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The effects of two-phase partial annealing on the impact energy absorption of AR400 steel

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ABSTRACT

This study aimed to evaluate whether the impact resistance of AR400 abrasion-resistant steel, known for its superior tribological properties and wear capabilities, could be enhanced through a two-phased partial annealing heat treatment process while maintaining material hardness and wear resistance. The hypothesis posited that successful heat treatment would improve the wear plate's combined impact and wear resistance, potentially enabling the use of thinner steel materials with comparable wear properties in traditional earth-moving machine wear packages. The study began by establishing the mechanical properties of control specimens through metallurgical analyses for baseline comparison. The Phase 1 heat treatment process involved heating specimens of three different material thicknesses to 1000 °C for 20 minutes, followed by oil quenching, which reduced the martensitic content and fostered a predominantly bainitic phase dispersion. Phase 2 involved heating the specimens to 750 °C for 20 minutes and rapidly quenching them in cool water. SEM analysis confirmed the bainitic dispersion and revealed that Phase 2 partial annealing only marginally influenced the phase dispersions established in Phase 1. The heat treatment significantly enhanced the materials' impact resistance and toughness but reduced hardness and brittleness. Material elongation nearly doubled across all thicknesses, indicating improved ductility, while Impact testing at -40 °C demonstrated substantial increases in impact energy absorption. These findings suggest that while the two-phased partial annealing process holds promise, further refinement is needed to optimise the balance between impact resistance, ductility, tensile strength, and hardness.

Keywords: abrasion-resistant steels, partial annealing, impact energy absorption, earth-moving machines, wear packages.

INTRODUCTION

The performance of abrasion-resistant steels is crucial in the South African mining industry, where equipment is subjected to severe wear and tear due to the harsh operating conditions where ground-engaging tools (GET) and earth-moving machines sustain both heavy-duty wear and impact. The operating conditions, in combination with the typical geological environment, are aggravated by the general byproducts, such as highly abrasive silica dust commonly encountered in South African mining operations [1], and contribute to the accelerated degradation of equipment, leading to higher maintenance costs and reduced operational efficiency. Implementing effective wear-resistant materials and regular maintenance practices is essential to mitigate these challenges and ensure the longevity of mining machinery, to mitigate the effects of wear on earth-moving machines, the mining industry lines the ground-engaging tools and components with wear packages comprised of abrasion-resistant low-carbon alloy plates, covering the surfaces exposed to wear and impact [2]. The selection of appropriate materials for GET and wear packages, such as abrasion-resistant steels, impacts the efficacy and longevity of machinery used in mineral mining; research indicates that the use of high-performance abrasion-resistant steels can significantly reduce maintenance costs and downtime, thereby enhancing overall productivity [3].

However, the poor performance of these steels can have detrimental effects on sustainability and efficacy within the industry. Inefficient abrasion resistance leads to frequent equipment failures, increased maintenance requirements, and higher operational costs [4], while the added weight caused by the addition of a wear package can significantly reduce the component production efficiency and payload [2]. This not only affects the economic viability of mining operations but also poses environmental challenges due to the increased need for material replacements and the associated waste generation [5]; this, in combination with the drive to transition earthmoving machines in South Africa to Hydrogen-Powered implements [6] as such, improving the performance of abrasion-resistant steel is essential for promoting sustainable and efficient mining practices in South Africa [5].

AR400 is quenched and tempered high-carbon alloy steel with a Brinell hardness number (BHN) of 360–444, the high material hardness attributed to the primarily bainitic and martensitic phase dispersion, has improved wear resistivity, which enhances the steel's wear resistance and toughness [7]. The material is widely used as liners to extend the production and service life of chutes, hoppers, dump truck beds, and face shovels and reduce wear and maintenance costs [8] and typically has a material thickness of up to 20 mm [2].

However, although ideal for applications where prolonged exposure to abrasive materials is common, AR400 is not exceptionally effective at absorbing sudden or high-impact forces typically associated with mining operations, as the high material hardness, responsible for the wear resistivity, is also inversely proportional to the material's impact energy absorption properties, leaving the material susceptible to cracking, fracturing or ultimately critically failing under sudden or heavy impact before the maximum wear life of the material or wear package has necessarily been reached [9].

This limitation is particularly evident in applications where components and wear packages are exposed to a combination of high wear and impact loading commonly associated with mining operations, as such, where an AR400 wear package can easily mitigate the effects of the constant abrasion from rock and ore, it may not perform as well when subjected to the impact of large, falling rocks or heavy machinery collisions typically found in loading and off-loading operation in open cast platinum mining [9]. In an attempt to counteract the above-mentioned, wear packages are often combined with more application-specific materials such as chrome carbide overlay (CCO) for the focused wear areas or SQL690 steel for impact absorption; however, this can ultimately become expensive and are still materials-focused on mitigating the effects of either wear or impact [2]. As it is a well-established principle that material toughness and hardness are inversely proportional, the aim of this study is to investigate whether the impact resistivity of an already hardened steel with superior wear resistivity can be improved using partial annealing to improve the impact energy absorption of AR400 while retaining, to an extent, the wear resistivity of the material.

