Failure Analysis of a High Pressure Butt-Weld Flange

F. Ahmed[1], F. Hasan[1] and L. Ali[1]

[1] *Metallurgical and Materials Engineering Department University of Engineering & Technology, Lahore, Pakistan*

Abstract

This paper constitutes the failure analysis of a 24-inch diameter 'Flange' that had been welded to a high-pressure gas transmission pipeline. The flange had ruptured catastrophically during the hydrostatic test that was conducted to testify the integrity of the flange as well as that of the weld joint. The rupture had occurred along the weld through the heat-affected-zone (HAZ) on the flange side. The flange, which was a steel forging (of Class 600 as per ANSI Standards) made from ~ 0.25 % carbon steel, was expected to exhibit good weldability. However, the metallographic examination revealed that the steel had a coarse grain-size and an in-homogenous microstructure wherein pearlite-rich regions, ~2-3 mm across in size, were sporadically distributed in the microstructure. The coarse grain-size coupled with the presence of pearlite-rich patches in the microstructure had locally reduced the weldability of the steel, i.e., increased its tendency towards HAZ cracking during welding.

Keywords: hydrostatic testing; heat-affected-zone; non-homogenous microstructure

1. Introduction

Sui-Northern Gas Pipelines Limited (SNGPL), which is the largest gas company in Pakistan, had purchased large diameter high-pressure butt-weld flanges in the year 2003 from a country, the name of which cannot be disclosed because of the sanctity of inter-country relationship.

These flanges were of class 600 as per ANSI specifications [1]. The flange was welded to the pipeline through multi-pass manual arc welding using low carbon electrodes. The very first of these flanges that was installed on a 24 inch diameter pipeline, ruptured catastrophically during the hydrostatic testing that was mandatorily carried out to testify the integrity of the weld as well as that of the pipeline and the flange after its installation. The failed flange was a 'weld-neck' type flange of 24 inch diameter that had been made by forging followed by machining to the required dimensions. The present paper describes the failure analysis of the flange.

2. Description of Failure

A weld-neck flange of 24 inch diameter which was welded to a high-pressure gas transmission pipeline, failed during the hydrostatic test conducted to verify the integrity of the flange as well as of the weld-joint. The flange was supposed to withstand a hydrostatic test pressure of ~2200 psi (for a design/operating gas pressure of ~1400 psi) as per ANSI class 600 specifications [1]. However, it was reported [2] that the flange had ruptured catastrophically before achieving the required test pressure.

As a consequence of the rupture, the flange had completely separated from the pipeline. The cracking had apparently occurred through the heat-affected-zone (HAZ) on the flange side, as illustrated in Figure 1. Since the weld-joint was left with the pipe, a circular ring containing the weld-joint was cut off the pipeline with the oxy-acetylene torch so that a new flange could be welded to the pipeline at this place. The circular 'ring' containing the entire weld and the ruptured flange were provided to the authors of this paper for detailed failure analysis. Unfortunately, the fracture face on the flange had suffered from physical damage at many locations during transportation, and this may have resulted in a possible loss of useful evidence.

3. Examination of Fracture

A detailed visual examination of the flange showed that the flange had parted along the circumferential weld apparently through the heat-affected-zone (HAZ) on the flange side. A photograph of the flange is given in Figure 2b, while a close-up view of the 'weld' in

Corresponding Author: F. Ahmed (furqanahmad786@gmail.com)

