Research Article

The Thickness Distribution of Oxidation Film on Tapered Pipe Surface in Dieless Drawing

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1. Introduction

Dieless drawing is a kind of flexible and plastic forming process without conventional dies, which can achieve a great reduction of wire and tube metals in single pass by means of local heating and cooling approach [1, 2]. Especially, owing to low production cost and high production efficiency, dieless drawing process has great application prospects in the forming process of hard-to-process pipes and wires [3], such as 304 stainless steel tapered pipes. But, oxidation film forms on the heated metal surface in the local heating zone during the deformation process, which not only affects the surface quality but also reduces the anticorrosion performance and service life of products. Therefore, the researches on thickness distribution of oxidation film on tapered pipe surface and its influence factors are of great significance to improve the surface quality of products, optimize process parameters of dieless drawing, and remove oxidation film.

An oxidation film with uniform thickness forms on the metal surface, and the oxidation kinetics curve obeys a linear law, or a parabolic law, or other laws when the metal is heated in a constant temperature and pressure environment [6–10]. As the metal matrix suffered elastic deformation or creep induced by a tensile stress, the surface oxidation film was prone to cracking and brittle rupture because of its worse plasticity, and then oxidation resistance deteriorated and the growth of oxide film was accelerated, thus the oxidation rate was affected severely by stress and deformation of metal [5, 11–13]. The present studies mostly focused on the growth rules of oxidation film on metal surface when metal suffered elastic deformation or creep of low strain rate at constant temperature. However, oxidation and large plastic deformation occurred at the same time in dieless drawing process of tapered pipes. In addition, deformation degree increased gradually with the increase in the drawing speed, thus geometric boundary of deformation area changed instantaneously and the metal temperature field was transient [14, 15]. The mechanism of oxidation is complex in dieless drawing process of tapered pipes and has not been reported in literatures.
The influence factors of metal oxide, the thickness distribution of oxidation film on tapered pipes surface, and the effect of process parameters in the dieless drawing process were studied by using AISI304 stainless steel in this paper, for a purpose to provide references for improving surface quality of products and optimizing the parameters of dieless drawing forming.

2. Experiment

AISI304 stainless steel pipes of Φ6×1 mm with a light surface were prepared for dieless drawing as shown in Figure 1, and the chemical composition of AISI304 stainless steel is shown in Table 1.

Tapered pipes with a 0.8° taper angle were processed by dieless drawing in air. The process parameters were as follows: induction heating temperature 900 to 1100°C, feed speed 20 to 40 mm·min⁻¹, the distance between heat and cold sources 15 to 45 mm, drawing speed according to [16] and the section reduction ratio was less than 57%. The profile morphology of oxidation film was observed and the thickness of three points was measured by CAMBRIDGE S-360 scanning electron microscope (SEM) and Image Tool such as graphics processing software.

AISI304 stainless steel specimens with a length of 110 mm were prepared for the following experiments: (1) the pipes were heated to 900°C in air, held for 150 s, and then cooled to the room temperature; (2) some specimens were deformed by tension test at 900°C in vacuum environment, strain rate 10⁻³ s⁻¹, deformation degree 5 and 10%, respectively, after experiment (1); (3) a part of specimens were reheated to 900°C after experiment (2) and held for 150 s, then cooled to the room temperature in air. The section and surface morphologies of the specimens after each experiment were observed by SEM.

<table>
<thead>
<tr>
<th>Alloy element</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
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<tr>
<td>wt%</td>
<td>0.08</td>
<td>2.0</td>
<td>0.045</td>
<td>0.03</td>
<td>1.0</td>
<td>10.5</td>
<td>18.0</td>
<td>Other</td>
</tr>
</tbody>
</table>

Table 1: The chemical composition of AISI304 stainless steel.

Figure 1: The image of AISI304 stainless steel pipes.

Figure 2: The image of 304 stainless steel tapered pipes after dieless drawing forming.

Figure 3: Thickness distribution of oxidation film on tapered pipes surface at the different induction heating temperatures.

3. Results

After dieless drawing forming, the surface of AISI304 stainless steel tapered pipes was oxidized with generating dark brown oxide, that contains mainly FeO, Fe₂O₃, Fe₃O₄, and FeCr₂O₄ [7, 8], as shown in Figure 2.

We defined the end of tapered pipe with a largest diameter of 6 mm as origin. The thickness distributions of oxidation film on the tapered pipe surface are shown in Figure 3, when the feed speed was 20 mm·min⁻¹, the distance between heat and cold sources 40 mm, the induction heating temperature 900, 1000, and 1100°C, respectively. Figure 3 indicates that the thickness of oxidation film (y) at the distance (L) of 40 mm from origin was 0.88, 1.11, 1.46 μm, respectively, for different heating temperatures. However, when L = 160 mm, y = 3.55, 4.4, 5.25 μm, respectively. The thickness of oxidation film on the surface of tapered pipes increased gradually with the increase in the induction heating temperature, and deformation degree.