If successful improvement of the impact energy absorption in pre-hardened abrasion-resistant steels could potentially lead to the use of thinner steels and material thicknesses with comparable wear properties, allowing for weight reduction and/or an extension of the component's service life, subsequently, the reduction in weight facilitates increased production outputs and efficient [10].

Partial annealing

Partial annealing is a heat treatment process used to relieve internal stresses and improve the mechanical properties of metals. It has been successfully applied to improve materials' impact energy absorption and enhance their mechanical properties, making them more resilient to impact forces [11], and can be achieved without significantly altering the microstructure or dispersions of the materials [12]. Research indicates that partial annealing can reduce the internal stresses that accumulate during cold working or other mechanical processes by heating the material to a temperature below the material's critical temperature, promoting the rearrangement of dislocations without significant grain growth [13].

Alfirano indicates that both the annealing temperature and holding time influence the change in the mechanical properties of the materials and recommends that the specimens be heated at an intercritical annealing temperature of 750 °C for holding periods of 6–18 minutes, followed by quenching (Figure 1) [14]. The controlled heating in partial annealing operations improves the material ductility and can often recover the toughness while retaining a degree of strength [13].

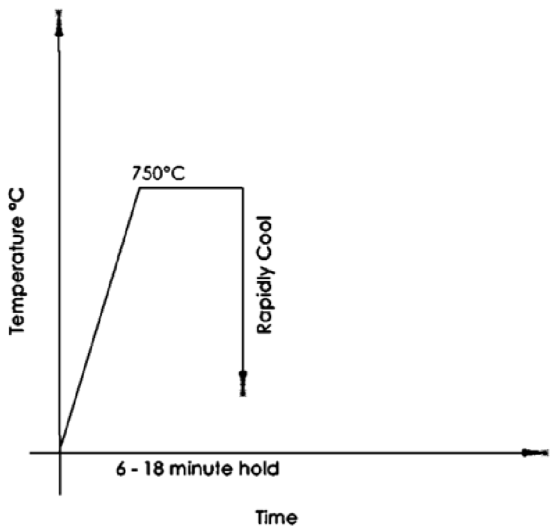

Figure 1. The inter-critical annealing process [14]

Lake found that successful partial annealing operations lead to the reduction of internal stresses, improving the resistance to crack propagation and failure under loading conditions while simultaneously enhancing ductility [15].

AR400 material properties

Any specific standard does not govern the mechanical properties of abrasion-resistant steels; rather, the material is generally known for its association with high ultimate tensile and yield strength and is designated to a specific abrasion-resistant category determined by the hardness of the material and where it falls in the nominal range typically associated by that hardness category [16]. Tables 1 and 2 summarise the mechanical properties and the maximum chemical composition typically associated with AR400 materials.

As there is no specific standard governing the material properties, the specifications listed above can vary depending on the manufacturer or supplier; as such, the consumers are largely reliant on the implementation of International Organisation for Standardisation (ISO) quality guidelines and standards for the metallurgical testing outcomes of abrasion-resistant steel and the properties and specifications detailed on the accompanying material certificates [16]. AR400 abrasion-resistant steel has a primarily martensitic microstructure with some retained austenite and bainitic dispersions, which, according to Powers, is typically characterised by the high density of dislocations and fine distribution of carbides; these contribute to its high hardness and wear resistance and proportional impact resistivity [18].

The retained austenite can often transform into martensite under stress; however, although this transformation does provide additional hardness and subsequent wear resistivity, it can also make the material more brittle [19]. Heat treatment processing and quenching media are also responsible for the change in material properties and morphology, creating a fine martensitic structure with uniformly distributed carbides; the variation in the heat treatment parameters will alter the grain morphology, dispersion, and microstructure and will impact the material hardness, toughness, and mechanical properties [18].

Heat treatment and oil quenching

AR400 abrasion-resistant steel is typically manufactured by undergoing a two-step heat treatment process, namely, quenching (Q) and tempering (T); traditionally, this process involves heat treating the stills above the material's critical temperature before rapidly water quenching the materials; the material is then reheated to below the material's critical temperature, depending on the manufacturer, and allowed to air cool, altering the material's grain morphology and structure with the aim of improving the material hardness

Table 1. AR400 mechanical properties [10]

Material	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
AR400	1000	1250	10
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	CEV
360–450	-40	20	0.52

Table 2. AR400 chemical composition [17]

	C	Mn	P	S	Si	Ni	Cr	Mo	B
Max (%)	0.18	1.70	0.025	0.010	0.80	0.50	1.00	0.50	0.005

and toughness [20]. Martensitic dispersions and microstructures are formed during the quenching phase, and this increases the material hardness but subsequently also makes it more brittle; additional tempering can reduce the brittleness and improve the material toughness by transforming some of the martensite into tempered martensite of bainite [20].

