An analysis of crack evolution of a 12Cr13 stainless steel during forging process

Guo, Wei-Min; Xu, Na; Ding, Ning; Shi, Jun-Bo; Wu, C.M. Lawrence

Published in:
Case Studies in Engineering Failure Analysis

Published: 01/10/2015

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

License:
CC BY-NC-ND

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1016/j.csefa.2015.10.002

Publication details:

Citing this paper
Please note that where the full-text provided on CityU Scholars is the Post-print version (also known as Accepted Author Manuscript, Peer-reviewed or Author Final version), it may differ from the Final Published version. When citing, ensure that you check and use the publisher's definitive version for pagination and other details.

General rights
Copyright for the publications made accessible via the CityU Scholars portal is retained by the author(s) and/or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights. Users may not further distribute the material or use it for any profit-making activity or commercial gain.

Publisher permission
Permission for previously published items are in accordance with publisher’s copyright policies sourced from the SHERPA RoMEO database. Links to full text versions (either Published or Post-print) are only available if corresponding publishers allow open access.

Take down policy
Contact lbscholars@cityu.edu.hk if you believe that this document breaches copyright and provide us with details. We will remove access to the work immediately and investigate your claim.

Download date: 02/05/2020
Case study

An analysis of crack evolution of a 12Cr13 stainless steel during forging process

Wei-min Guo a,⁎, Na Xu a, Ning Ding a, Jun-bo Shi a, C.M. Lawrence Wu a,b

⁎Shandong Province Material Failure Analysis and Safety Assessment of Engineering Technology Center, Shandong Analysis and Test Center, Shandong Academy of Sciences, Jinan 250014, People’s Republic of China

a,b Department of Physics and Materials Science, City University of Hong Kong, Kowloon Tong, Hong Kong

A R T I C L E   I N F O

Article history:
Received 20 August 2015
Received in revised form 6 October 2015
Accepted 20 October 2015
Available online 30 October 2015

Keywords:
Phosphorus
Crack
Cleavage fracture
Forging process
12Cr13 steel

A B S T R A C T

The analysis of an abnormal crack of a forging plate is presented in this work. The crack was found after forging process. Macro-analysis, SEM, composition inspection, metallographic analysis, inclusion analysis, EPMA and EDS were implemented. SEM shows that cleavage fracture is the main feature of the fracture surface, according to which it can be decided that the fracture is brittle fracture. XRF and carbon and sulphur analyzer indicate regular composition condition of the plate. EPMA and EDS suggest phosphorus segregation spread a lot around the crack. The results indicate that: brittleness caused by phosphorus segregation around crack zone is the main reason that cracks generate in the 12Cr13 steel during forging. As all we know, phosphorus has deleterious effect on toughness of steel because of its enrichment on grain boundaries, which can weaken the bond strength of grain boundary. Its existence should be avoided and microstructure of the steel should be homogeneous when good plasticity and toughness are wanted.

© 2015 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Forging offers potential savings in energy and material, especially in medium and large production quantities, where tool costs can be easily amortized. In addition, for a given weight, parts produced by forging exhibit better mechanical and metallurgical properties and reliability than those manufactured by casting or machining [1]. However, there are kinds of failure cases that can happen during forging, such as surface cracks, pouring laps and gross piping. Causes for forging failure are mainly attributed to forging process, fatigue and hydrogen damage [2].

There are essentially four principal fracture modes [3]: dimple rupture, cleavage, fatigue, and decohesive rupture, among which, dimple rupture is mainly caused by overload and the fracture exhibits numerous cuplike depressions; cleavage is a low-energy fracture that propagates along low-index crystallographic planes feature as cleavage steps, river patterns, feather markings, chevron (herringbone) patterns, and tongues; fatigue fracture is the result of cyclic loading and occurs in three stages: initiation, propagation and fracture, each of which has its own characteristic on the fracture surface; decohesive rupture is generally rupture along grain boundaries caused by segregation of such elements as hydrogen, sulphur, phosphorus, antimony, arsenic, and carbon or by the halide ions, or by the routes of penetration by the low melting point metals, such as gallium, mercury, cadmium and tin.

⁎ Corresponding author. Tel.: +86 15053168760.
E-mail address: guowm1808@hotmail.com (W.-m. Guo).

http://dx.doi.org/10.1016/j.csefa.2015.10.002
2213-2902/© 2015 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Phosphorus is known for intergranular segregation which can lead to lower grain boundary cohesion of steels [4]. For ferrite or martensitic steels, this segregation at grain boundary can lead in much stronger brittleness [5].

The intention of the work was to judge when and why this 12Cr13 stainless steel cracked.

