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FAILURE ANALYSIS OF PRESTRESSED CONCRETE STEEL BAR DURING THE INITIAL DRAWING PROCESS

ANALISIS KEGAGALAN PADA TULANGAN BAJA BETON PRATEGANG PADA PROSES PENARIKAN AWAL

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ABSTRACT

Reinforced concrete is a common structural material used in the modern era. High tension steel provides strength to the concrete structure to reduce internal tensile forces and eliminate cracking. Failure of reinforcing steel causes the reinforced concrete to not have optimal strength and has the potential to cause failure in the main structure. The present paper describes the investigation of the failure case in the prestressed concrete bar (PC bar) during the manufacture of prestressed or pre-tensioned concrete. The failure occurred in the head section area during the initial drawing process. The chemical composition and tensile test showed the raw material complied to the manufacturer's specification. The fractography and microscopic examination of the failure area showed the characteristics of brittle fracture. Stress concentration in the head section and the tempering process of PC bar after quenching process at an inappropriate temperature caused temper embrittlement to be the cause of failure during the initial drawing process.

Keywords: failure analysis, prestressed concrete, PC bar, tempering, temper embrittlement

ABSTRAK

Beton bertulang adalah struktur material yang umum digunakan pada konstruksi era modern. Baja berkekuatan tinggi memberikan kekuatan pada struktur beton bertulang untuk mengurangi atau menghilangkan beban tarik internal dan menghilangkan adanya retak. Kegagalan pada baja penguat dapat menyebabkan struktur beton tidak mempunyai kekuatan yang optimal dan berpotensi menyebabkan kegagalan pada struktur utama. Artikel ini menjelaskan investigasi yang dilakukan pada kasus kegagalan yang terjadi pada baja penguat beton bertulang pra-tekan atau yang biasa disebut PC bar saat pemberian tegangan awal pada proses manufaktur. Kegagalan terjadi pada area kepala pada saat proses penarikan awal. Komposisi kimia dan hasil uji tarik menunjukkan bahwa baja yang digunakan telah sesuai dengan spesifikasi manufaktur. Uji fraktografi dan uji mikroskopis pada area yang mengalami kegagalan menunjukkan karakteristik patah getas. Dari analisa yang dilakukan, adanya konsentrasi tegangan pada area kepala atau head section dan proses tempering yang dilakukan setelah proses quenching pada temperatur yang tidak tepat menyebabkan terjadinya "temper embrittlement" menjadi penyebab terjadinya kegagalan pada penarikan awal PC bar saat proses manufaktur.

Kata kunci: *analisis kegagalan, prestressed concrete, PC bar, tempering, temper embrittlement*

INTRODUCTION

Reinforced concrete is widely used in structural materials in the modern era because the tensile strength of concrete without steel bar reinforcement is low. Prestressed or pre-tensioned concrete is a type of reinforced concrete. Prestressing is the process of presenting an initial compression load to the concrete to lower internal tensile forces and decrease or eradicate cracking. High tension steel in the shapes of wires, strands, and high strength bars is used to provide high tension in the concrete [1, 2]. Strands are the most common form of prestressed reinforcement and high strength rods are used for segmented structures because it can

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efficiently bond short parts [3]. Prestressing steel bar is initially tensioned between the fixed cantilever and anchored then the concrete is cast around and cured. High tension steel wire is released from the anchor after the concrete has reached its required strength. Illustrates in Figure 1.

The prestressed concrete bar (PC bar) needs to be capable to withstand high initial stress, typically between 1000 and 1900 N/mm^2 tensile strength [4]. PC bar raw material used in this investigation, comply to JIS G 3137 "Small diameter steel bars for prestressed concrete" have minimum tensile strength 1275 N/mm^2 and 5% elongation [5]. The PC bar raw material needs to be heat treated to increase tensile strength as per Indonesian Standard SNI 7701:2011 minimum 1420 N/mm^2.