The rate of cooling following heat treatment processing greatly influences the material's microstructure, phase dispersions, and grain morphology. As this study aims to improve the impact resistivity, it is necessary to select an appropriate quenching media to control the rate of cooling following heat treatment and the formation and concentration of phase dispersions. Table 3 details the austenitic transformation depending on the rate of cooling.

Oil is largely considered a moderate cooling medium and, according to Paulo, can be used in applications where a balance between toughness and hardness is required; this is in comparison to the effects of rapid quenching mediums like water, which typically result in martensitic dispersions that, in turn, often result in crack propagation and brittleness [21].

Moderate oil cooling results in the formation of upper and lower bainitic dispersions and some martensite, which subsequently improve steel's impact resistance [21].

MATERIALS AND METHODS

This study employed a two-phased approach to heat treat and partially anneal the AR400 specimens, with the objective of enhancing the material's impact energy absorption capabilities while maintaining its wear resistance.

Table 3. Transformation of austenite through cooling rate [20]

Rate of cooling	Resulting phase dispersion
Slow cooling	Pearlite and proeutectoid phase
Moderate cooling	Bainitic phase (upper and lower)
Rapid cooling	Martensitic phase

The initial phase involved establishing the mechanical properties and chemical composition of the control specimens through metallurgical testing, which served as a baseline for comparison with the partially annealed specimens.

This preliminary step was essential due to the absence of a governing standard for the mechanical properties of abrasion-resistant steels. By first determining the baseline properties, the study ensured a robust framework for evaluating the effects of the partial annealing process on the material's performance.

The results of the control specimen's metallurgical evaluation were quantitatively compared to the metallurgical properties of the specimens that underwent the two-phase partial annealing process, as illustrated in Figure 2 below, to evaluate the processing's efficacy in improving the altered specimens' impact energy absorption properties. All metallurgical testing and examinations were done in compliance with the relevant ISO specifications and standards, as detailed in Table 4.

Zhang established that the partial annealing processing does not significantly alter the microstructure or dispersions of the materials [12]. As such, the purpose of the phase one heat treatment process is to marginally alter the structure of the control specimens by decreasing the martensitic phase dispersion and increasing the concentration of bainite. This aims to enhance the material's structural toughness while reducing the brittleness caused by the presence of martensite. It is achieved by heat treating the specimens at 1000 °C for 20 minutes, followed by moderate cooling through oil quenching. Upon completion of this phase, the sample phase dispersion is reestablished through optical microscopy (OPM).

The study investigates the proposed two-phase partial annealing process across three material thicknesses commonly utilised as wear packages in the mining industry. The objective is to evaluate the efficacy of this processing method for different material thicknesses.

Subsequently, in phase two, the specimens are partially annealed at 750 °C for 20 minutes and rapidly cooled by quenching in cool water. The material's hardness, impact resistance,

Table 4. AR400 mechanical properties [16]

Metallurgical test	ISO standard	Metallurgical test	ISO standard
Brinell hardness	ISO 6506-1	Tensile test	ISO 6892-1
Spectrometric analysis	ISO 6507-1	Notching and Impact	ISO 148-1

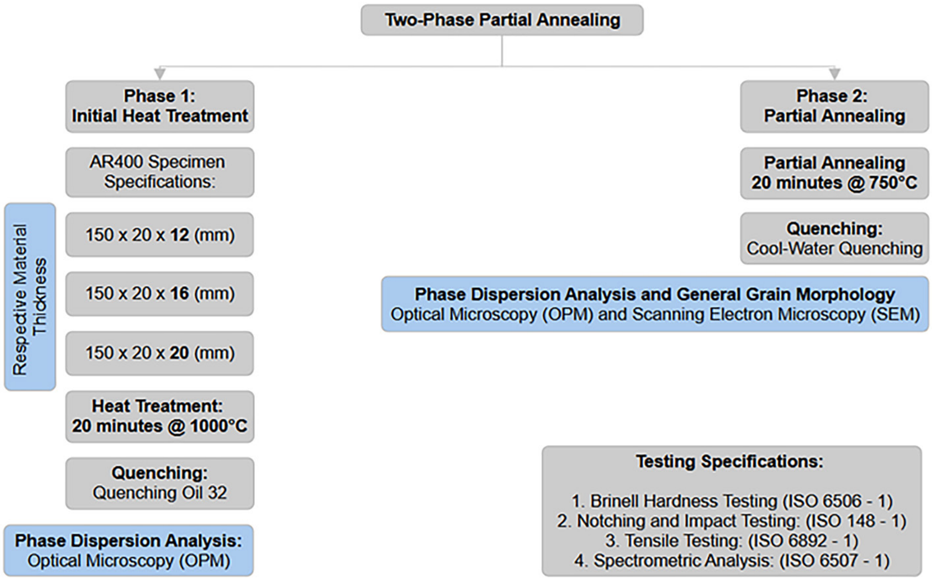

Figure 2. The partial annealing process [16]

tensile strength, and yield stress are then examined through metallurgical analyses and quantitatively compared to the same properties established for the control specimens, while the general morphology, dispersion, and grain structure of the heat-treated specimens were established through OPM and scanning electron microscopy (SEM). This comparison evaluates the effects of the two-phase partial annealing approach and subsequent material properties changes.