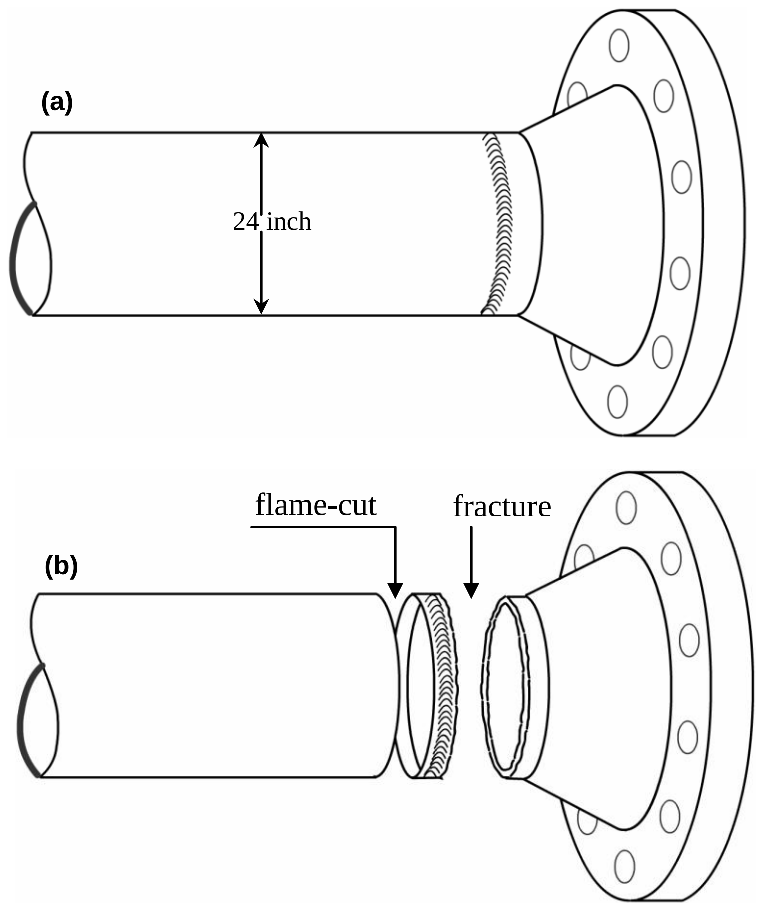

Figure 1: A schematic illustration showing the location of the fracture. It also shows the location at which the weld-joint was cut off the pipeline with the oxy-acetylene torch so that a new flange could be welded to the pipeline at this place.

Figure 2a. The circular ring containing the 'weld' (shown in Figure 2b) had been removed from the main pipe by gas cutting close to the weld.

From the visual examination of the fracture surface on the circular ring, and with the help of the 'chevron' marks, the point where the fracture crack had initiated was identified; a close-up photograph of this region is shown in Figure 3a and a macro-section taken across the weld-line is shown in Figure 3b. It can be seen from these photographs that an approximately 2.7-3 mm deep portion of the crack with an essentially smooth fracture surface was oriented along the 'Vee' of the weldment / flange interface. This crack had all the characteristics of a HAZ crack that may form during the post-weld cooling. Additionally, as indicated by the chevron marks, it was this portion of the crack from which the fracture had initiated. These observations clearly indicated that a crack, which was about 2.5-3 mm deep and about 50-60 mm long, had formed in the HAZ on the flange side during the post-weld cooling. A diagrammatic illustration of the HAZ crack is reproduced in Figure 4. Unfortunately, the fracture face on the flange, corresponding to the location seen in Figure 3a, had suffered from physical damage during transportation, and was of little use to present investigation.

It may be pointed out that the quality of the weld, as evident though its physical inspection, was excellent. No such shortcomings as unhealthy weld-bead or any undercut were observed on either side of the weld. It is relevant to point out that M/s SNGPL has a large team of highly skilled welders, and there is no case on the record in the forty years history of SNGPL in which careless welding may have been identified as a cause of the HAZ failure.

