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FRACTURE OF DRILLING HEAD PIPE CONNECTION DUE TO QUENCHING OF HEAT AFFECTED ZONE (HAZ)

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The drilling head pipe connection is made of quenched and tempered steel 34CrNiMo6. The steel characteristic is high hardenability. Due to unsuitable and untested welding technology the heat affected zone (HAZ) cooling rate after welding surpassed the upper critical cooling rate. During horizontal drilling of the rock, the resulting brittle martensite could not bear the dynamic loads which led to a brittle fracture of the pipe connection.

Key words: welding, heat affected zone (HAZ), martensite, fracture

INTRODUCTION

In a construction engineering rock drilling technologies are used in the tunneling and various pipelines construction. Sintered carbides and diamond composites are used as cutting-abrasive materials [1]. Due to large forces cracking of cutting tools is common phenomenon which is also known from the other branches of the industry [2, 3].

A company dealing with vertical and horizontal drilling was faced with occasional phenomenon of the conical horizontal drilling heads remaining in the rock walls. They established occasional cracking of the water feed pipe connections (diameter 34 mm, wall thickness 13 mm, length 150 mm) welded by stainless filler material to the drill head tip (Figure 1). The buyer of the drilling heads decided to investigate the reasons of the pipe connection cracking.

INVESTIGATIONS

Several tests were performed, such as visual examination, chemical analysis of the pipe connection material (quantometer Thermoelectron corporation ARL 3460), macroscopic and microscopic examination of the pipe connection material and heat affected zone (HAZ) of the weld perpendicular to the fracture surface (light metallography, grinding by emery papers up to #4 000, polishing by diamond paste 1 μm, etching by 2 % nital) as well as hardness measurements HV10 (device GNEHM Härteprüfer Swiss Max 300).

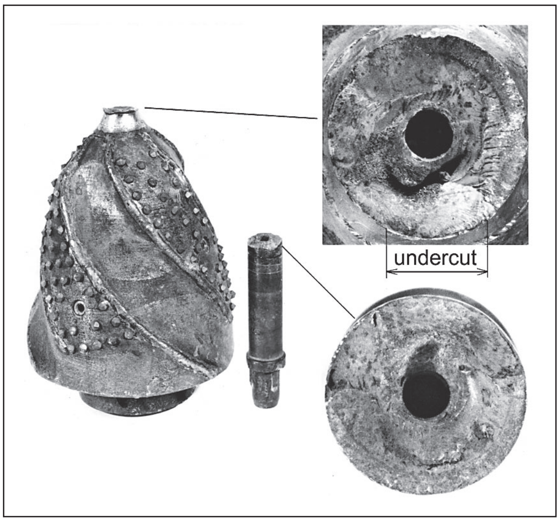

Figure 1 Drilling head with broken pipe connection

RESULTS AND DISCUSSION

Visual examination

The pipe connection fracture exists beside a weld of bright metallic surface, obviously made with stainless steel filler material. At some places the undercuts are seen (Figure 1). Result is a notched effect at these places. The pipe connection and both fracture surfaces are highly corroded. On the fracture surfaces, no bright metallic surface is seen which would indicate that no partial break through a stainless weld exists (this was confirmed also by a metallographic examination). Due to highly corroded fracture surfaces we did not search for the crack initiation place.

Chemical and metallographic analyses

Chemical composition of the material (wt. %: C = 0,34; Si = 0,27; Mn = 0,60; P = 0,010; S = 0,023; Cr = 1,66; Ni = 1,61; Mo = 0,23) proves that the pipe connection is made of quenched and tempered steel 34CrNi-

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Mo6 (EN 10027-1) or 1.6582 (EN 10027-2), respectively. Its characteristic is high hardenability with temperature $M_S \approx 370$ °C [4, 5]. According to data obtained in [4] maximal hardness of the front surface, obtained by Jominy test, achieves 546 –735 HV (50 – 58 HRC).

A macroscopic examinations showed the pipe connection break in the HAZ (Fig. 2a, 2c) where also secondary cracks exist (Figure 2e). A straight profile of the fracture surface and a configuration of the secondary cracks give proof of a brittle fracture.

The pipe connection material is in quenched and tempered state with tempered martensite microstructure (Figure 2 b, f) Due to quenching and the resulting martensite the quenched HAZ was maximally hardened (Figure 2 b, d, g).

The etching agent »nital« had no etching effect on the weld which proves the use of stainless steel filler material.

Theoretical analysis of welding technology

Due to its good hardenability, the 34CrNiMo6 steel belongs into the group of hardly weldable steels. The narrowest area of the under-cooled austenite at a temperature of $T \approx 370$ °C and in the time period of $t \approx 20$ s is evident from the contionous cooling transformations (CCT) diagram [4, 5]. From the hardness measurement results, it can be concluded that the HAZ cooling times were shorter than the lower critical time determining the start of the bainite transformation.