Sample preparation for metallurgical examination and heat treatment processing

The as-received specimens were wire-cut to the dimensions specified in Figure 2, a method chosen to minimise the impact of traditional hot working processes on the materials' mechanical properties. Subsequently, specimens designated for metallurgical testing were prepared in accordance with the relevant ISO specifications for metallurgical tests.

Specimens intended for Optical Microscopy (OPM) and Scanning Electron Microscopy (SEM) analysis were also wire-cut to the appropriate size. The surfaces of these specimens were then meticulously ground and polished to prepare them for mounting. This preparation was crucial for determining the phase dispersion and general grain morphology of the specimens subjected to the proposed two-phase partial annealing process. The specimens were etched with 2% Nital to reveal the microstructure and phase dispersion.

RESULTS AND DISCUSSIONS

This section discusses the outcomes of the metallurgical analysis conducted on the control and heat-treated specimens. This analysis aims to observe changes in mechanical properties, phase dispersion, and microstructure across different material thicknesses.

The results for the control specimens were compared to those of the heat-treated specimens to evaluate the efficacy of the proposed processing method, with a particular focus on properties related to impact energy absorption and tribology.

Control specimen properties

The properties in this section are used as a baseline to compare and evaluate the changes resulting from the proposed heat treatment processing. The specimens in the section were not altered and evaluated in the as-received condition.

Spectrometric analysis

The spectrometric analysis detailed in Table 5 establishes the concentration of the primary chemical components typically associated with AR400 steel. The results reveal that the individual alloying elements comply with the typical standard and with the specifications outlined in the ISO 6507-1 testing standard.

The table above shows that the 12 mm specimens have approximately 15% less carbon than

Table 5. AR400 chemical composition [16]

12 mm	C	Mn	P	S	Si	Ni	Cr	Mo	B
	0.13	0.87	0.017	0.007	0.35	0.01	0.33	0.17	0.0008
16 mm	C	Mn	P	S	Si	Ni	Cr	Mo	B
	0.15	0.96	0.014	0.005	0.34	0.01	0.38	0.16	0.0012
20 mm	C	Mn	P	S	Si	Ni	Cr	Mo	B
	0.15	1.21	0.013	0.004	0.36	0.01	0.35	0.01	0.0007

the 16mm and 20 mm specimens. This reduced carbon content is typically associated with abrasion-resistant materials that have a higher hardness than typically specified for this specific material grade, increasing material brittleness.

Mechanical testing

Table 6 presents the findings of the metallurgical analysis, which assessed the mechanical properties of the 12 mm, 16 mm, and 20 mm control specimens. All testing and evaluations were conducted in accordance with the relevant ISO recommendations and standards for AR400 materials. The tensile testing results indicate that the elongation, yield, and ultimate tensile strength for specimens of each material thickness meet the recommended specifications, with only negligible differences observed between the various thicknesses.

The results show that, similarly to what was found in the spectrometric analysis of the carbon concentration, the Brinell hardness of both the 16 mm and 20 mm specimens is the same, while the Brinell hardness of the 12 mm specimens is 7% higher, which can be attributed to the reduced carbon concentration found for the 12 mm specimen.

Despite the relatively consistent hardness measurements observed for the control specimens, all three material thicknesses failed to meet the hardness range specified in the ISO 6506-1 standard for Brinell Hardness evaluation of AR400 steels. Specifically, the 16 mm and 20 mm specimens exhibited hardness values 12% above the maximum allowable limit, while the 12 mm specimen exceeded the hardness limit by 3%.

According to the ISO 148-1 specification for V-Notch and Impact Testing, the minimum required impact energy absorption for AR400 at -40 °C is an average of 45 KV/J across three material specimens per sample.

The metallurgical analysis revealed that the 12 mm and 16 mm specimens did not meet this minimum specification, likely due to the material's increased hardness and consequent brittleness. Conversely, the 20 mm specimen was the only one to satisfy the minimum impact energy absorption requirements for AR400 steel.

Table 6. AR400 mechanical properties [16]

12 mm control specimen			
Yield load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
89.9	1172.7	1336.1	11
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
477	-40	39	102.4
16 mm control specimen			
Yield load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
143.2	1187.9	1360.0	12
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
444	-40	29	164.0
20 mm control specimen			
Yield Load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
152.4	1229.9	1391.70	12
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
444	-40	56	152.4

OPM analyses of control specimen phase dispersions

The initial OPM analysis of the control specimens revealed that regardless of their material thickness, all three specimens have a primarily martensitic phase dispersion with some bainite, as illustrated in Figure 3. This is consistent with the material dispersions in the literature review for AR400 abrasion-resistant steels, which are rapidly cooled through cool-water quenching.

