After unitary processing:

\[ F^* = (F_1^*, F_2^*, F_3^*) = (0.22, 0.43, 0.35) \]

\[ F_1^2 = (a_1, a_2, a_3, a_4, a_5, a_6, a_7) = (0.164, 0.082, 0.164, 0.131, 0.131, 0.131, 0.164, 0.164) \]

\[ F_2^2 = (a_8, a_9) = (0.44, 0.56) \]

\[ F_3^2 = (a_{10}, a_{11}, a_{12}, a_{13}) = (0.25, 0.25, 0.29, 0.21) \]

The Manufacturability evaluation value of cylinder pipe was given according to the given weighting coefficient shown as table 5.

<table>
<thead>
<tr>
<th>Table 5 evaluation value of Manufacturability</th>
</tr>
</thead>
<tbody>
<tr>
<td>evaluation value</td>
</tr>
<tr>
<td>Quantized value</td>
</tr>
</tbody>
</table>

4.3 Assessment process

The quantized value of sub-element evaluation results was decided to obtain evaluation matrix \( R \). Supposed that evaluation value of the jth element from the ith factor \( F_i^2 \) was \( r_{ij} \), and then the evaluation result of the ith factor \( F_i^2 \) could be express as:

\[ R_i = [r_{i1}, r_{i2}, r_{i3}, \ldots, r_{im}]^T (i = 1, 2, 3) \]

The quantity evaluation value was given by the satisfaction degree of every influence element, and the sub-element was statistic value of frequency.

\[ R_1 = [r_{11}, r_{12}, r_{13}, r_{14}, r_{15}, r_{16}, r_{17}]^T = [0.9, 1.0, 0.8, 1.0, 1.0, 0.9, 0.8]^T \]

\[ R_2 = [r_{21}, r_{22}]^T = [0.95, 0.65]^T \]

\[ R_3 = [r_{31}, r_{32}, r_{33}, r_{34}]^T = [0.7, 0.75, 0.8, 0.75]^T \]

The relative evaluation result set \( B \) was calculated by matrix which formed by relative weighting co-efficiency and quantity evaluation value of every influence element. The formula \( B_i \) was as follow:

\[ B_i = F_i^2 \cdot R_i (i = 1, 2, 3) \]

then:

\[ B_1 = 0.164 \times 0.9 + 0.082 \times 1.0 + 0.164 \times 0.8 + 0.131 \times 1.0 + 0.131 \times 1.0 + 0.164 \times 0.9 + 0.082 \times 1.0 + 0.164 \times 0.8 = 0.9016 \]

\[ B_2 = 0.44 \times 0.95 + 0.56 \times 0.65 = 0.782 \]

\[ B_3 = 0.25 \times 0.7 + 0.25 \times 0.75 + 0.29 \times 0.8 + 0.21 \times 0.75 = 0.752 \]

therefore, \( B = \begin{bmatrix} 0.9016 \\ 0.782 \\ 0.752 \end{bmatrix} \)

The evaluation result \( A \) was obtained by weighting of influence factors and relative evaluation result set.

\[ A = F^* \cdot B = 0.22 \times 0.9016 + 0.43 \times 0.782 + 0.35 \times 0.752 = 0.798 \]

So, the result is yes as showed in table 5.

5 Conclusions

Chemical composition, mechanical property and wall thickness were presented as evaluation index of cylinder pipe Manufacturability considering the material and performance requirement of cylinder standard. The difficulty degree to manufacture was wall thickness, mechanical property and chimical composition from the statistic results. TPS was applied to evaluate the Manufacturability of pipe and the result was 0.798 which means it can be manufactured.

Reference


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