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TECHNICAL ARTICLE

Development of AISI A2 Tool Steel Beater Head for an Impact Crusher in a Sinter Plant

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Abstract Failure analysis of a tool steel (AISI A2) beater head of an impact crusher and development of suitable heat treatment process to improve its performance have been presented. The beater heads were failing prematurely by brittle fracture from its pin-hole locations. The investigation consisted of visual inspection, fractography, chemical analysis, characterization of microstructures using optical and scanning electron microscopes (SEM), EDS analysis, and determination of micro-hardness profile. Microstructural characterization using SEM and EDS analysis revealed significant amount of coarse continuous Cr-carbide networks in the martensite matrix. It increased hardness (64 HRC) as well as heterogeneity of the matrix as depicted by the micro-hardness profile, and decreased the toughness (3 J) since coarse carbide networks are very hard and brittle. The austenitizing temperature as well as tempering temperature of heat treatment was found lower at the manufacturer's end. The new recommended heat treatment resulted in lower amount of discontinuous Cr-carbides along with significant amount of fine precipitates uniformly distributed throughout the matrix which led to an optimum combination of both hardness (59 HRC) and toughness (6.5 J) required for the application. The beater heads manufactured following the recommended heat treatment exhibited better performance (life increased by 4 times) compared to the earlier ones.

Keywords Impact crusher · Hammers · AISI A2 · Tool steel · Carbide network · Brittle fracture · Toughness · Heat treatment

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Introduction

Sinter is used as a raw material in blast furnace for iron making. Sintering is a process of agglomeration of base mix into a porous mass, by incipient fusion. The base-mix materials are prepared by proportionate mixing of iron ore fines, ground flux materials, ground coke breeze, and revert mix, followed by layer wise stacking of the same in the storage yard. The granulation of raw materials for base mix is an important quality factor for sinter. The correct granulation is achieved by crushing in an impact crusher, followed by sieving and mixing different granulations in appropriate ratios. Limestone and dunite, used as fluxes in sinter, are reclaimed by means of a wheel on boom reclaimer and sent to three 150 tph Hammer Mills, called primary crushers from where they are then sent to secondary crushers (Hammer Mills), where they are ground to a size of 3.2 mm. After crushing, these materials are screened and stored in proportioning bins.

The impact crusher is extensively used for crushing the raw materials like limestone, dolomite, and dunite in the bedding and blending plant for sinter preparation. It crushes the raw materials using multiple rotating beater heads (hammers) by impact against the grinding liners fixed on the impact walls of the machine [1]. The beater heads are connected to a rotor shaft with the help of beater arms arranged circumferentially in a zig-zag fashion (Fig. 1). The fineness of the granulated product of the crusher can be altered by adjusting the distance between the rotating hammer heads and the impact walls.

The beater heads of the impact crusher were failing very frequently (within 15 days) under brittle fracture. Gradual wear of the beater head at the striking face is a normal mode of failure while its sudden brittle fracture is a concern. The hammer heads or beater heads in an impact

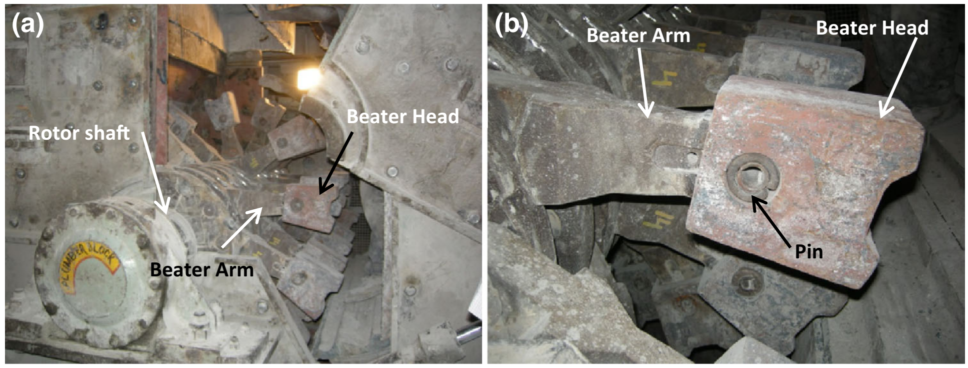

Fig. 1 (**a**) Impact crusher showing rotor shaft-beater head assembly, (**b**) closer view of a beater head