Partially annealed specimen properties

The properties discussed in this section are evaluated in accordance with the relevant ISO testing specifications for AR400 steels. These properties are then compared to the results of the control specimens to assess the effectiveness of the proposed heat treatment process and to determine if the impact energy of the specimens has improved compared to the as-received specimens.

OPM analyses – phase 1 heat treatment processing

The proposed Phase 1 heat treatment process decreased the martensitic content in the specimens and promoted the formation of a primarily bainitic structure, enhancing the materials' impact resistance and toughness (Figure 4–6). The OPM analyses of the specimen structure show a primarily bainitic structure with a combined upper and lower bainitic concentration, detailed in Table 7.

Mechanical testing – phase 2 partial annealing

The properties detailed in Table 8 summarise the metallurgical analyses and testing conducted on the partially annealed specimens following the completion of phase 2. Similarly to the control

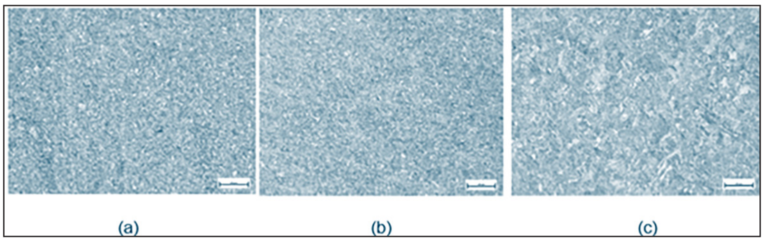

Figure 3. Control specimens phase dispersion: (a) 12 mm, (b) 16 mm, and (c) 20 mm, etched with 2% Nital [16]

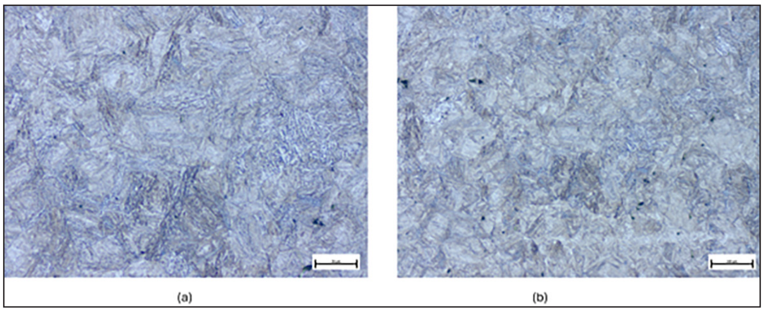

Figure 4. 20 mm OPM micros (a) 50 µm and (b) 100 µm, etched in Nital-2 [16]

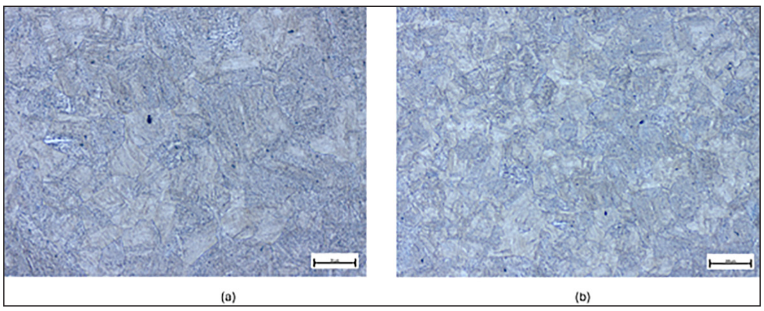

Figure 5. 16 mm OPM micros (a) 50 µm and (b) 100 µm, etched in Nital-2 [16]

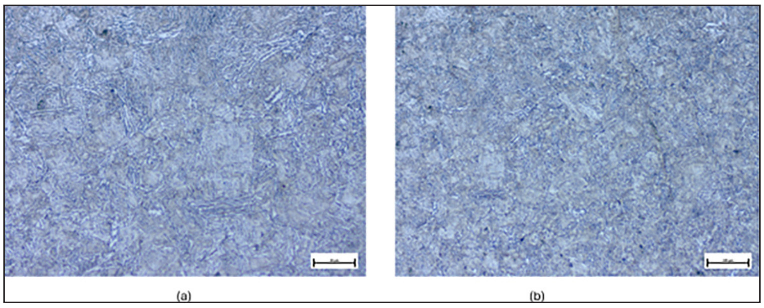

Figure 6. 12 mm OPM micros (a) 50 µm and (b) 100 µm, etched in Nital-2 [16]

Table 7. Phase 1 OPM analyses – phase dispersions [16]

Specimen	Ferrite %	Pearlite %	Bainite %	
			Upper	Lower
20 mm	-	-	65	35
16 mm	-	-	60	40
12 mm	-	-	60	40

Table 8. Phase 2 mechanical properties [16]

12 mm control specimen			
Yield load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
15.69	595.9	691.2	22.9
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
249	-40	117	18.20
16 mm control specimen			
Yield load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
19.64	696.9	789.6	18.7
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
284	-40	202	22.25
20 mm control specimen			
Yield load (kN)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
19.41	666.3	750.8	21.9
Hardness (HB)	Impact value temp (°C)	Impact value (KV/J)	Max load (kN)
270	-40	218	21.87

specimens, the mechanical properties of the 12 mm, 16 mm, and 20 mm control specimens were examined according to the relevant ISO recommendations and standards for AR400 materials.