Short PC bar uses high strength in bar form because it is more efficient compared to wire or strand form. Steel bar has lower strength compared to the wire or strands, but it has enough used in short span prestressed concrete [1].

According to the manufacturer, PC bar investigated in this journal was made from medium carbon steel processed by quenching and tempering at 430 ^oC. Quenched steel caused the presence of martensite phase, while increasing ultimate tensile strength, causing the material to be brittle. This brittle material caused by quenching can improve its properties by tempering [6]. The temperature in the tempering process is the most sensitive parameter. If it is too low the steel still brittle and if it is too high the strength will decrease significantly [7].

In the head section area, the bulging part is made by cold heading. The cold heading process is defined as a forming process that is accomplished sans the use of an additional thermal source [8].

The potential failure in this process is the appearance of cracks or microcracks [9]. The presence of cracks or microcracks can cause the PC bar to break during the making process so that the pretension given is not optimal and produces concrete that does not meet specifications.

This paper reports the investigation of the failure of PC bar during the initial drawing process. By understanding the root cause, the similar failure would not occur. Figure 2 shows the failure located in the head section area.

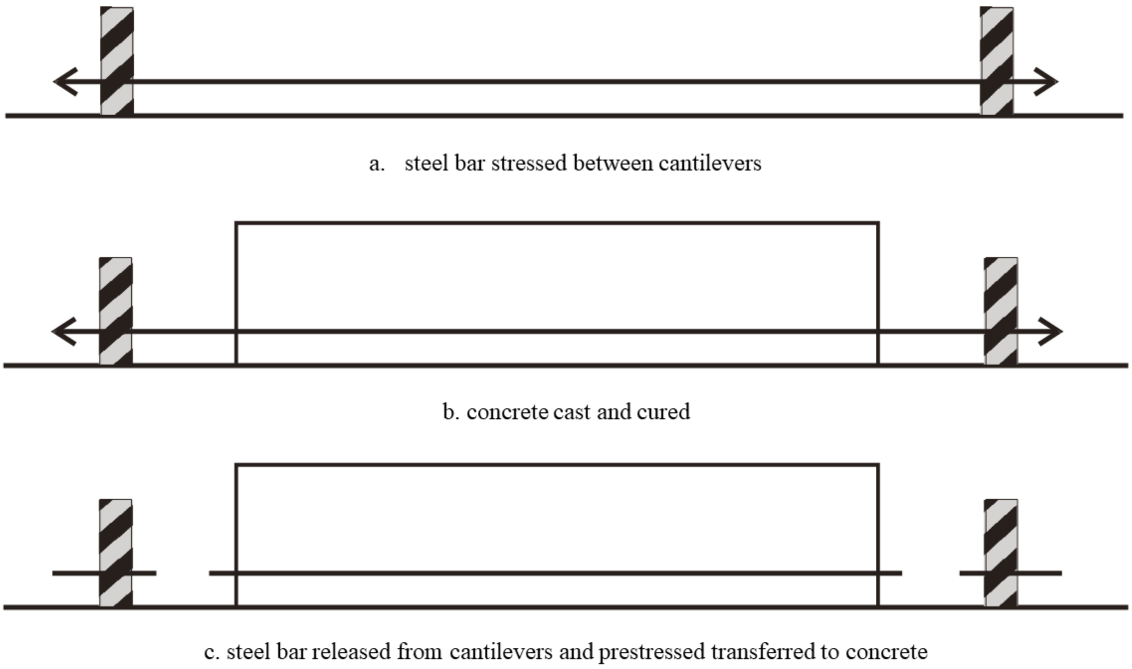

Figure 1. Pretension Procedure

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Figure 2. Failure Location

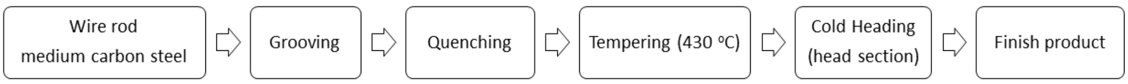

Figure 3. PC Bar Production Process

MATERIAL AND METHODS

PC bar raw materials chemical composition as per JIS G3137 "Small diameter steel bars for prestressed concrete" in weight percent maximum of 0.030% P, 0.035% S, and 0.30% Cu with specifications used for steel wire quenching or tempering. Based on information from the manufacturer, Figure 3 shows the manufacturing process.

