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Investigation of morphological and mechanical properties of hardened and tempered AISI 4340 steel

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Abstract: AISI 4340 steel is widely used in high risk industries due to its excellent mechanical strength and impact resistance. The mechanical properties of AISI 4340 steel can be significantly enhanced through heat treatment, particularly tempering at controlled temperatures. This study investigates the effect of tempering on the microstructure and mechanical properties of AISI 4340 steel. The experimental analysis includes characterization before and after heat treatment to assess changes in strength, toughness, and ductility. The results demonstrate that tempering at 450°C for 45 minutes optimally improves impact energy and ductility while slightly reducing hardness and strength. Conversely, tempering at 550 °C results in a more pronounced increase in impact energy and ductility, but at the cost of a greater reduction in hardness and strength. Microstructural examination confirms the formation of tempered martensite, contributing to the observed mechanical behavior. The findings provide valuable insights into optimizing heat treatment parameters for AISI 4340 steel to achieve a balanced combination of strength, toughness, and ductility for industrial applications.

Keywords: AISI 4340 steel; tempering; mechanical properties; heat treatment.

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INTRODUCTION

Low alloy AISI 4340 steel has found application in the military establishment, critical parts of aircraft, and nuclear power plants, attributable to its mechanical properties such as tensile strength, stiffness, exceptional processability, optimal hardness, and improved weldment.[1, 2] Nickel in steel, compared with other medium and low alloy steels, enhances tensile toughness and hardness.[3] It was reported that high-strength steels in industries suffer from unexpected brittle failure.[4] The catastrophic failure of engineering components in service conditions, shutdown of power plants, and elevated impairment costs of engineering machine components are serious consequences when plants are operating.[5, 6] Dual-phase structure of steel by various means has been planned nowadays for the proud performance of structural steel.[7] Reported work clarified the effect of quenching and tempering treatment for optimizing properties of AISI 4340 steel.[8] Additionally, quenching and tempering treatment dramatically increases the ultimate tensile strength of the steel.[9] Published work rectified that the quenching and tempering heat treatment to develop the tempered martensitic steel.[10] Moreover, the hardening treatment of AISI 4340 steel substantially increased the toughness and minimized brittle fracture.[11, 12] Furthermore, the recommendation regarding the toughness and strength of AISI 4340 steel, in any case, one of the best heat treatments for homogenization, normalizing, quenching, and tempering, inter-critical annealing, austempering, and martempering is required.[13] Subsequently, it was demanded that the upgrading of mechanical properties of AISI 4340 steel by numerous heat treatments procedure and by controlled the metal forming processes.[14] Likewise, apply an inter-critical quenching process to produce austenite phase for TRIP steel.[15] Nevertheless, difficulties in metal forming processes and its budgets operating equipment in process industries. In alternative, it was conveyed that a substantial alteration in the mechanical properties of steel is achieved by intermediate quenching treatment.[16] For the advancement of AISI 4340 steel isused in quench and temper form, though, it is susceptible to embrittlement when tempered at temperatures ranging from 300ºC to 400ºC.[17] The embrittlement problems addressed by many researchers in their findings that vicissitudes in micrographs and mechanical properties at diverse tempering temperatures.[18] Temper heat treatment can be used as a stress relief procedure, confirm ingreduction of tensile residual stresses, which have badly influence on fatigue life of components.[19] Despite of widespread usage in industries AISI 4340 steel and detailed study of the mechanical performance of material, there is fewer work is published in literature about the effect of heat treatment parameters on residual stresses.[20] Objective of present work to optimize mechanical properties of steel AISI 4340 through hardening treatment. The hardening method improve the strength and stiffness of materials by treating at specified temperature followed by quench in water and oil medium.[21] Temper treatment practice in ferrous materials is use ful after hardening.[22] In tempering procedure steel is subjected to heating and cooling below transformation temperature range and takes time for cooling at asuitable rate.[23] Tempering treatment cause of reduction in hardness and increases the toughness to get the desired mechanical properties.[24, 25] Hence, in current study, AISI 4340 high strength low alloy steel has been designated and treated at suitable temperature to stabilize the microstructure for optimization of mechanical properties. AISI 4340 steel applied in machine components, butit is required for service condition in various forms extending from aircraft structures to automotive crank shafts, where diverse characteristics are required.[26] In this study, hardening and tempering techniques are employed to alter the mechanical properties and microstructure of AISI 4340 high strength low alloy steel through heat treatment. In addition, outcomes of this research were likened with conventional hardening and tempering of steel. Conclusively, the optimal situations for attaining the highest toughness have achieved.

EXPERIMENTAL PROCEDURE

Material

Work material for heat treatment procedure was made by partitioning of AISI 4340 steel bar into cross-sectional areas of 0.621 m^2 and 0.914 m^2 length. The material in the form of a billet is rolled into a round bar and then cooled in air manufacturing procedure of AISI 4340 steel in an industrial unit.