The 16 mm partially annealed specimen exhibits the highest yield load, 19.64 kN, and yield point, 696.9 MPa, indicating superior yield strength compared to the 12 mm and 20 mm specimens. The 12 mm specimen has the lowest yield point, 595.9 MPa.

Similarly to the results observed in the yields strength, the 16 mm specimen exhibits the highest tensile strength, 789.6 MPa, similar to the ultimate tensile strength of traditional impact plates like SQL690; this is followed by the 20 mm specimen, 750.8 MPa, and the 12 mm specimen, 691.2 MPa. Although the yield and ultimate tensile strength of the materials are relatively uniform across the material thicknesses, it shows an approximately 40% reduction in the same mechanical properties when compared to the same properties of control specimens

In contrast, the elongation of the material, regardless of the material thickness, nearly doubled, with the 12 mm specimen demonstrating the highest elongation, 22.9%, suggesting better ductility compared to the average elongation across all three material thicknesses of the control specimens.

However, similarly to the significant reduction observed in the tensile properties, the material hardness of the partially annealed specimens also appears to be largely diminished, while the 16 mm specimen has the highest hardness value, 284 HB, followed by the 20 mm, 270 HB and 12 mm, specimens with 249 HB.

The results show that the 20 mm specimen's impact value at -40 °C is highest with 218 kV/J, having increased by approximately 390% when compared to the same thickness in the control specimens, indicating a significant increase in impact resistance and energy absorption. It is followed by the 16 mm specimen with 202 kV/J and the 12 mm specimen with 117 kV/J, resulting in an approximately 700% and 300% increase in impact energy absorption, respectively.

SEM and OPM analyses – phase 2 partial annealing

The initial observations of changes in phase dispersion and grain morphology were made using optical microscopy (OPM) analyses. These analyses provided a broad overview of the microstructural transformations occurring within the specimens. However, a closer inspection was necessary to gain a more detailed and precise understanding of these changes.

This was achieved through SEM analysis, allowing for a higher-resolution microstructure examination. SEM analysis revealed finer details of the phase dispersions and grain morphology, confirming the initial findings from OPM and providing deeper insights into the material's microstructural characteristics (Figure 7).

The SEM and OPM micros analysis indicates that all three oil-cooled specimens examined in this section exhibit a predominantly bainitic microstructure, with a clear differentiation between upper and lower bainite.

Notably, the concentration of lower bainite appears to be inversely related to the material thickness. As illustrated in Figure 8, the 12 mm specimen demonstrates a 100% lower bainite dispersion, characterised by irregular polygonal grain sizes.

This aligns with the Phase 1 OPM analysis conducted after the initial heat treatment, confirming that the Phase 2 partial annealing heat treatment did not significantly alter the materials' phase dispersions.

The concentration of lower bainite decreases as material thickness increases. This trend is evident in the 16 mm specimen depicted in Figure 9, which exhibits a microstructure comprising 20%

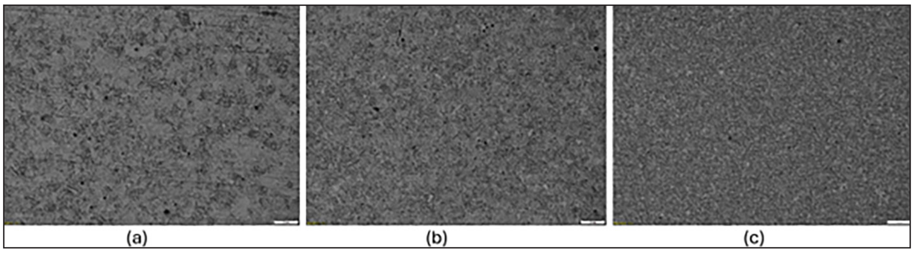

Figure 7. Partially annealed OPM micros (a) 20 mm – 100 µm, (b) 16 mm – 100 µm, (c) 12 mm – 100 µm, etched in Nital-2 [16]

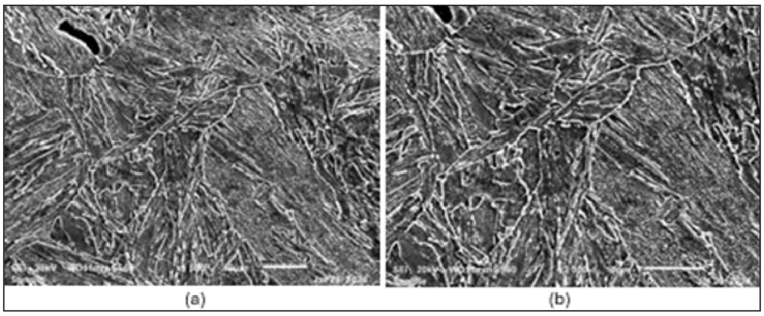

Figure 8. 20 mm SEM (a) x1500, (b) x2000, etched in Nital-2 [16]