The HAZ width varies along the pipe connection circumference (Figure 2 c). On the left side, the HAZ is larger due to already accumulated heat which results from a cylindrical shape of the pipe connection. In spite of the accumulated heat, the cooling times are still shorter than the lower critical time for bainite formation so that the larger HAZ is qenched as well. This means that the accumulation of heat input in the pipe connection by welding had no significant effect on the cooling rate decrease in the HAZ. At a known HAZ width, the heat input in the material Q_w can be assessed from the equation [6]:

$$\frac{1}{T_{\max} - T_0} = \frac{4.13 \cdot \rho \cdot c_p \cdot d \cdot Y_{HAZ}}{Q_w} + \frac{1}{T_m - T_0} \qquad (1)$$

where $T_{\max}$ is the maximal temperature (°C) at a distance of Y_{HAZ}; T_0 is the room or preheat temperature, $T_0 = T_p$ (°C); T_m is the melting temperature of welded material (°C); ρ is the density of welded material (g/mm³); c_p is the specific heat of welded material (J/g·°C); Y_{HAZ} is the width of heat affected zone (mm); d is the thickness of welded material (mm); and Q_w is the heat input (J/mm). If put into the equation (1): $T_{\max} = A_{C1} \approx 725$ °C [4, 5], $T_0 = 20$ °C, $T_m = 1\,510$ °C, $\rho = 7{,}84 \cdot 10^{-3}$ g/mm³ [5], $c_p = 0{,}46$ J/g·°C [5], $d = 13$ mm and width of the heat affected zone (measured from the Figure 2c) for the initial stage ($Y_{HAZ} = 3{,}0$ mm) and for the final stage ($Y_{HAZ} = 7{,}3$ mm) the results are: $Q_w = 774$ J/mm for initial welding stage and $Q_w = 1\,840$ J/mm for the final welding stage (we assumed that this is the final point of two opposite half of circle welds). From the equation for transition thickness d_{tr} (mm) [7]:

$$d_{tr} = \sqrt{\frac{Q_w}{2 \cdot c_p \cdot \rho} \cdot \left(\frac{1}{500 - T_0} + \frac{1}{800 - T_0} \right)} \qquad (2)$$

is got: $d_{tr} = 19$ mm ($d_{tr} > d_{pipe}$) for lower heat input $Q_w = 774$ J/mm. So a two-dimensional heat flow equation for welding pipe connection to drilling head is appropriate. The cooling time $t_{8/5}$ (s) is calculated by the following equation [7]:

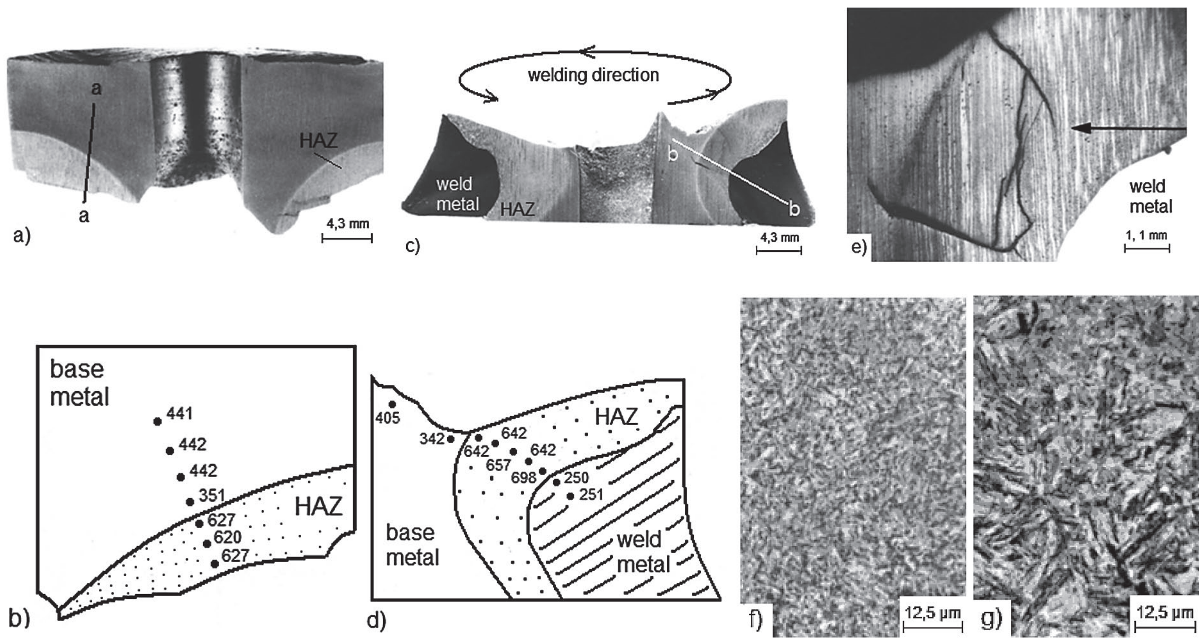

Figure 2 Metallographic characteristics of the pipe connection: (a, c) HAZ macrostructure, (e) secondary cracks in HAZ, (f) microstructure of the pipe connection (tempered martensite), (g) HAZ microstructure (martensite), (b, d) hardness HV10 in the weld area