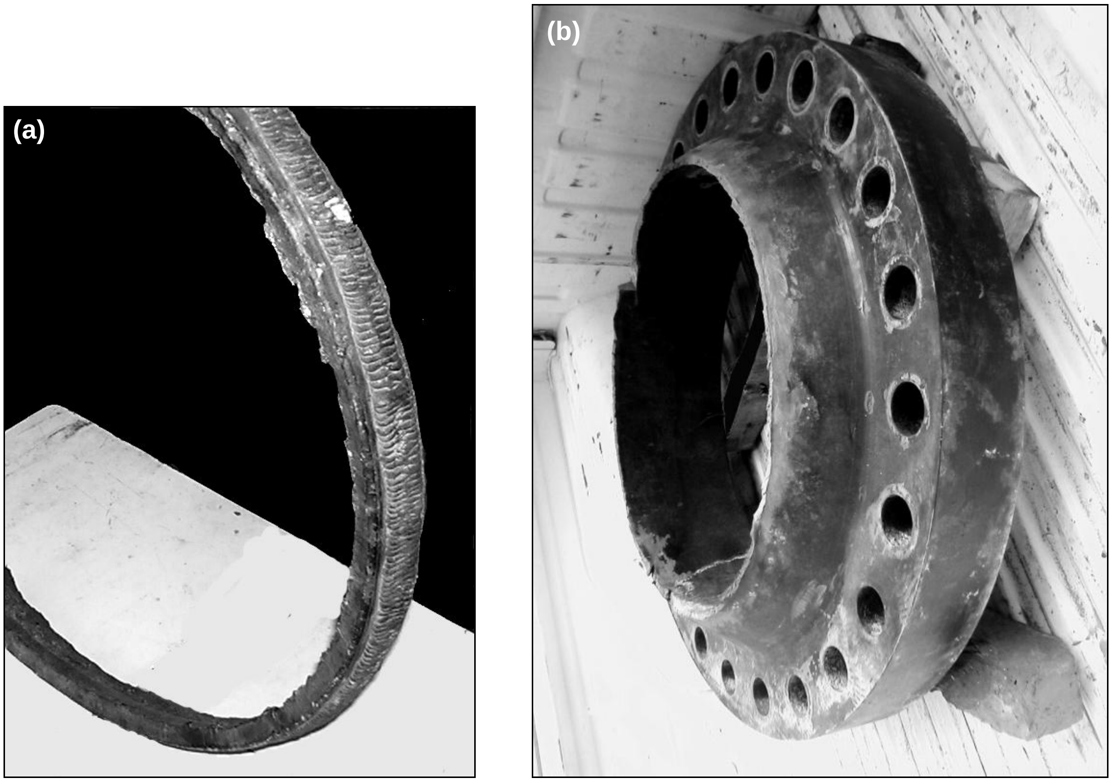

Figure 2: The 24-inch diameter flange that had ruptured during hydrostatic testing (Figure 2b) alongwith a close-up view of the weld region that has been removed from the pipe by gas-cutting (Figure 2a).

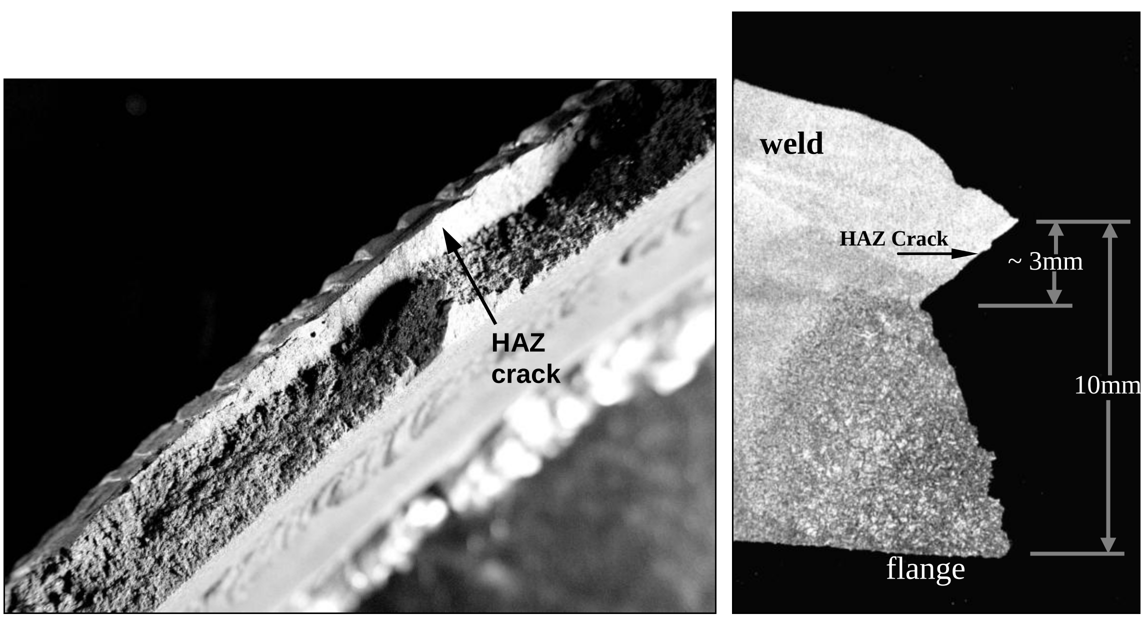

Figure 3: (a) The region of fracture initiation in the HAZ on the flange side of the weld. (b) A macro-section taken across the weld line of the sample shown in (a).