2. Background

The plate was produced and hot forged by a steel company. Forging process was carried out as following: start-forging temperature was 1150 °C and finish-forging temperature was 850 °C. When forging process was finished, annealing process was carried out. The crack was found several days after that when the buyer received the plate. It was the user's authorization that we do failure analysis for the failure 12Cr13 steel plate. The size of the plate we received is like 200 mm × 200 mm × 30 mm. The crack is shown in Fig. 1(a) and it crosses the plate. The plate shown is cut from a forging ingot and the crack is about 1.5 in. in depth as shown in Fig. 1(b).

3. Experimental procedures

Chemical analysis, visual inspection, fractography, metallographic analysis were used for the analysis. The plate's chemical analysis was carried out via X-ray fluorescence (XRF); fractography was performed by using a scanning electron microscopy (Zeiss Supra 55); for the metallography, the samples were polished and etched (aqua regia) and observed on an optical microscopy (Zeiss Axio Observer A1m); EDS (Oxford INCAx-act) and EPMA (Shimadzu EPMA-1600) were used to analyze the micro-zone composition and element mapping.

4. Results

4.1. Fractography

Fractographic evaluation constitutes a powerful analytical technique dedicated to identify the fracture mechanism(s) in the context of failure analysis of machine components [6]. The overall view of the fracture surfaces observing by SEM of the forging plate is presented in Fig. 2. Fractography characteristics shown in Fig. 2(b) indicate the intergranular feature and cleavage feature of the fracture surface, which means it is brittle fracture. Cleavage fracture is a transgranular, low-energy fracture that occurs primarily by separation of atomic bonds on low-index atomic planes [7].

4.2. Metallographic analysis

A sample was cut from the plate fracture zone. This sample was metallographically prepared and observed in an optical microscope, in no etched and etched conditions. The microstructure, without etching, revealed low quantity of defects such as micro-pores and non-metallic inclusions, as shown in Fig. 3.

The microstructures shown in Fig. 4(a) and (b) revealed ferrite and dots of (Cr, Fe)₂₃C₆ type carbides. No decarburization was observed on both sides of the crack. Since quenching crack characteristics of the organizations on both sides without decarburization phenomenon is the significant difference from materials crack and forging cracks [8], the crack displayed on the forging plate is cold crack. Lots of segregation bands distribute in the crack zone on both sides.

![Fig. 1. Crack position and depth in the forging plate](image-url)
4.3. Chemical analysis of the forging plate

Measured and specified compositions of the plate are shown in Table 1. It can be seen the overall composition of the forging plate is in accordance with the standard value [9].
Fig. 4. Metallography structures of forging plate: (a) and (b) metallography from optical analyzer; (c) and (d) metallography from SEM; (e) and (f) EDS results for points in (d).

Table 1
Chemical composition of the forging plate, wt.\%.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>S</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtained</td>
<td>0.14</td>
<td>0.0019</td>
<td>0.79</td>
<td>0.68</td>
<td>0.019</td>
<td>12.85</td>
<td>0.59</td>
<td>0.014</td>
</tr>
<tr>
<td>Expected</td>
<td>&lt;0.15</td>
<td>&lt;0.030</td>
<td>&lt;1.00</td>
<td>&lt;1.00</td>
<td>&lt;0.040</td>
<td>11.50–13.50</td>
<td>&lt;0.60</td>
<td>–</td>
</tr>
</tbody>
</table>

4.4. Microanalysis

Fig. 4 (c) and (d) shows the (c) and (d) metallography from SEM and EDS results for points in Fig. 4(d) are as shown in (e) and (f). It is indicated that the segregation (point 1 in Fig. 4(d)) has high level of P element included and no P is found in the matrix structure (point 2 in Fig. 4(d)).

The distributions of composition were examined respectively by using electron probe microanalysis (EPMA-1600), as shown in Fig. 5. It is obvious that there is phosphorus segregation in the failed steel.
5. Discussions

It can be seen from the experimental results that total composition of the steel plate is in accordance with GB/T 1220-2007 stainless steel bars, and optical microstructure show ferrite and dots of carbides, which is normal in forging state. However, optical microstructure and SEM also indicate element segregation around crack zone, which turns out to be P segregation tested by EDS and EPMA. It is illustrated above that phosphorus harms ductility by segregating to grain boundaries. It can be seen from Fig. 6 that increasing phosphorus reduces impact energy and raises the nil-ductility transition temperature [10]. The transition temperature is significantly affected by phosphorus and/or silicon content, but is affected little by other elements present within the normal variations in composition. During forging or rolling, phase transformation (γ → M) happens, which can cause volume stress large enough for cracks. Full annealing is required to soft the steel for machining.

6. Conclusions

This forging 12Cr13 stainless steel is caused by phosphorous segregation. Phosphorous segregation weakens the bond strength of grain boundary and crack initiates from phosphorous segregation grain boundary when forging. It is important to
dephosphorizing the steel and uniform the structure. Full annealing process, suitable temperature schedule and reduction range are suggested to soft the steel and relief phase transformation ($\gamma \rightarrow \alpha$) stress, which can make the steel easy to process and avoid cracks [11].

References