Material verification, fractography analysis, and microstructure analysis need to be done to determine the cause of failure. The verification method used is by testing the chemical composition using OES (Optical Emission Spectroscopy) Ametek model LAB LAVM10 and tensile test Zwick Roell type Z250 strain rate and load as per JIS Z2241:2011 "metallic materials – tensile testing – method of test at room temperature" to ensure that the material used is complied the specification from the manufacturer. Fractography analysis using light microscopy Olympus Type BX53M to determine the fracture sequence to detect any macroscopic features relevant to fracture initiation or propagation, and to see the fracture pattern [10]. Microstructure analysis was done by using Scanning Electron Microscope (SEM) JEOL type JSM-7610F to determine failure patterns that occur on a micro scale.

RESULT AND DISCUSSION

Failure analysis on PC bar can be done by analyzing its chemical composition. The chemical composition needs to be verified to determine whether the raw materials conform to the specifications. If the chemical composition already conforms, the other cause of failure is the heat treatment process. PC bar raw material needs to be heat-treated to increase the tensile strength.

The chemical composition examination using OES are expressed as weight percent 0.011% P, 0.007% S, 0.026% Cu, 0.305% C, 1.630% Si, 0.741% Mn, and 0.016% Cr. This material has an alloying element of silicon that can improve flowability during the cold heating process [11]. The material's tensile strength is 1567 N/mm^2, which means the PC bar comply with JIS G 3137.

The fracture that occurs as shown in Figure 4 shows almost no change in dimensions in the fault area. This indicates a sudden brittle failure without allowing the steel to go through the plastic deformation and elongation stage [12, 13]. Figure 5 shows a relatively small radius in the head area that can lead to stress concentrations that can contribute to brittle fracture. Unlike a ductile fracture, a brittle fracture is a condition in which the material has low toughness. The ability to absorb energy due to external forces should be indicated by the occurrence of plastic deformation but does not occur in brittle fractures.

The cross section of the fractured area (Figure 6) shows that the darker area indicates microstructure changes. Microstructure analysis needs to be focused on this area (Figure 7). Area A is the notch area, there is no indication of decarburization at the surface which means a crack does not appear before the failure. Area B located in the failure area shows the grain finer than A and C. The grain movement pattern (flowline pattern) tends to move sideways looking for space or areas that make it easier to move, causing the middle area to have finer grains [10] and confirmed with SEM (Scanning Electron Microscope). Figure 8 indicates that the fracture that occurs is an intergranular brittle fracture.

Quench steels containing manganese (Mn), silicone (Si), nickel (Ni), or chromium (Cr) alloys are susceptible to temper embrittlement. These alloying elements will encourage impurities in the form of phosphorus (P), antimony (As), tin (Sn), or arsenic (Sb) to appear on the surface between grains as segregation [14]. Brittleness easily occurs in steel after being heated or tempered in the range of 370 ^{o}C – 575 ^{o}C and occurs very quickly in the range of 450 ^{o}C – 475 ^{o}C [15].

Based on the chemical composition of the tested PC bar, the main alloying elements are silicon (Si) and manganese (Mn). The weight percent of these two elements is above 0.5%, it is enough and meets the requirements to push impurities to the surface [15]. Meanwhile, the tempering temperature used during the PC bar manufacturing process is 430 ^{o}C. This temperature is included in the forbidden temperature range [15].