crusher are exposed not only to wear, but also to impact or shock loads. Therefore, toughness of the beater head material is an important factor for extended service life of the hammers apart from its hardness or wear resistance properties [2–6]. A huge number of beater heads had to be replaced every month because of their frequent breakage which led to high maintenance cost and loss in production. Several works on alloy cast irons and tool steels like AISI H11, H13, D2 and M2 are available in the existing literature [2–10] which deals with the microstructural and mechanical characterizations. But work on air hardening tool steel AISI A2 and its application as a beater head material in impact crusher (hammer mill) is rare in the open literature. Further, no industrial or application data on the performance of AISI A2 tool steel as a crushing hammer is available in the existing literature. This work has presented the analysis of root cause for the premature failure of the AISI A2 beater heads and development of suitable heat treatment process to improve their performance.

Experimental Procedure and Results

Site Visit and Visual Observation

The sinter plant has two raw materials bedding and blending (RMBB) units, namely, RMBB#1 and RMBB#2, which have 6 and 7 impact crushers. The impact crushers crush the flux materials used in sintering like lime stone, dolomite, pyroxenite, etc. The primary crushers which rotate at an rpm of around 675 first crush the raw materials from a mesh size of −50 mm into a size of −15 mm. These are then again crushed with the help of secondary crushers having an rpm of around 830 into a size of −3.15 mm. The capacity of a crusher is approximately 125 t/h and it contains 40–52 beater heads.

Figure 1(a) shows a rotor shaft-beater head assembly. Beater heads are attached to the beater arms with the help of pins inserted through the holes present in the beater heads as shown in Fig. 1(b). Figure 2(a) and (b) shows failed beater heads which fractured from their pin-hole locations. The fracture surfaces (Fig. 2c and d) of the failed beater head reveal bright granular appearance suggesting brittle fracture. The other end of the beater head was found to be worn out (Fig. 2a and b) due to abrasion or impact with input flux materials while crushing. While gradual wear of the beater head surface is a desired mode of failure, fracture from the pin-hole locations during service is a concern which must be addressed.

Fractography

A small sample containing fracture surface was cut near the location of pin-hole from where the fracture initiated. The sample was ultrasonically cleaned for examining the fracture surface. The fracture surface was examined using a scanning electron microscope (SEM) (model: JXA6400, JEOL, Japan) operated at an accelerating voltage of 15 kV. Micrographs at various locations of the fracture surface were recorded at various magnifications. Examination of the fracture surface near crack initiation region as shown in Fig. 3 revealed cleavages indicating brittle fracture. Brittle fracture of the beater head suggests its failure under impact load during service.

Materials

A small piece of sample was cut from the failed beater head and prepared for its chemical analysis. Chemical analysis of the sample was carried out using x-ray fluorescence spectroscopy (XRF); carbon (C) and sulfur (S) content of the sample were determined using combustion infrared technique. The chemical analysis of the beater head is compiled in Table 1. The chemical analysis is found to be closer to AISI A2 (ASTM A681) grade of air hardening medium-alloy cold-work tool steel with marginally higher amount of chromium (Cr) and lower