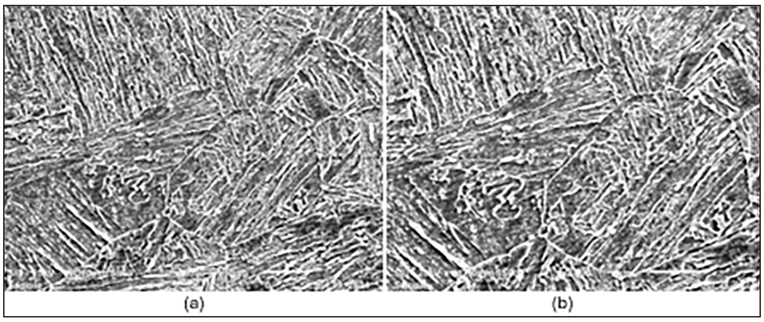

Figure 9. 16 mm SEM (a) x1500, (b) x2000, etched in Nital-2 [16]

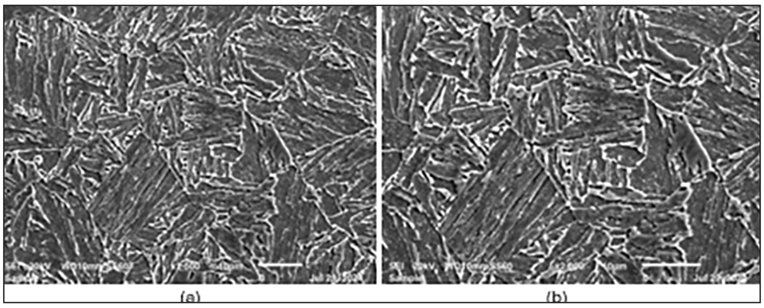

Figure 10. 12 mm SEM (a) x1500, (b) x2000, etched in Nital-2 [16]

upper bainite and 80% lower bainite. In contrast, the 20 mm specimen shown in Figure 10 displays an even distribution of upper and lower bainite, characterised by uniform polygonal grain size and geometry.

CONCLUSIONS

The objective of this study was to evaluate whether the impact resistance of pre-hardened steel, AR400 abrasion-resistant steel, known for its superior tribological properties and wear capabilities, could be enhanced through a two-phased partial annealing heat treatment process while maintaining a degree of the material hardness and wear resistance.

The hypothesis posited that successful heat treatment would improve the wear plate's combined impact and wear resistance, potentially enabling the use of thinner steel materials with comparable wear properties. This could reduce weight and/or extend the component's service life, thereby increasing production efficiency and output.

The Phase 1 heat treatment process effectively reduced the specimens' martensitic content, fostering a predominantly bainitic phase dispersion. SEM analysis provided a closer inspection, confirming the bainitic dispersion and revealing that the Phase 2 partial annealing only marginally influenced the phase dispersions. This resulted in a combined upper and lower bainitic structure across all three material thicknesses. This transformation significantly enhanced the materials' impact resistance and toughness; however, in turn, it reduced the material hardness and brittleness.

The study's outcome shows a significant difference in the material hardness, yield, and ultimate tensile strength following the two-phase partial annealing heat treatment processes when compared to the same values established through metallurgical examination for the control specimens. Conversely, the material's elongation nearly doubled across all thicknesses, with the 12 mm specimen exhibiting the highest elongation (22.9%), approximately 200% greater than the elongation established for the control specimens, indicating improved ductility. However, the hardness of the partially annealed specimens was significantly reduced, with the 16 mm specimen showing the highest hardness value (284 HB), followed by the 20 mm (270 HB) and 12 mm (249 HB) specimens.

The impact testing at -40 °C, following the completion of the proposed to-phase partial heat treatment processing, demonstrated the 20 mm specimen's superior impact value of 218 kV/J, which increased by approximately 390% compared to the control specimens. This was followed by the 16 mm and 12 mm specimens, respectively, showing approximately 700% and 300% increases in impact energy absorption. These results confirmed that the proposed two-phase partial annealing processing successfully improved the material impact resistivity.

In conclusion, the Phase 1 heat treatment process, followed by Phase 2 partial annealing, significantly enhanced the materials' impact resistance and ductility. This improvement is particularly noteworthy as it suggests the potential for these materials to better absorb energy and withstand impacts, which is crucial for applications requiring high toughness. However, this process also led to a reduction in tensile properties and hardness, which are critical for maintaining wear resistance and overall structural integrity.

The observed decrease in tensile strength and hardness indicates that while the materials became more ductile and impact-resistant, their ability to resist deformation under stress and their wear resistance were compromised. This trade-off highlights the complexity of optimising heat treatment processes to achieve a balanced set of mechanical properties.