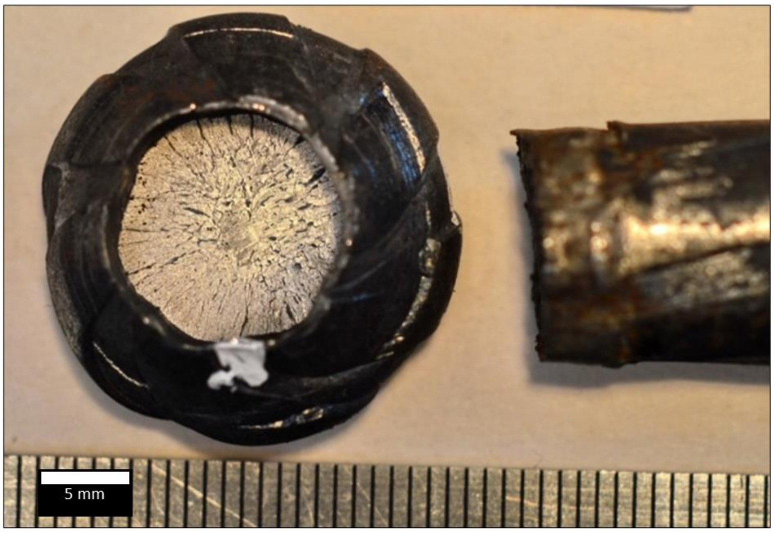

Figure 5. Cross Section of the Fractured Area

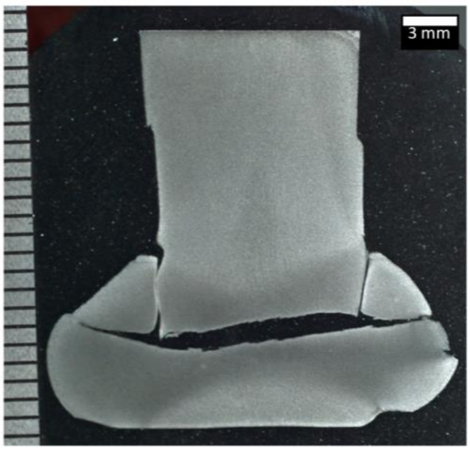

Figure 4. Fractured PC Bar at the Head Area

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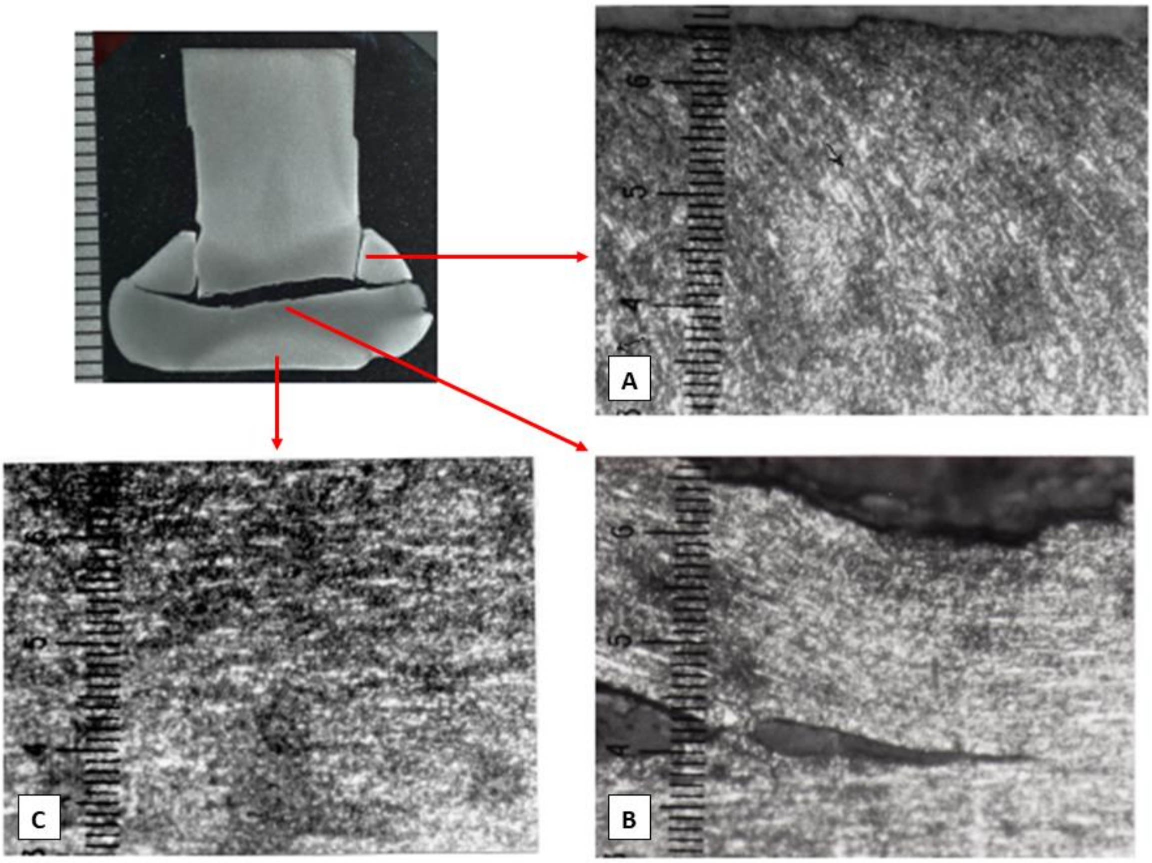