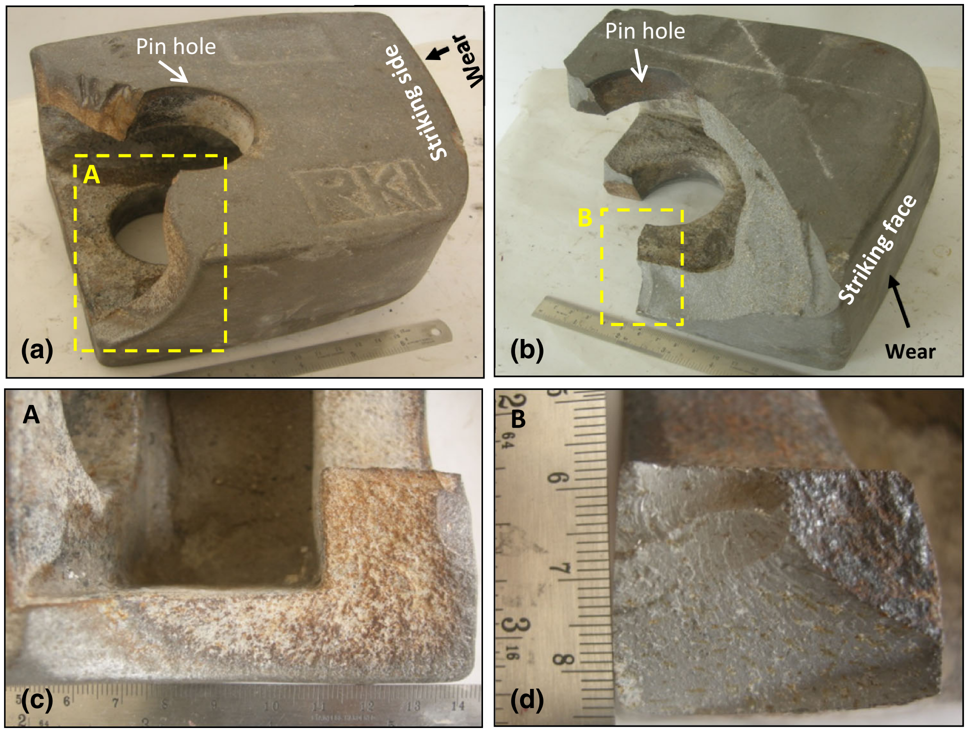

Fig. 2 (**a**, **b**) Beater head samples failed from the pin-hole locations, (**c**, **d**) closer view of fracture surfaces near the pin-hole of the beater heads

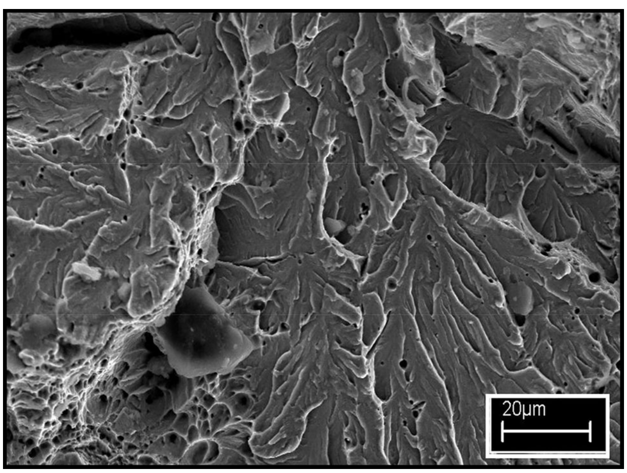

Fig. 3 Fractography (at ×2000) of failed beater head shows cleavages indicating brittle fracture

amount of vanadium (V). Manganese, chromium, and molybdenum are the principal alloying elements in this grade of steel, which impart high hardenability and the steel can be hardened in air. AISI A2 provides an optimum combination of wear resistance and toughness required for crushing operation of raw materials in service. The heat treatment cycle given to the beater head as received from the manufacturer is presented in Fig. 4. The as-cast material was heat treated at 850–870 °C for 1 h/in. followed by air cooling. The air-cooled material was tempered in two stages in the temperature range of 175–200 °C for 3 h/in.

Microstructural Examination

A sample was cut from the failed beater head for microstructural examinations at the cross-section. The sample was then mounted in resin, ground, and polished using standard metallographic technique. The cross-section was examined under optical microscope (Leica, model: DMRX, Germany) after etching using Villela's reagent (1 g picric acid, 5 mL hydrochloric acid, and 100 mL ethanol). Typical micrographs at the cross-section of the broken beater head are shown in Fig. 5(a) and (b). Microstructural examination at the cross-section of the beater head reveals martensite matrix with networks of chain-like massive primary carbides at the grain boundaries (Fig. 5a and b). The carbides appear as bright phases which are preferentially clustered along grain boundary. The area fractions of carbides were measured at various fields using image analysis software. The average area fraction of carbides was found to be 7.2 ± 0.45%.

The most significant material properties required for the beater head component are hardness, toughness, and wear resistance. As the amount of carbides increases, the hardness and wear resistance also increase but care has to be taken in heat treatment to avoid loss of toughness [2, 3, 6, 7]. The clusters of coarse carbides detrimentally affect the toughness; the carbides being brittle are susceptible to initiate cracks during an impact in service [2, 8, 9].

