Failure Analysis of the Semi-permanent Coupler Used in Metro Rail

M A Morsy1,*, S Khafagy2 and ES Mosa3

1Welding and NDT Dept., CMRDI, Cairo, Egypt
2TIMS, Cairo, Egypt
3Al-Azhar University, Faculty of Engineering, Mining and Petroleum Engineering Dept., Egypt

*Corresponding author

Abstract. Failure analysis of the semi-permanent coupler which failed in service of Metro rail was conducted in order to know the reason for failure. The examinations include visual, photo detection, chemical analysis, hardness measurements, tensile and v-notch impact test, microstructure and SEM observation of fracture surface. Chemical analysis and tensile test shows that the coupler material can be classified as grade B cast steel in AAR M201 steel casting specification. Although the microstructure of the coupler material shows incomplete homogenization indicating the improper conduction of heat treatment, the v-notch impact results is accepted according to this specification. The fracture surface shows the existence of much porosity at the internal surface of the hollow like pipe- coupler and the fracture started at these sites showing beach marks. SEM observation of the fracture surface shows fatigue striations indicating the occurrence of fatigue started at the porosity defects. The cast defects act as a stress concentration site for fatigue crack initiation. Crack occurred, propagated, and connected the defects to each other. The occurrence of collision resulted in bending of the female part of the coupler (plastic deformation occurs) at the lower thin wall (~ 5.41 mm thickness). Moreover, opening of the previously formed fatigue crack and accelerating the failure were occurred. Recommendations were explained to prevent the occurrence of this failure.

Keywords: failure analysis; coupler; chemical analysis; mechanical testing; microstructure; fracture surface; fatigue; porosity; crack

1. Introduction
The automatic coupling Scharfenberg coupler was designed in 1903 [1]. Firstly, it was used in transit trains and later on, it was utilized in passenger service trains. The main advantage of this coupler is the applying of electrical and pneumatic engagement and automatic disengagement. Otherwise, the major disadvantage is its low maximum tonnage, which is unsuitable for cargo operations. This coupler connects two cars together in order to transfer the axial compressive and tensile loads and to damp the received impact by each car through shock absorption that increases the crash worthiness. Any increase in train’s speed causes the acting loads to be augmented. This will lead to reduce the lifetime of the coupler and increase the damage intensity of the coupler [2]. Also, semi permanent coupler now has anti climbing function that reduces the risk of car damage and increase the survival of passengers [3].

Seshu et al [4] changed the design of the rail way coupler of AAR type E in order to avoid the high stress concentration in the knuckle of this coupler. Huang et al [5] discovered that aside from the coarse dendritic cast structure containing porosity, the wrong repair welding procedure may affect on the...
formation of micro-cracks that propagated during service and connected to the cast defects and as a result the knuckle failed.

Figure 1. Semi-permanent coupler before and after fracture.

In Egypt metro train, a fracture was occurred at the train coupler, which resulted in a complete stop of the metro train. Central Metallurgical research and Development Institute was asked to investigate the cause of failure of the coupler.

The received coupler had failed at the female coupler shank (without shock absorption) as shown in Figs.1a to 1f. The aim of this study is to determine the failure causes of the coupler with regarding to the metallurgical and mechanical point of view.
2. Experimental Procedure
The fracture parts of the screw coupler were first subjected to visual examination, photographed by camera, fracture surface was macro-photographed to determine the origins of fracture and the direction of crack growth. Ultrasonic cleaning was conducted to the fracture surface and then observed by Scanning Electron Microscope (SEM). The material was analyzed using optical emission spectrometry. The material was grinded and polished for observation of microstructure by optical microscope after etching with Nital. Tensile testing was conducted using universal testing machine according to ASTM -E8 M. and V-notch impact test was conducted according to ASTM E23-12.

3. Results

3.1. Chemical and Mechanical Testing of Fractured Coupler Material
Table 1 explains the chemical analysis of the coupler material. Chemical composition shows that the coupler material meet the requirement of AAR-M201 steel casting specification Grade B cast steel [12].

Table 1. Chemical analysis of the coupler material, wt%.

| C    | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Al  | Bal. |
|------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0.26 | 0.48| 1.29| 0.019| 0.02| 0.11| 0.017| 0.06| 0.016| Fe    |

3.2. Microstructure of the Coupler Material
Figure 2 shows the microstructure of the coupler material. It is ferrite and perlite structure in the cast form. The formation of pearlite at the austenite grainboundary, Fig. 2 indicating that the normalizing process does not conduct properly. It is decided that the microstructure of tempered martensite has a high fatigue resistance than normal ferrite-pearlite structure [8, 9, 11]. Also, the grain refinement structure has a high resistance to fatigue failure [8, 9].

3.3 Mechanical Properties of the Coupler Material
Mechanical properties were determined from the reminder part of the coupler with a thickness of 9.5 mm and the test result is shown in Table 2 and 3. The mechanical properties fulfill the requirement of AAR-M201 steel casting grade B.