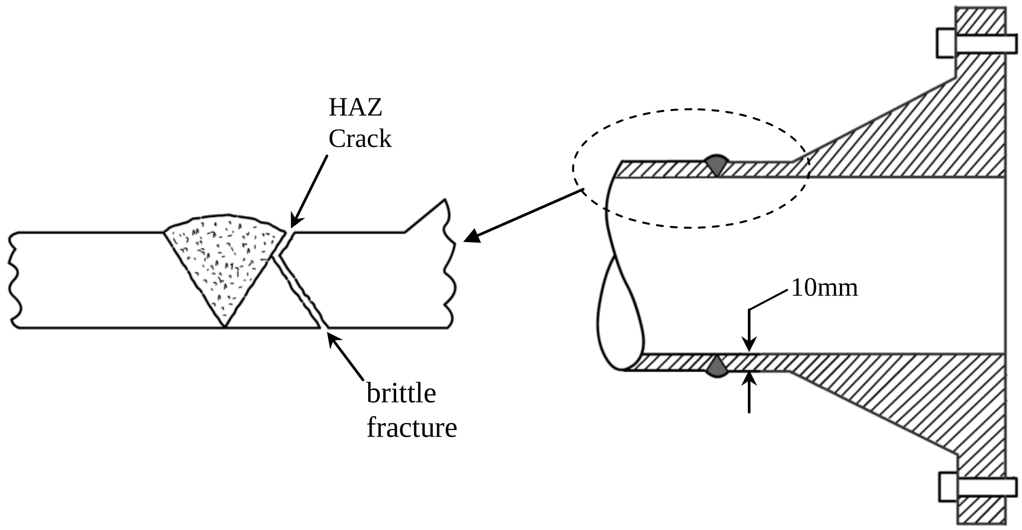

Figure 4: A diagrammatic illustration of the orientation and location of initial crack with respect to the weld.

4. Examination of Flange Material

It was important to note that the fracture had occurred on the flange side of the weld through the HAZ, suggesting the presence of either some brittle micro-constituents or the residual stresses in the HAZ on the flange side. This observation necessitated the need to examine, as a first step, the chemical composition of the flange material. A small piece taken from the flange was tested with an arc-emission-spectrometer for its composition, with the results given in Table 1.

The carbon equivalent of this composition works out to be about 0.42 % calculated with the help of the equation:

$$CE\ (IIW) = C + (Mn)/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

This equation is followed by API 5L [3], MSS [4], and ASME Pressure Vessel and Boiler Code [5].

This value of carbon-equivalent (i.e., 0.42% approx.) was within the specified range allowed by the ANSI standards; the maximum allowable carbon equivalent being 0.47% for the section thickness not exceeding 2 inch and 0.48% for the section thicknesses of more than 2 inch [4]. Specifying the carbon equivalent, is aimed at insuring the use of a steel of good enough weldability that will not develop cracking during welding [6] under the conditions normally encountered in the gas fields or at the transmission pipelines.

Table1: Chemical analysis of steel of the Flange.

Elements	Percentage concentration
Carbon	0.258
Silicon	0.366
Manganese	0.860
Sulfur	0.017
Phosphorus	0.022
Chromium	0.0118
Molybdenum	0.0047
Vanadium	0.0028
Nickel	0.0157
Copper	0.131

It can be argued that the measured carbon equivalent which was close to the top limit of the allowable range could have played a part in embrittling the HAZ through the formation of brittle phases and/or by causing the residual stresses. However, this argument could not stand on its own without a support from some valid microstructural evidence. Hence, the chemical composition (i.e., a high carbon equivalent) could not be taken as a possible cause of the cracking as such.