Table 1 Chemical analysis (wt%) of beater head sample

Sample	C	Mn	Si	S	P	Cr	Mo	V	W
Beater head	1.01	0.67	0.50	0.030	0.026	5.7	1.02	0.12	0.010
ASTM A681 type A2	0.95–1.05	0.4–1	0.1–0.5	0.03 max	0.03 max	4.75–5.5	0.9–1.4	0.15–0.5	…

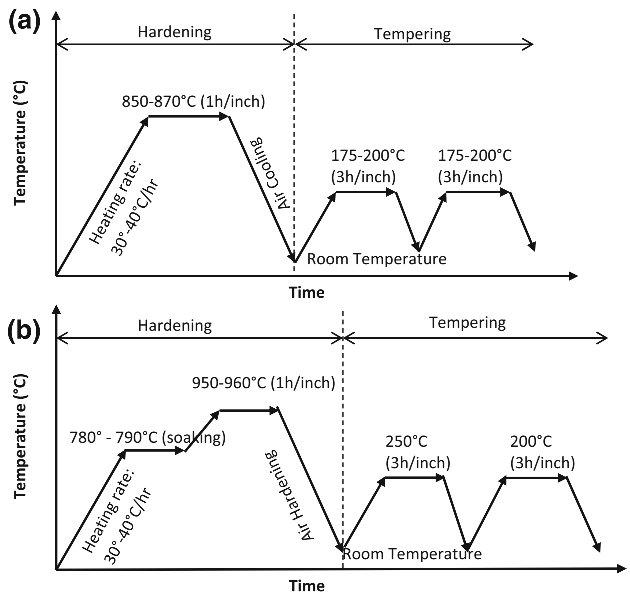

Fig. 4 (**a**) Typical heat treatment schedule given by the manufacturer of beater head, and (**b**) recommended heat treatment cycle of beater head

Scanning Electron Microscopy and EDS Analysis

The etched cross-section of the sample was examined with the help of the scanning electron microscope (SEM) operated at an accelerating voltage of 15 kV for its microstructural as well as elemental characterizations. Micrograph showed coarse carbide network at the grain boundary along with some fine globular precipitates with the martensitic matrix (Fig. 6a and b). Energy dispersive spectroscopy (EDS) of the grain boundary network as well as fine precipitates (as marked in Fig. 6a and b) was carried out for their elemental characterization and the results of the analyses were compiled in Table 2. The results of EDS analysis indicate that the grain boundary network and the fine precipitates within the matrix are chromium carbides. The carbide stoichiometry could not be determined by EDS micro-analysis. But literature survey on similar materials [2, 10, 11] like AISI H11, H13, M2, D2 and so on, and electron probe micro analysis of similar carbides discussed in earlier literature [5, 12–15] suggests the grain boundary carbide network to be of M_7C_3 type (Primary Carbide) and the fine globular precipitates as $M_{23}C_6$ (where M = Cr) type (Secondary Carbide). The skeleton-like morphology of massive carbide network at the grain boundary as shown in Fig. 6(b) is apparently indicative of its eutectic origin (primary carbide), i.e., origin at the solidification stage [2, 5, 8–10, 13]. On the other hand, fine globular precipitates within the matrix indicate secondary carbides which form during heat treatment of the casting [2, 5, 8, 11].

Measurement of Hardness

Both macro- and micro-hardness values were measured at the cross-section of the sample prepared from the failed beater head following the standard ASTM E384. Macro-hardness values were measured in a Vickers hardness testing machine with a load of 30 kgf. Five measurements were taken at random locations of the cross-section to get the average macro-hardness value; the macro-hardness value was found to be 781 ± 12 HV30 (equivalent to ≈64 HRC). The macro-hardness of the AISI A2 tool steel material was higher for its beater head application as higher hardness of the material adversely affect its toughness. Micro-hardness hardness values were measured at a regular interval of 500 μm by a micro-Vickers hardness testing machine with a load of 50 gf and an indentation duration of 15 s; the micro-hardness profile is shown in Fig. 7(a). The hardness values are found to be varied in the range of 600–1000 HV0.05. Apart from hardness profile, micro-hardness values on some grain boundary carbide network were also measured separately. The average micro-hardness of carbide network was measured to 1375 ± 15 HV0.05; the measured micro-hardness value of carbide network is found to be similar to the value (1400 HV) for M_7C_3 type of primary Cr-carbide reported in other existing literature [12, 16].

Measurement of Impact Toughness

The impact tests of the samples were carried out using V-notch Charpy specimens in accordance with IS 1757:1988 [17] with the help of a standard impact testing machine (Striking Energy: 300 ± 10 J) at ambient temperature. At least three tests were carried out to get the average impact energy values of the beater head sample. The average impact energy value of the samples was 3 ± 0.2 J.