Figure 6. Macrostructure of the Head Section Failure Area

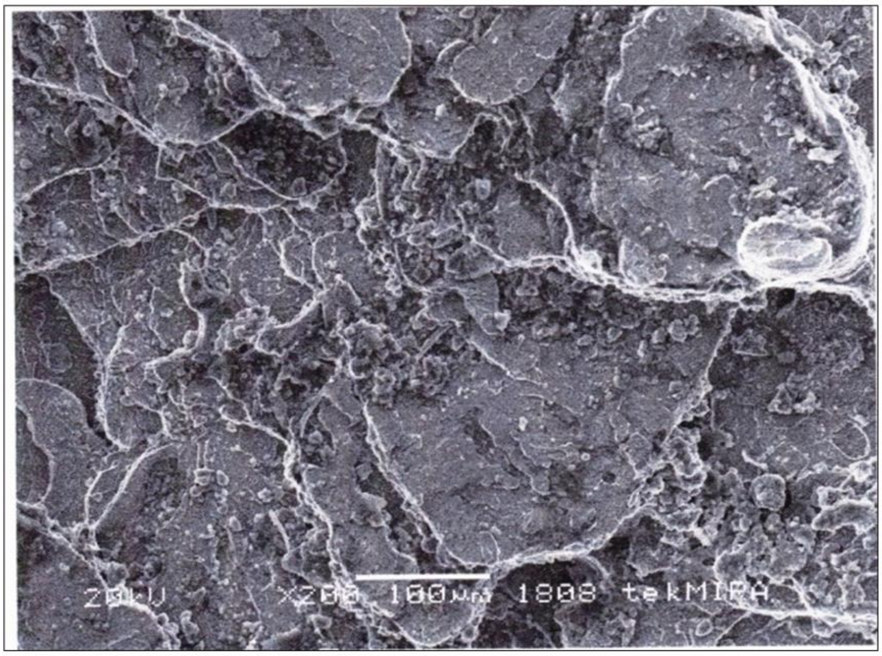

Figure 7. Microstructure of the Failure Surface Area

CONCLUSION

Failure of the PC bar material during the prestressed concrete manufacturing process that occurred during the pretension process in the head section area showed a brittle fracture. This brittle fracture was caused by the tempering process conducted at an inappropriate temperature, causing temper embrittlement. The bulging part in the PC bar head section area becomes an area with the highest stress concentration so the brittle fracture occurs in that area. To avoid the occurrence of similar types of failures, the tempering process at an inappropriate temperature 370 ^{o}C - 575 ^{o}C should be avoided.