5. Metallography

In order to explore whether or not any abnormality was present in the structure of the flange steel, a small piece cut from the flange neck was metallographically examined for its macro as well as microstructure. The macroscopic examination did not reveal any such feature (e.g., any in-appropriate grain flow or large non-metallic inclusions) that could be objected against. However, the microscopic examination showed that the microstructure was somewhat inhomogeneous in terms of the distribution of pearlite. A low-magnification view illustrating the microstructural heterogeneity is shown in Figure 5.

Selected micrographs taken from the sample are given in Figure 6. The microstructure shown in Figure 6(a) was the typical microstructure observed at most places in the welding-neck area of the flange. This microstructure which comprised about 25-30% pearlite and 70-75% ferrite, was consistent with an approximately 0.25% carbon steel, i.e., the value of the carbon-content as determine through the chemical analysis given in Table 1. The grain size measured at locations similar to the one shown in Figure 6a, was comparable with ASTM size 3.5.

However, an odd feature observed in the microstructure of the flange was the presence of pearlite-rich ‘patches’ in the microstructure, such as the one shown in Figure 6 (b and c). The microstructure of Figure 6c taken from a pearlite-rich region shows this region to be predominantly composed of the pearlite phase with only about 20-25 % ferrite. The microstructure of Figure 6b which was taken from the edge of a pearlite-rich area illustrates sharp and distinct changes in the level of pearlite-content across the microstructure.

It can also be noted from the microstructure given in Figure 5 that the coarse-grained pearlitic-rich regions were typically 2.5-3 mm across, and were sporadically distributed in the microstructure. It was important to note that these coarse-grained pearlite-rich patches were comparable in size with the depth of the HAZ crack (i.e., ~2.5-3 mm) as can be seen in Figure 3b.

It was noted that other than the coarse grain-size and the presence of pearlite-rich patches, the flange steel (forging) was quite clean with a low inclusion content and was free from any ‘banding’ in the microstructure.

6. Discussion

It is not within the scope of the present work to discuss or comment on the origin of the in-homogeneity, i.e., the presence of pearlite-rich patches that were observed in the microstructure. This effect could have been caused by some micro-segregation of silicon or manganese (and, as a result, also of carbon). On the other hand, the pearlite-rich regions (containing widmanstatten ferrite) could only be the transformation product of large prior-austenite grains that are sometimes observed in as-forged (not normalized) microstructures, especially when the stock had been soaked in the furnace for too long before it was taken out for forging.

Whether the pearlite-rich regions are formed from large prior-austenite grains or by some micro-segregation, such regions would be expected to exhibit a relatively higher hardenability, i.e., the tendency to transform into non-equilibrium phases, during post-weld cooling. As a result, these regions shall be expected to be relatively more sensitive to post-weld cooling

Figure 5: A low magnification panoramic view of the Flange Steel showing a sporadic distribution of large-grained pearlite-rich areas in the microstructure.

rates. Coarse-grained steels are known to exhibit lower toughness in the HAZ [7,8], and thus require careful post-weld cooling for satisfactory results. The effect of initial grain size on weldability has even prompted studies that have lead to a proposed modification of the Carbon-Equivalent equation so as to include an index related to the initial grain-size [9].