Heat Treatment of Beater Head in Laboratory for Improvement

The heat treatment given by the manufacturer of the beater head yielded a microstructure with significant coarse grain

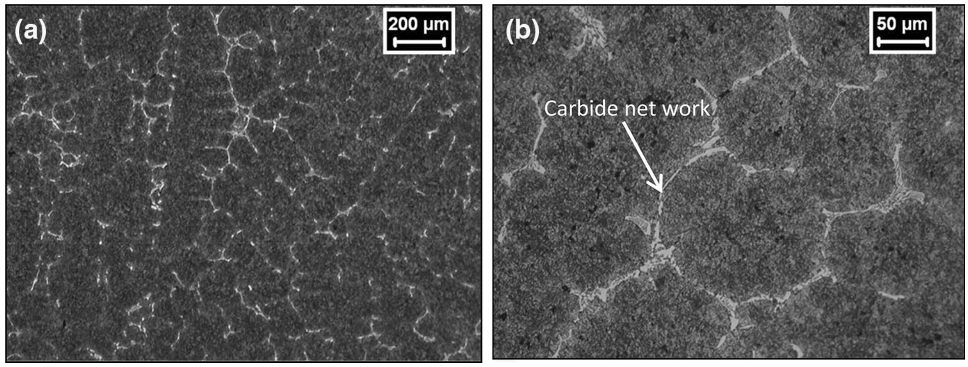

Fig. 5 Microstructures of failed beater head: (**a**) Microstructure (at ×50) shows martensite matrix along with carbide networks at the grain boundaries, and (**b**) microstructure at magnified view (at ×200) shows continuous carbide network at the prior austenite grain boundary

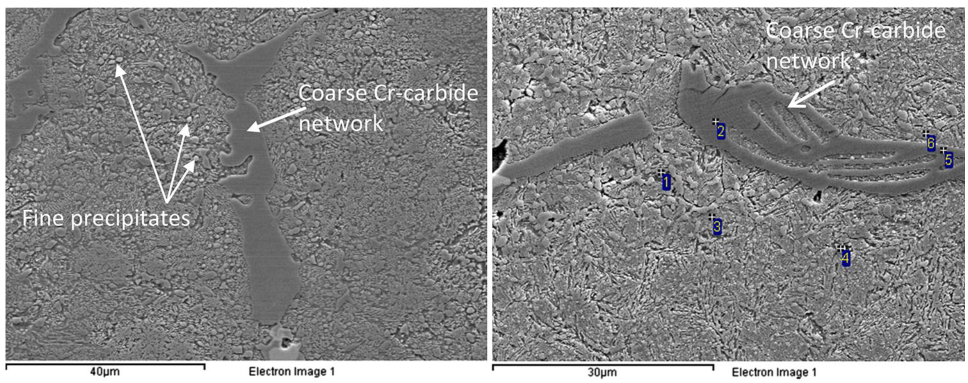

Fig. 6 SEM micrographs at the cross-section of beater head sample: (**a**) micrograph (at ×1000) shows coarse carbide network at the grain boundary along with fine precipitates within martensite matrix, and (**b**) micrograph (at ×1500) shows locations of EDS analysis on the coarse carbide network as well as fine precipitates within the matrix

Table 2 Results of EDS analysis (wt%) at different locations as shown in Fig. 6

Locations	C	Si	Cr	Mn	Fe	Mo	Remarks
1	11.71	0.40	16.68	0.68	64.5	6.03	Secondary carbide
2	19.35	…	40.92	…	30.63	8.71	Primary carbide
3	…	1.00	4.83	0.50	92.71	0.96	Matrix
4	9.64	0.48	12.40	…	73.72	3.76	Secondary carbide
5	17.21	…	31.67	…	45.08	6.03	Primary carbide
6	…	1.05	5.33	…	92.23	1.39	Matrix

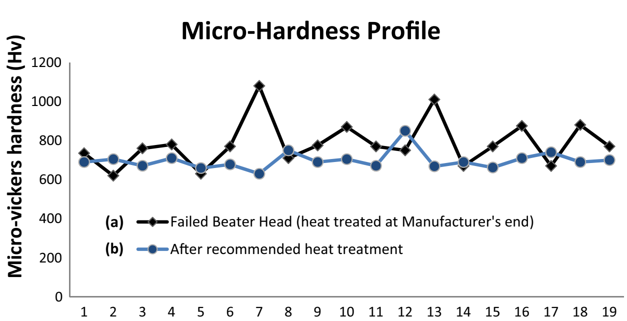

Fig. 7 Micro-hardness profiles measured at the cross-section of the beater heads: (**a**) Failed beater head, and (**b**) after recommended heat treatment

boundary carbide networks. The coarse grain boundary carbide network adversely affects the toughness of the material making it prone to fracture under impact [2, 8]. During present investigation, a suitable heat treatment was given to some as-cast beater head material (supplied by the same manufacturer). The heat treatment was carried out in a controlled-atmosphere furnace. The material was pre-heated to 788 °C and held at this temperature until thoroughly soaked. Then, it was heated to 954 °C and held for 1 h/in. of greatest cross-section. After austenitization, the material was removed from the furnace and cooled in air followed by immediate tempering in two stages at a temperature of 200–250 °C.