Fig 1. Experimental Setup of AISI 4340 steel bar

Chemical configuration

The surface of the specimen was prepared by grinding and followed by polishing to eliminate the earth particles and additional contamination. An Optical Emission Spark Spectrometer is engaged to determine the chemical elements present in the samples. Argon gas is used as an inert atmosphere gas medium through purifier in spectrometer. After argon gas stabilization the specimen was positioned on an anvil and clamped.[27] As a minimum of three sparks per specimen were made on different positions of the polished surface for the average and standard deviation. Percentage of the elements presents in AISI 4340 steel at the initial stage of the study is discussed in Table I.[28]

TABLE I. Chemical analysis of AISI 4340 steel before heat treatment.

Elements	C	Si	Mn	Cr	Mo	Ni	T	Cu	Co	P	S	Balance
Wt %	0.37	0.25	0.70	0.82	0.02	0.11	0.14	0.15	0.006	0.016	0.019	Fe

Heat treatment procedure

The standard specimens for impact and tensile test were prepared from the round bars of AISI 4340 steel placed in a muffle furnace for hardening at 850 °C for 45 minutes, then followed by oil quenched in Mineral oil. The hardened heat-treated work material was tempered at 350 °C, 450 °C and 550 °C and kept cool down to touch the room temperature.

Hardness testing trials

Hardened and tempered samples were investigated by a Vickers hardness testing machine HM-100 Series (HV-100) Japan to measure the resistance to indentation.[29] Indentation was made on well-surface prepared specimens. The 20 kgf load was applied for indentation, and dent were examined by microscope. Indentation was measured at an appropriate distance from the sample edge to avoid any edge effects. Three different interpretations were made to identify the hard value of standard specimen.

Charpy impact testing technique

Impact testing for energy absorption of heat-treated samples was conducted by applying the force of a swinging pendulum. The geometry of specimens for the Charpy impact test accordance with ASTM standard E23 with charpy impact testing machine XJJD-50 China.[30] The 3D of the specimens was made according to ASTM standard E23.

Tension testing

In the tension test, standard samples were fixed in grip of the tensile testing machine (ZwickRoell SE-250KN, ZwickRoell Group, Germany) equipped with an electronic load cell . The Upper crosshead of the tension testing machine dragged the specimens upward to failure with a constant crosshead speed of 10 mm s^{-1}, to regulate a preliminary strain rate of 2.8×10^{-4}. Stress-strain diagram showing the mechanical properties such as yield strength, ultimate tensile strength and toughness before fracture. The dimension of tensile test samples accordance with ASTM standard E8.[31]

RESULTS AND DISCUSSION

AISI 4340 steel as received condition

At first, the chemistry of AISI 4340 steel were analyzed and given in Table II.1. In chemical analysis, it was evident that the 0.82% Cr, is an allying element present in the steel to enhance resistance against degradation. As the determination of strength and toughness of primarily samples by vickers hardness testing at applied load of 30kg, energy absorption and strength are specified in Table II.

TABLE II. Mechanical properties of the work material before treatment.

Material	HVN (30kg)	Impact E (J)	UTS (MPa)	Breaking stress (MPa)	% Elongation
AISI 4340 before treatment	135	9.5	715	468.73	33.92

Pictorial views of as-received samples of AISI 4340 steel confirm the identification of ferrite structure and pearlite phase in micro-examination, and as a lighter phase structure is ferrite. Micrographs were recorded via a light optical microscope.

Heat treatment

This contemporary study is capable of enhancing the energy absorption and strength of AISI 4340 low-strength high-alloy steel via heat heat-treated process; consequently, once the work pieces were ready for mechanical characterization. In the begging selected samples were subjected to harden at 850 ºCfor 45 minutes and followed by quenching practice. Secondly, sectioned were tempered consequently at 350ºC, 450ºC and 550ºC for 45 minutes and quenched in air.[32,33]

Hardening procedure of AISI 4340 steel

The Confirmation of harden heat treatment of AISI 4340 steel, it was found that Vicker hardness values have increased considerably as 625 (30kg), whereas energy absorbed and internal reactive force has declined in curve, to values as 7.53 J and 1520 MPa. Achieved results of hardening of AISI 4340 steel reduces the ductility and uphill the brittleness. The micrograph contains very fine-grained martensitic regions. Since martensitic regions have BCT crystal structure and deliberated as the hardest phase structure.[34] The pictorial views of hardening treatment procedures have good agreement with the outcomes deliberated previously.

Tempering technique of AISI 4340 steel

Tempering treatment after hardening procedure improves strength and ductility of martensitic phase structure of AISI 4340 steel, whereas decreases the hardness.[35] Findings of tempering heat treatment are arranged in tabular form Table III. Statistical analysis of mechanical properties materials (AISI 4340 steel) describes in comparison graph and describes in Fig. 2.

TABLE III. Mechanical Properties of work material after temper treatment.