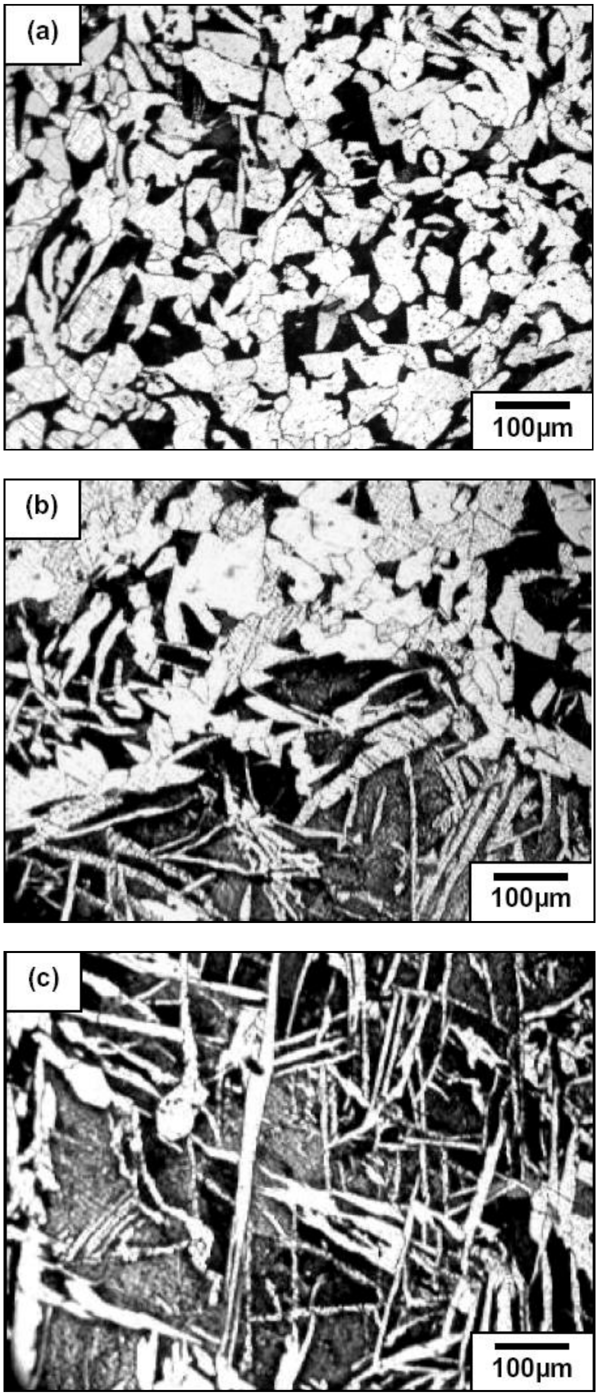

Figure 6. Microstructures taken from a small piece cut from the 'welding-neck' of the flange. Fig 6(a) shows the typical microstructure observed at most places in the welding-neck area of the flange, while Figs 6(b and c) show the presence of large grained pearlite-rich regions in the microstructure.

It may be added that although the steel had a large average grain-size as such (ASTM size 3.5), the grains in the pearlite-rich areas were much bigger than ASTM size 1.

It is clearly reflected from the above discussion that although the chemical composition of the flange steel was in compliance with specified carbon-equivalent, the presence of large-grained pearlite-rich patches had 'locally' reduced the weldability, i.e, sensitivity to HAZ cracking. It is thus logical to believe that HAZ cracking observed on the flange side was caused by the low-weldability of the flange steel, which in turn was related to the presence of coarse-grained pealite-rich areas.

In order to obtain a microstructural evidence for the formation of any non-equilibrium phases in the HAZ on the flange side, samples were taken from the 'weld-ring', seen in Figure 2a. However, only a few patches of 'un-tempered martensite' were observed in the samples examined, while there was plenty of evidence for areas similar to 'tempered martensite'. Typical microstructures taken from the HAZ on the flange side are shown in Figure 7. It must be remembered that the weld-ring from which these samples were taken had been removed from the pipeline by oxy-acetylene flame-cutting after the rupture. The gas-cutting was conducted so close to the weld-line (so as not to reduce the length of the pipe) that the temperature of the weld (ring) could have easily risen to a level so as to 'temper' the HAZ microstructure on both sides of the weld. The observance of very little un-tempered martensite in the HAZ should therefore not be taken as an evidence against the explanation for HAZ cracking as given above.

It must be remembered that (as explained above in Sec. 2 and 3) the fracture face on the flange, corresponding to the location of HAZ cracking (seen in Figure 3) had suffered from physical damage during transportation, and was thus not of any real use to the present investigation. In case this location was available for microstructural examination, it may have been possible to see the HAZ microstructure without the effect of the tempering caused by gas-cutting.