Microstructural Characterization After Heat Treatment in Laboratory

A sample was prepared form the beater head block heat treated in the Laboratory for examination of the microstructure following the procedure as described in "Microstructural Examination" section. The optical microstructures are shown in Fig. 8(a) and (b). The microstructures reveal predominantly martensitic matrix with a small amount of primary eutectic carbides at the grain boundary. But these carbides are not in the form of continuous network rather they are discontinuous and present at some discrete locations on the grain boundaries unlike that observed in Fig. 5(a) and (b). Scanning electron microscopy (SEM) as well as EDS analysis of the carbides was carried out to study their morphology and type. SEM and EDS analyses show discontinuous primary Cr-carbides (M_7C_3 type) at the grain boundary and numerous globular fine carbide particles (secondary carbides-$M_{23}C_6$ type) uniformly distributed throughout the matrix as illustrated in Fig. 9 and Table 3.

Mechanical Characterization After Heat Treatment in Laboratory

After carrying out the heat treatment of the as-cast beater head block in the Laboratory, the sample was tested for hardness and impact toughness values following the procedure described in "Measurement of Hardness" and "Measurement of Impact Toughness" sections, respectively. The macro-hardness values were measured to be 670 ± 10 Hv (equivalent to ≈59 HRC). A profile of micro-hardness values measured at the cross-section of the sample is shown in Fig. 7(b). The hardness of the beater head block heat treated in the Laboratory shows lower values (600–750 HV) compared to that (600–1000 HV) heat treated at manufacturer's end. The present hardness values are in agreement with that (≈60 HRC) of a typical AISI A2 tool steel [10, 18]. Further, the measured micro-hardness profile (Fig. 7b) is observed to be relatively smooth or uniform compared to that of earlier one. The impact test of the samples prepared from the heat treated beater head was carried out using V-notch samples. The impact energy value was measured to be 6.5 ± 0.3 J which showed significant improvement (117%) in toughness compared to that of manufacturer's. These differences with respect to hardness profile and impact toughness between the two types of samples (i.e., manufacturer's heat-treated sample and present Laboratory heat-treated sample) are because of the new heat treatment schedule which yields a homogeneous matrix relatively free from coarse continuous network of primary carbides. Coarse continuous network of carbides increases the hardness but it decreases the toughness increasing the tendency to fracture along coarse carbide network under impact load [2, 8].

Discussion

Analyses to find out the root cause of failure of beater heads of an impact crusher have been presented followed by development of the same through proper heat treatment. Both microstructural and mechanical characterization of the failed beater head sample indicated improper heat treatment. Coarse primary carbide networks which are detrimental were formed during casting; during heat treatment fine globular precipitates of secondary carbides which were uniformly distributed throughout the matrix were formed from the coarse continuous carbide network

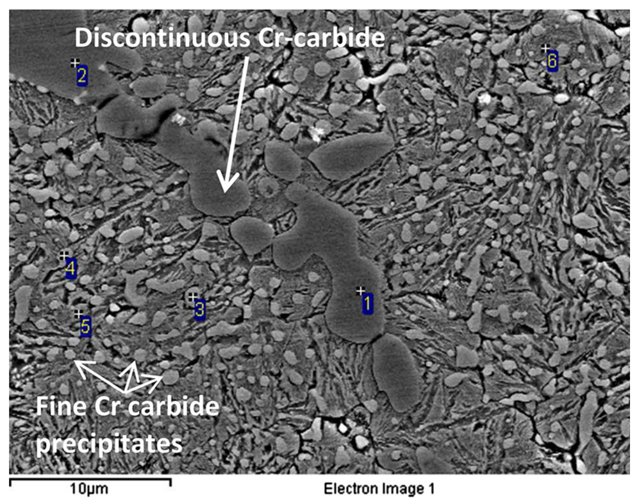

Fig. 9 Discontinuous carbide network (at ×2500) at prior austenite grain boundary along with fine globular Cr-carbide precipitates within the matrix