Table 2. Tensile test properties and hardness of the coupler material.

| Specimen number | Average ultimate tensile strength, Mpa | Average Yield Strength, Mpa | Average Elongation percentage, % | Average hardness, HV |
|-----------------|----------------------------------------|-----------------------------|----------------------------------|---------------------|
| 36              | 537                                    | 382.7                       | 28                               | 170                 |

Table 3. V-notch impact test results of coupler material

| Specimen number | A, J | B, J | C, J | Average, J |
|-----------------|------|------|------|-------------|
| 36              | 36   | 38   | 34   | 36          |

Figure 2. Microstructure of the link material (ferrite-pearlite structure).
3.4. Fracture Surface of Coupler

Figure 3 shows the fracture surface of the coupler (the coupler like a tube and this figure represent the part that has the origin of cracks). The existence of surface porosity which is a cast defect may acts as a stress concentration sits for initiation of fatigue cracks [3-8]. Beach marks were observed at the initiation sites as shown in Fig. 3.

![Internal surface porosity](image)

**Figure 3.** Crack initiation site showing the existence of internal surface porosities at the same line.

![SEM observation](image)

(a) Low magnification and (b) High magnification.

**Figure 4.** SEM observation showing the fatigue striations of the fracture surface at the starting point of crack.

Figure 4 shows the SEM observation at the initiation site of fracture surface shown in Figs. 1f and 3. Fatigue striations was observed that indicating the fatigue failure mechanism (see Figs. 4 a & b).
Figure 5. SEM observation of the crack propagation zone.

Figure 5 shows the SEM observation of crack propagation zone where the secondary cracks were observed. The cast defects act as a stress concentration site for fatigue crack initiation [4-7]. The fatigue cracks start at the cast defects as shown in Fig. 3. Crack occurs and propagates, and connects the defect to other defects [5, 6]. The occurrence of collision resulted in bending of the female part (plastic deformation occurs) of the coupler at the lower thin wall (~ 5.41 mm thickness) as shown in Fig. 1e. Moreover, this also causes opening of the previously formed fatigue crack and accelerating the propagation and termination of the fatigue failure as shown in Figs. 1 and 3.

Checking for the existence of internal porosity in the other new couplers resulted in the observation of much internal porosity in many couplers that may affect on the occurrence of fatigue and a decrease in the fatigue resistance of the coupler.

4. Concluding Remark and Recommendation

From the foregoing results of internal surface finish of the coupler (very rough surface finish with the existence of many surface porosities), the improper homogenization of microstructure as a result improper heat treatment and the abrupt change in the velocity of metro train; all contribute to the occurrence of fatigue failure of coupler. The following recommendation should be applied:

1. The coupler standard concerning the material specification, heat treatment processes, mechanical properties, dimension, surface finish, and inspection criteria should be applied before, during and after manufacture of the coupler.
2. Regular check for the existence of fatigue cracks is important to prevent the catastrophic failure of the coupler.
3. The existence of internal or external surface porosity has a great adversely affect on the fatigue resistance.

References

[1] Arthurton R.I.D., “Automatic couplers for railway Rolling Stock and Continuous Braking of Freight Trains”, Proceeding of the Institution on Mechanical Engineers, Vol. 156,1: pp74-78, Frist published Jun 1, 1947.

[2] http://voith.com/corp-en/connection-components-couplings/railway-couplers.html

[3] Daunys P., Putnaite D. Stress strain analysis for railway carriage automatic coupler SA3. Mechanika 2004; 2:46.

[4] Chunduru S. P., Kim M. J., Mirman C., failure analysis of rail road couplers of AAR type E, “Engineering failure analysis journal, 18 (2011) 374-385.

[5] Huanhang J., Xia L., Zhang Y. and Li S., “Investigation on brittle fracture mechanism of a grade E cast steel knuckle” Case studies in Engineering failure analysis journal 2(2014)15- 24.

[6] Hertzberg RW. Deformation and fracture mechanics of engineering materials. John Wiley & Sons; 1996.
[7] Brooks CR., Choudhury A. Metallurgical failure analysis. New York: McGraw Hill; 1993.
[8] Fatigue and microstructure, in proceeding of the ASM Materials Science Seminar, American Society of Metals, 1979.
[9] ASM Handbook Volume 1 Properties and selection: Iron, steels, and High performance alloys ASM Handbook Committee, Fatigue Resistance of Steels, 1990 P673-688.
[10] Mousa S.M., Noughabib V., Dehghania K., Pouranvaric M., “Failure analysis of automatic coupler SA-3 in railway carriages”. Engineering Failure Analysis Journal 14 (2007) 903–912
[11] ASM Handbook Volume 11 Failure Analysis and Prevention ASM Handbook Committee, Failure related to casting, (1990) 242-255.
[12] AAR_M201 Steel Casting Specification Grade B cast steel for coupler and freight car draft components (2012).