The morphology of the HAZ crack, as seen in Figure 3, is similar to that of hydrogen-assisted cracking, and also to cracks which may form at stress-concentration sites (under-cut) at the weld roots. Whereas it is possible that the stress concentration at the weld root

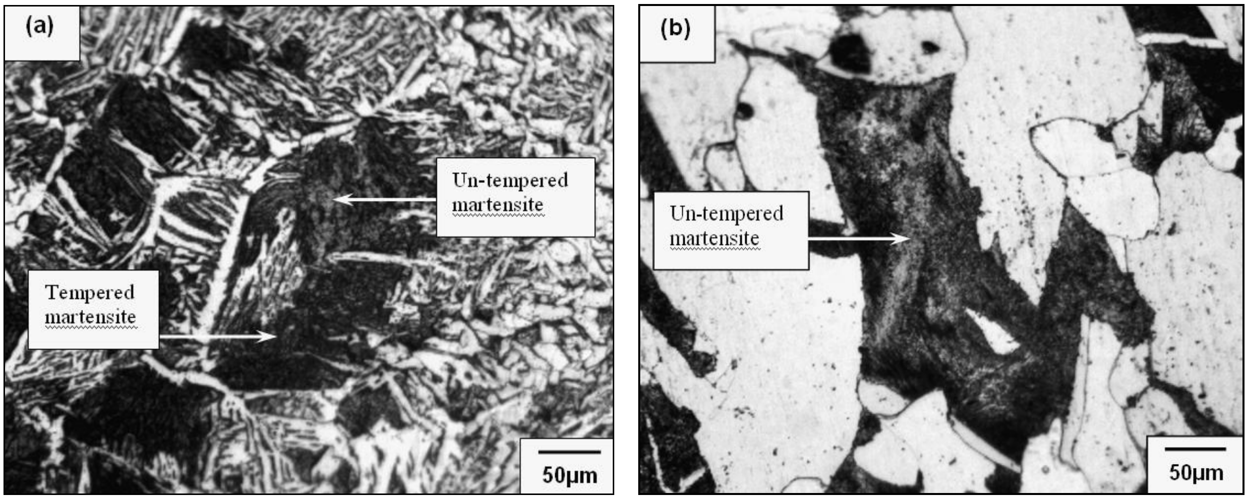

Figure 6: Microstructures taken from a small piece cut from the 'welding-neck' of the flange. Fig 6(a) shows the typical microstructure observed at most places in the welding-neck area of the flange, while Figs 6(b and c) show the presence of large grained pearlite-rich regions in the microstructure.

may have had some part in the initiation of the crack at this location, it is very unlikely that any hydrogen assistance was involved in the present case. In the SNGPL's welding practice, every care is taken to prevent any hydrogen pick up by the welds.

It was thus concluded that it was the poor weldability (caused by coarse grain-size and localized pearlite segregation) of the flange steel that was responsible for the HAZ cracking.

6. Conclusions

The flange which fractured during the hydrostatic testing was made from a steel that was: (a) coarse grained, and (b) contained pearlite-rich regions which were sporadically distributed in the microstructure. These pearlite-rich regions, which were typically about 2.5-3 mm across, had in affect locally reduced the weldability of the flange steel, which became responsible for HAZ cracking during welding.

Acknowledgement

The authors are grateful to SNGPL, Pakistan, especially Mr. Sharaq Ahmad Senior G.M transmission for their valuable guidance and support provided during this investigation.

REFERENCES

[1] ASME/ANSI B 16.5; *Pipe flanges and flanged fittings*, (1996), 1-2.

[2] Private Communication; *Sui-Northern Gas Pipeline (Transmission Division)*, 2004.

[3] API specification 5L; *Specification for line pipe*, 42nd ed, (2000), 8.

[4] MSS Steel Pipeline Flanges; *Manufacturers Standardization Society of the valve and fitting industry*, Inc. 127 Park Street, N.E. Vienna, Virginia 22180, 1996.

[5] ASME Pressure Vessel and Boiler Code. Section II, Part A, Ferrous materials specifications, Materials; *Specification for carbon steel forgings for piping applications*, (1999), 180.

[6] Ito, Y. and Bessyo, K.; *Journal of Japanese Welding Society*, 37(9), (1968) 938-941.

[7] Eroğlu, A., Aksoy M. and Orhan, N.; *Materials Science and Engineering A*, 269(1999) 59-66.

[8] Eroğlu, A. and Aksoy, M.; *Materials Science and Engineering A*, 286(2000) 289-297.

[9] Kasuya, T. and Hashiba, Y.; *Carbon Equivalent to Assess Hardenability of Steel and Prediction of HAZ Hardness Distribution*. Nippon Steel Technical Report, No. 95, January 2007.