The findings suggest that the two-phased partial annealing heat treatment process holds promise but requires further refinement. Future investigations should focus on fine-tuning the heat treatment parameters to enhance the desired properties without significantly compromising others. This could involve exploring different annealing temperatures, durations, and cooling rates to achieve an optimal balance between impact resistance, ductility, tensile strength, and hardness.

Ultimately, the goal is to develop a heat treatment process that maximises the performance of the material across all relevant properties, potentially enabling the use of thinner, lighter steel components with extended service life and improved efficiency. Continued research and experimentation will be essential to achieving this balance and unlocking the full potential of these advanced materials.

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REFERENCES

1. ESP, Ground Engaging Tools, Equipment Spare Parts Africa (Pty) Ltd, Johannesburg, 2025.
2. Le Roux W., Beneke L. W. and Adegbola T. A. Evaluation of composite and standard liner plates on hydraulic face shovels operating in platinum mines, South African Journal for Science and Technology, 2022; 40(1): 127–139.
3. Allen C., Protheroe B. E. and Ball A. The selection of abrasion-corrosion-resistant materials for gold-mining equipment, Journal of the South African Institute of Mining and Metallurgy, 1981; 289–297.
4. Mukherjee A., Biswas C., Ghosh S., Majumder A., Sawrav K. and Banerjee S., Comparison of abrasion resistance of selected structural steels: A study, International Journal of Advances in Engineering and Management (IJAEM), 2022; 4(3): 232–238.
5. Barker K. C. The development of abrasive-corrosive wear resistance of steels by microstructural control, Cape Town: University of Cape Town (UCT), 1988.
6. Viljoen N. Driving the hydrogen economy in South Africa, Anglo American, 2022.
7. Frydman S., Konat L. and Pekalski G. Structure and hardness changes in welded joints of Hardox steels, Structure and hardness changes in welded joints of Hardox steels Archives of Civil and Mechanical Engineering, 2008; 8: 15–27.
8. Zhu X., Lin J., Jiang S., Cao A., Yao Y., Sun Y., Li S. and Zhang Z. Study of the effects on the strengthening mechanism and wear behavior of wear-resistant steel of temperature controlling in heat treatment, Nanomaterials, 2024; 14(14): 1–16.
9. Zou J. L., Liu S. L., Zheng Z. B., Long J., Huang Y., Zheng K. H. and Tian Z. Research on impact–abrasion–corrosion behavior of three typical wear-resistant steels under high impact energy, Journal of Materials Engineering and Performance, 2022; 31: 434–4356.
10. ESB, Wear-resistant steel, ESB, 2025.
11. Rao P. N., Rengaswamy J. and Singh D. Effect of annealing on microstructure and mechanical properties of Al 6061 alloy processed by cryorolling, Materials Science and Technology, 2013; 29(1): 76–82.
12. Zhang Q., You N., Wang J., Xu Y., Zhang K. and Wang S. Effect of temperature-dependent low oxygen partial pressure annealing on SiC MOS, Nanomaterials, 2024; 192(14): 1–8.
13. Mohapatra S., Poojari G., Satpathy B., Das S. and

Das K. A comprehensive study on the effect of annealing temperature on the tensile and impact behavior of automotive-grade medium manganese steel (Fe-6.22Mn-0.18C), Journal of Materials Engineering and Performance, 2023; 33: 5348–5363.

14. Alifrano A., Wibawa S. and Hidayat M. Effect of intercritical annealing temperature and holding time on microstructure and mechanical properties of dual phase low carbon steel, Applied Mechanics and Materials, 2014; 493: 721–726.
15. Lake P. B. and Grenawalt J. J. Partially annealed high strength cold rolled steels, JSTOR - SAE International, 1978; 86(1): 718–729.
16. Meyer W., Jamiru T., Beneke L. W. and Adegbola T. A. The effects of microstructure dispersion on the mechanical properties of abrasion resistant steels, Pretoria, Gauteng, 2024.
17. SSAB, AR400F Checmial Composition, SSAB, 2025.
18. Powers M., Derby B., Shaw A., Raeker E. and Misra A. Microstructural characterization of phase-separated co-deposited Cu–Ta immiscible alloy thin films, Journal of Materials Research, 2020; 35: 1531–1542.
19. Astafurova E., Reunova K., Zagibalova E., Astapov D., Astafurov S. and Kolubaev E. Microstructure, phase composition, and mechanical properties of intermetallic Ni-Al-Cr material produced by dual-wire electron-beam additive manufacturing, Metals, 2024; 75(14): 1–13.
20. Leeco Steel, Exploring Steel Plate Heat Treatment Processes, Leeco Steel, Illinois, 2020.
21. Metallurgical Engineering, Transformation of Austenite, Metallurgical Engineering, 2024.
22. Paulo, Different Media for Quenching Metal Explained, Paulo, St Louis, 2017.
23. IMP Labs, Appendix A: Control Specimen Independent Metallurgical Test Results, IMP Labs, Benoni, 2023.
24. Dillinger, Dillidur 400 - Wear Resistant Steels, Dillinger, 2016.