Figure 4 shows the effect of the distance between heat and cold sources (S₀) on the thickness of oxidation film, when the feed speed was 30 mm·min⁻¹, the induction heating temperature 1100°C, respectively. When L = 160 mm, y = 3.41, 4.24, 5.21 μm for S₀ = 15, 30, 45 mm, respectively. The oxidation film thickenened with the increase in the distance between heat and cold sources.

Figure 5 shows the thickness variation of oxidation film at different locations with the increase in feed speed (V₀), when the induction heating temperature was 1100°C, the distance between heat and cold sources was 35 mm, respectively. In Figure 5, the thickness of oxidation film y = 5.55, 4.87, 4.38 μm at the locations of L = 160 mm, corresponding to V₀ = 10, 20, 30 mm·min⁻¹, respectively. The oxidation film thickened with the reduction in the feed speed.
4. Discussion

The oxidation degree of metal was affected strongly by temperature, time, and atmosphere [4–6]. The oxidation speeded up and the oxidation film thickened with the increase in the induction heating temperature. The temperature of metal in heating zone and deformation zone rose and the oxidation rate was accelerated, as the induction heating temperature was increased in the dieless drawing process. As a result, the oxidation film on pipe surface thickened when the induction heating temperature was elevated (Figure 3). There was more metal in high temperature zone and the metal stayed longer at high temperature, so that the oxidation film thickened when the distance of heating and cooling sources was increased (Figure 4). This is because that the oxidation film thickens with the oxidation time. Similarly, the pass time of metal through high-temperature zone elongated and the oxidation film thickened, when drawing speed was decreased by reducing feed speed with an identical rate ratio (Figure 5).

In dieless drawing process of AISI304 stainless steel tapered pipes, the oxidation time is shortened with the increase in drawing velocity and tapered pipe length, however, oxidation film thickens, as shown in Figures 3–5. On one hand, the research indicates that oxidation film forms on the heated metal surfaces at high temperature, but the oxidation film blisters and cracks due to inner stress in it, which were found on the surface morphology of oxidation film when AISI 304 stainless steel is heated to 900°C without deformation as shown in Figure 6(a). Many tiny channels consist of microcracks in the oxidation film, and oxygen atoms can go through these channels and then react directly with metal matrix, which cause the increase in oxidation rate. On the other hand, the metal suffers a large plastic deformation in the deformation zone during the dieless drawing process, and surface oxidation film is also changed.

Figures 6(b) and 6(c) show the surface morphology of oxidation film when the parameters are as follows: the induction heating temperature 900°C, the deformation degree 5 and 10%, respectively, in vacuum environment. Figure 6 suggests that there are massive cracks and ruptures in the surface oxidation film on the deformed metallic matrix. From the section plans of oxidation film, undeformed oxidation film reveals continuous floe structure(Figure 6(d)), while deformed oxidation film reveals discontinuous mass structure (Figure 6(e)). That indicates that the deformation of metal matrix introduces many ruptures of the oxidation film adhered to it. This is because that the oxidation film prefers brittle rupture due to its low plasticity, and a large amount of cracks are induced, and then the fresh metal surface is revealed, although a certain plastic flow occurs in surface oxidation film along the direction of deformation. However, metal oxidation resistance drops down and new oxidation speeds up rapidly when the fresh metal surface contacts with oxidizing atmosphere directly. Figure 6(f) shows the section of surface oxidation film which formed at 900°C in air after the deformation in vacuum environment. Due to the existence of many cracks in oxidation film, the thickness of oxidation film formed for a shorter oxidation time during the deformation process is even greater than that generated on the undeformed metal for a longer time, which brings some difficulties to the control and evaluation methods for oxidation degree in the dieless drawing process. By Figures 6(b) and 6(c), it is seen that, the density and width of cracks in oxidation film are enlarged with the deformation degree of metal matrix. As a result, the thickness of new oxidation film increases with the increase in deformation degree. In the dieless drawing process, tapered pipes extend with the raise of the drawing speed and deformation degree, and the thickness of oxidation film increases gradually from the larger diameter end to the smaller diameter end along tapered
pipes. Deformation caused the raise of outer oxidation film thickness and inner oxidation depth. But the influencing mechanism and function mechanism of the applied stress and metallic deformation still need to be researched further.

5. Conclusions

The following conclusions were derived from this work.

1. On tapered pipes surface in dieless drawing process, the thickness of oxidation film distributed unevenly and increased from the larger diameter end to the smaller diameter end along the tapered pipes.

2. The metal oxidation rate was accelerated, and the oxidation film thickened gradually on the surface of tapered pipes, when the induction heating temperature was raised or the distance between heat and cold sources was extended, or the feed speed was decreased during the dieless drawing deforming.

3. In the dieless drawing process, the forming of massive cracks in oxidation film induced by deformation of metal matrix was the major cause behind the increase in the oxidation rate and oxidation film thickness.

4. The thickness of oxidation film increased due to the enlargement of the density and width of cracks in the oxidation film when the deformation degree was raised in the dieless drawing process.

References


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