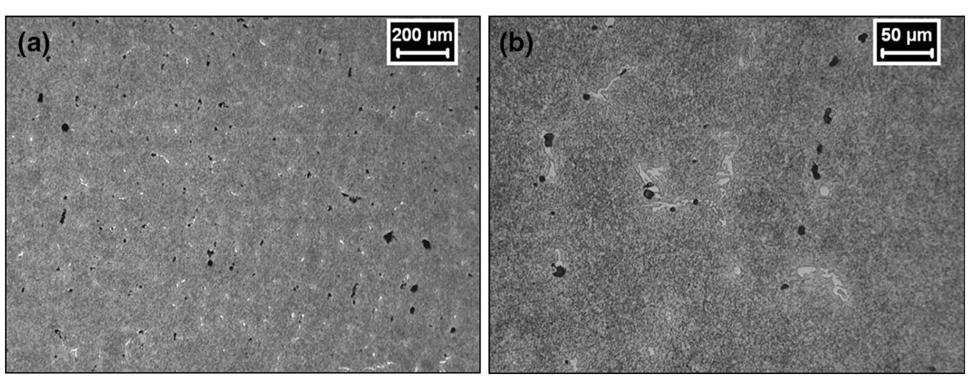

Fig. 8 (**a**) Microstructure (at ×50) of beater head after suggested heat treatment, (**b**) Microstructure (at ×200) shows martensite matrix with discontinuous carbides at discrete locations on the prior austenite grain boundary

Table 3 Results of EDS analysis (wt%) at various locations as shown in Fig. 9

Locations	C	Si	V	Cr	Mn	Fe	Ni	Mo	Remarks
1	10.93	…	0.41	34.81	…	47.08	…	6.77	Primary carbide
2	12.26	…	…	30.57	0.58	44.19	0.13	12.28	Primary carbide
3	8.46	0.30	…	16.79	0.73	67.54	…	6.19	Secondary carbide
4	4.97	0.59	…	9.15	0.70	80.91	…	3.68	Secondary carbide
5	…	0.87	…	4.62	0.57	92.52	…	1.41	Matrix
6	…	0.78	…	5.08	0.52	92.50	…	1.11	Matrix

making them discontinuous or isolated at certain locations apart from reducing their amount [5]. The heat treatment schedule (Fig. 4) given by the manufacturer showed a lower austenitizing temperature during hardening as well as temperature during tempering [2, 18]. Because of lower austenitizing temperature during heat treatment, the massive primary carbides which generated fine secondary carbides afterwards were not fully dissolved in the matrix; this yielded coarse carbide network with a little amount of fine secondary carbide precipitates imparting brittleness or poor toughness to the material [2, 5, 19].

A proper heat treatment schedule as described in "Heat treatment of Beater Head in Laboratory for improvement" section was recommended to the manufacturer to improve the microstructure of beater head; austenitizing temperature was increased to 954 °C after preheating at 788 °C and tempering temperature was increased to 200–250 °C. The new heat treatment ensured significant dissolution of coarse primary carbide network in the matrix followed by precipitation of fine globular secondary carbide particles uniformly distributed throughout the matrix (Figs. 8 and 9). The recommended heat treatment schedule resulted in improved microstructure having an optimum combination of both hardness and toughness. The impact toughness of the material was found to increase from 3 to 6.5 J, i.e., by 117% with a hardness value desired as per the specification of the grade AISI A2. The hardness profile (Fig. 7b) also exhibited a relatively smooth trend compared to the earlier one ensuring a more uniform matrix. The new beater heads manufactured following the recommended heat treatment schedule, in fact, exhibited better performance compared to the earlier ones; the service life improved from 15 days to 2 months, i.e., by 4 times. The mode of failure of the new beater heads also changed from sudden brittle fracture to gradual wear at the striking face, the desired one.

Conclusion

The following conclusions can be drawn from the above analyses:

(1) Visual observation of the fracture surface as well as fractography of the failed AISI A2 tool steel beater head indicated that it failed from the pin-hole location in brittle mode under impact load in service.

(2) Microstructural examination revealed significant amount of coarse grain boundary networks of primary Cr-carbides. Coarse Cr-carbide networks resulted in higher hardness (64 HRC) and lower toughness (3 J) of the tool steel material making it brittle.

(3) Analysis of the heat treatment schedule given to the beater head exhibited that its improper microstructure was a result of lower austenitizing (850–870 °C) as well as tempering (175–200 °C) temperature during heat treatment at manufacturer's end.