$$t_{8/5} = \frac{Q_w^2}{4 \cdot \pi \cdot \lambda \cdot \rho \cdot c_p \cdot d^2} \cdot \left[\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{800 - T_0} \right)^2 \right] \quad (3)$$

where λ is the heat conductivity (J/mm·s·°C); for other tags see Eq. (1).

If put into the equation Q_w = 774 J/mm or Q_w = 1 840 J/mm respectively, T_0 = 20 °C and λ = 0,0377 J/mm·s·°C [5], the results are: $t_{8/5} \approx$ 5,5 s for initial welding stage and $t_{8/5}$ > 31,5 s for final welding stage. This means approx. 75 % martensite microstructure according to CCT diagram in [4, 5] also with consideration of the maximum calculated heat input. The above findings clearly indicate that preheating of the pipe connection made of steel 34CrNiMo6 is obligatory; after welding, it should be subjected to slow cooling down or even tempering after welding. The proposed minimal preheating temperature and the inter-pass temperature for steel AISI 4340 (American steel similar to 34CrNiMo6) is T_p = 288 °C [8]. The quenched and tempered steel preheating temperature is defined also by the carbon equivalent C_{ekv} calculation by the following equation [9]:

$$C_{ekv} = C+Mn/6+Cr/5+Mo/4+Ni/15+V/14 \quad (4)$$

where C, Mn, … are alloying elements in steel (wt. %). According to the equation (4) the carbon equivalent of the pipe connection steel 34CrNiMo6 is C_{ekv} = 0,94, which indicates that preheating temperature between T_p = 250 to 350 °C is required [9]. A similar result of minimal preheating temperature is obtained also with Séferian method. The carbon equivalent according to Séferian C_{sef} is calculated by the following equation [10]:

$$C_{sef} = C+[(40\ Mn+40\ Cr+20\ Ni+28\ Mo)/360] \quad (5)$$

where: C, Mn, … are alloying elements in steel (wt. %). The minimal preheating temperature T_p^{min} (°C) based on a known carbon equivalent C_{sef} is calculated by the following equation [10]:

$$T_p^{min} = 350 \cdot \sqrt{C_{sef} \cdot (1 + 0,005 \cdot d) - 0,25} \quad (6)$$

where d is the welded material thickness (mm). Considering the carbon equivalent C_{sef} = 0,7 and a wall thickness of the pipe connection d = 13 mm, the calculated minimal preheating temperature is equal to T_p^{min} = 246 °C.

From the equation (3) at lower heat input Q_w = 774 J/mm it follows: if the preheating temperature is $T_p = T_0$ = 250 °C, the cooling time is equal to $t_{8/5} \approx$ 26 s; if T_p = 350 °C, the time is equal to $t_{8/5} \approx$ 82 s. At higher heat input Q_w = 1 840 J/mm it follows: if the preheating temperature is T_p = 250 °C, the cooling time is $t_{8/5} \approx$ 184 s; if T_p = 350 °C, the time is $t_{8/5} \approx$ 463 s. This means that depending on the selected preheating temperature and selected heat input, 20 % to aproximately 85 % of bainit is expected in the HAZ, which is clearly evident from the CCT diagram [4, 5]. Unfortunately, the mentioned CCT diagram can not be directly used for the HAZ cooling down because of a too low austenization temperature (in the CCT temperature $T\gamma$ = 840 °C; HAZ is heated to T_{HAZ} < 1 510 °C!). Compared to the CCT diagram for heat treatment, in case of HAZ all the fields in CCT diagram (bainite, pearlite and ferrite) is shifted even more to the right [11] which gives a better hardenability and a martensitic microstructure also at longer cooling times $t_{8/5}$. So the fully or mainly martensitic microstructure in the HAZ is normal for welding of the 34CrNiMo6 steel without or too low preheating and without tempering after welding.

CONCLUSIONS

The reason of the horizontal drilling head pipe connection break is inappropriate welding technology. Welding without or too low preheating temperature and without tempering after welding resulted in maximal HAZ hardening. Due to its good hardenability the 34CrNiMo6 steel is poorly weldable so additional precautions must be taken during welding, such as preheating and tempering after welding for example. Based on the theoretical and practical findings, at usable welding technology tempering after welding is necessary for discussing case. Due to dynamic loads of the pipe connection on drilling head the undercuts are inadmissible since due to stress concentration at these places.

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