REFERENCES

[1] C. W. Dolan and H. R. Hamilton, *Prestressed Concrete*. Springer International Publishing, 2019. doi: 10. 1007/978-3-319-97882-6.

[2] X. Li, J. Zhang, B. Liu, H. Jiang, and X. Min, “Bond stress distribution analysis between non-prestressed steel strand and concrete in novel beam-to-column connection,” *Eng. Struct.*, vol. 242, p. 112523, Sep. 2021, doi: 10.1016/ j.engstruct.2021.112523.

[3] H. Wang, G. Gan, K. Zeng, K. Chen, and X. Yu, “Study on Flexural Performance of Prestressed Concrete Steel Strand Square Piles with Reinforcement,” *Buildings*, vol. 12, no. 11, p. 1801, Oct. 2022, doi: 10.3390/buildings12111801.

[4] R. Gilbert and N. Mickleborough, *The Design of Prestressed Concrete*. Taylor & Francis, 1990.

[5] “JIS G 3137:2020. Small diameter steel bars for prestressed concrete,” Japanese Industrial Standard Committe, 2020.

[6] R. E. Smallman and R. J. Bishop, “Strengthening and toughening,” in *Modern Physical Metallurgy and Materials Engineering*, Elsevier, 1999, pp. 259–296. doi: 10.1016 /B978-075064564-5/50008-2.

[7] M. A. Gebril, M. S. Aldlemey, and A. F. Kablan, “Effect of Tempering on Mechanical Properties and Corrosion Rate of Medium and High Carbon Steel,” *Adv. Mater. Res.*, vol. 685, pp. 81–85, Apr. 2013, doi: 10.4028 /www.scientific.net/ AMR.685.81.

[8] S.-J. Yoo, D.-L. Lee, and D.-T. Chung, “Prediction of cold heading quality with high strain rate compression tester,” *Wire J. Int.*, vol. 30, no. 9, pp. 84–89, 1997.

[9] T. A., K. F., B. V., Z. M., and F. B., “Holistic crack prediction in cold forging processes through a temporal and phenomenological distinguishing crack criterion,” in *Special Edition: 10th International Conference on Technology of Plasticity, ICTP 2011*, 2011, pp. 929 – 934. [Online]. Available: https://www. scopus.com/inw ard/record.uri?eid=2-s2.0-84898063031&partnerID=40&md5=52dd9 cf795c58fc380279602110f3717

[10] “Visual Examination and Light Microscopy,” in *Fractography*, ASM International, 1987, pp. 91–165. doi: 10.31399/asm.hb.v12.a0001834.

[11] I. Özdemir, Ü. Cöcen, and K. Önel, “The effect of forging on the properties of particulate - SiC - reinforced aluminium-alloy composites,” *Compos. Sci. Technol.*, vol. 60, no. 3, pp. 411–419, Feb. 2000, doi: 10.1016/S0266-3538(99)00140-2.

[12] V. Tvergaard and A. Needleman, “Analysis of the cup-cone fracture in a round tensile bar,” *Acta Metall.*, vol. 32, no. 1, pp. 157–169, Jan. 1984, doi: 10.1016/0001-6160(84)90213-X.

[13] A. Sabih and J. A. Nemes, “Internal ductile failure mechanisms in steel cold heading process,” *J. Mater. Process. Technol.*, vol. 209, no. 9, pp. 4292–4311, May 2009, doi: 10.1016/ J.JMATPROTEC.2008.11.023

[14] V. V Zabil’skii, “Temper embrittlement of structural alloy steels (review),” *Met. Sci. Heat Treat.*, vol. 29, no. 1, pp. 32–42, 1987, doi: 10.1007/BF0073 5489.

[15] S. Mackenzie, “Overview of the Mechanisms of Failure in Heat Treated Steel Components,” in *Failure Analysis of Heat Treated Steel Components*, ASM International, 2008, pp. 65–66. [Online]. Available: www.asminternational.org