(4) The new recommended heat treatment schedule (preheating at 788 °C, austenitizing at 954 °C followed by two stage tempering at 200–500 °C) resulted in small amount of discontinuous carbide networks with significant amount of finely distributed precipitates of secondary carbides within tempered martensite matrix. The improved microstructure yielded an optimum combination of hardness (59 HRC) and toughness (6.5 J) which led to an increase in service life of the beater heads by four times.

References

1. Y. Umucu, V. Deniz, S. Cayirli, A new model for comminution behavior of different coals in an impact crusher. Energy Sources A **36**(13), 1406–1413 (2014)
2. M. Pellizzari, A. Molinari, The application-oriented heat treatment of tool steels. Mater. Manuf. Process. **24**(7–8), 723–728 (2009)
3. B. Smoljan, An analysis of relationships between behavior and microstructure constitution of hot-work tool steel. Mater. Manuf. Process. **24**(7–8), 786–790 (2009)
4. P. Hansson, Modern prehardened tool steels in die-casting applications. Mater. Manuf. Process. **24**, 824–827 (2009)
5. A.E. Karantzalis, A. Lekatou, H. Mavros, Microstructural modifications of as-cast high-chromium white iron by heat treatment. J. Mater. Eng. Perform. **18**, 174–181 (2009)
6. J.O. Agunsoye, V.S. Aigbodion, O.S. Sanni, Effect of heat treatment on microstructure and mechanical properties of NF 6357A cast alloy for wear resistance application. J. Miner. Mater. Charact. Eng. **10**(11), 1077–1086 (2011)

7. C.R. Gagg, Premature failure of thread rolling dies: material selection, hardness criteria and case studies. Eng. Fail. Anal. **8**, 87–105 (2001)
8. M.F. Mirjana, Iron-chromium-carbon-vanadium white cast irons—microstructure and properties. Chem. Ind. **68**(4), 413–427 (2014)
9. G. Mukhopadhyay, S. Bhattacharyya, Cracking of a tool steel guide roller in a Bar Mill. J. Mater. Eng. Perform. **12**, 594–603 (2012)
10. D. Viale, J. Béguinot, F. Chenou, G. Baron, Optimizing microstructure for high toughness cold-work tool steels, in *Proceedings of the 6th International Tooling Conference, Use of Tool Steels: Experience and Research*, ed. by J. Bergstrom, G. Fredriksson, M. Johansson, O. Kotik, F. Thuvander (Karlstad University, Karlstad, 2002)
11. N. Mebarki, P. Lamesle, D. Delagnes, C. Levaillant, F. Delmas, Relationship between microstructure and mechanical properties of a 5%Cr hotwork tool steel, in *Proceedings of the 6th International Tooling Conference, Use of Tool Steels: Experience and Research*, ed. by J. Bergstrom, G. Fredriksson, M. Johansson, O. Kotik, F. Thuvander (Karlstad University, Karlstad, 2002)
12. A. Ray, D. Mukherjee, B. Sarkar, S. Mishra, Influence of microstructure on the premature failure of a second-intermediate sendzimir mill drive roll. J. Mater. Eng. Perform. **3**(5), 649–656 (1994)
13. K.M. Ibrahim, M.M. Ibrahim, Heat treatment in high chromium white cast iron Ti alloy. J. Metall. **2014**, Article ID 856408 (2014). doi:10.1155/2014/856408
14. N.F. Garza-Montes-de-Oca, R. Colás, W.M. Rainforth, On the damage of a work roll grade high speed steel by thermal cycling. Eng. Fail. Anal. **18**, 1576–1583 (2011)
15. M.M. Dhobe, I.K. Chopde, C.L. Gogte, Investigations on surface characteristics of heat treated tool steel after wire electro-discharge machining. Mater. Manuf. Process. **28**(10), 1143–1146 (2013)
16. F.J. Belzunce, A. Ziadi, C. Rodriguez, Structural integrity of hot strip mill rolling rolls. Eng. Fail. Anal. **11**, 789–797 (2004)
17. Bureau of Indian Standards, *Method for Charpy Impact Test (V notch) for Metallic Material*, IS 1757 (Bureau of Indian Standards, New Delhi, 1988)
18. ASTM International, *Standard Specification for Tool Steels Alloy*, ASTM A681-08 (ASTM International, West Conshohocken, 2008)
19. R. Schneider, J. Perko, G. Reithofer, Heat treatment of corrosion resistant tool steels for plastic moulding. Mater. Manuf. Process. **24**, 903–908 (2009)