Material	Tempering temp. (ºC)	HVN (30kg)	Impact E (J)	UTS (MPa)	% Elongation
AISI4340	350	232.6	10.49	1400.69	22.59
	450	219	20	1456.98	29.32
	550	198.13	39	1255.07	30.99

It was discovered that toughness and hardness of work material are affected by heating in furnace for hardening and followed by tempering at disparate temperature scale. Hardening treatment achieved the utmost hardness and tensile strength and reduces percentage elongation.[36] As reported by researchers that phase change of AISI 4340 steel might be due to quenching route, an abrupt changes occur in crystal structural phase from gamma (γ) i.e., FCC to BCT and martensitic phase structure.[37] Rapid intensification in Vicker hardness and strengths occurs during transformation in platelets of martensite phase, producing enormous alteration also observed the same trend on similar type of material.[38] It can be seen in tempering procedure, improvement of hardness, ultimate strength and toughness is shown in Fig. 2 .

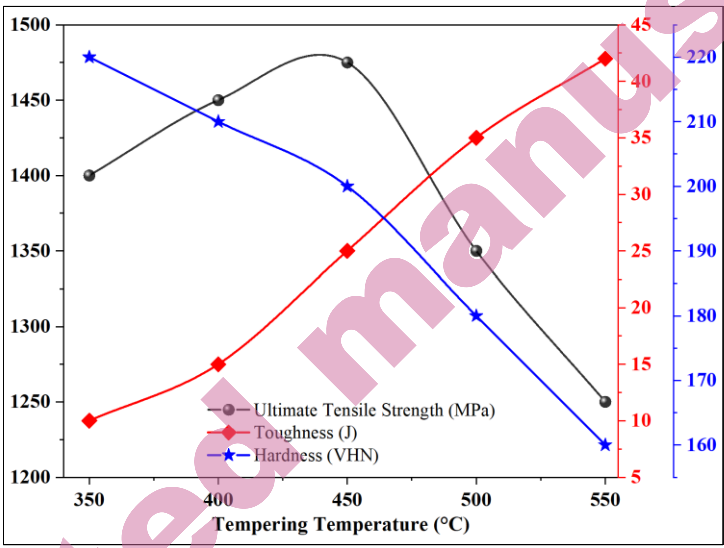

Fig 2. Comparative analysis of mechanical properties after tempering of hardened AISI 4340 steel at 350 ºC -550 ºC for 45 minutes.

The comparing analysis of heat treatment procedure hardness and strength are drastically byduced as 625 to 232.6 HVN at 30kg, and 1520 -1400.69 MPa respectively, whereas it enhances the energy absorption as 7.53 - 10.49 J. Based on the results it can be investigated that internal stresses produced by reason of change in martensitic morphology and retained its ductility. Although, a notable change in mechanical properties of the AISI4340 steel was obtained after tempering at 450 ºC for 45 minutes. Furthermore, data interpretation after heat treatment of AISI 4340 Steel showed the decline in hardness values and increases in strengths and toughness. This can be attributed to the fact that the section was tempered at 550 ºC for same times decreases in hardness and tensile strength but an increase in toughness. Hence, tempering heat treatment practice of AISI 4340 steel at 450 ºC achieves the hardness, tensile strength, and toughness.[13] Experimental evidence shows that low-carbon Mn-Si-Cr steel, when quenched after the hardening procedure, causes phase conversion and affects the mechanical properties.

Scanning electron microscopy analysis

High strength low alloy steel is designed particularly to space shuttle, aircraft, and structure of missile for defense. AISI 4340 steel was subjected to heating and cooling process, achieved resistance to fracture, and enhanced tensile strengths. By the procedure of heat treatment, mechanical strength properties of high strength low alloy steel transmuted with tempering and subsequent quenching.[39] Phase change of steel occurs by hardening and tempering technique. The transformed microstructures like retained austenite, lower bainite, martensite and some carbides were recognized by means of high-resolution transmission electron microscope.[40] It can also be discussed that retained austenite is capable to capture cracking and increases resistance to fracture of low alloy medium carbon steel. Furthermore, the research finding clarifies that the cracks traveling thru martensite are impassable while passing through a region of retained austenite. If internal reactive forces are functional, crack harvest the branches and started to increase close to austenite region, therefore,extra energy absorbs through martensite plates and promotes the toughness of steel. AISI 4340 steel captivating lower bainite and tempered martensite dual phase is extensively studied concerning its mechanical properties. It is notified that the dual micrograph steel provides the heal their combination of strengthand toughness equated with wholly martensitic structures.[41] As has been cited earlier in optical micrographs inquiries, the detailed information regarding variations occurring thru phase alteration process, hence, it was found essential to inspect hardened and tempered work pieces by using SEM.The micrograph in Fig. 3(a) shows evidence of dual-phase microstructure containing lower bainite and martensitic structure of AISI 4340 steel tempered at a temperature of 350 ºC for 45 minutes. SEM microstructure captured at high resolution and magnification is displayed in Fig. 3(b), sign of dual phase micrographs of lower bainite and martensite plates layered with austenitic phase structure on the grain boundaries. A compaarable topography was detected (Fig.s 3(c) and 3(d)), the specimens inspected with high resolution SEM after tempering at 450 ºC and 550 ºC for 45 minutes.

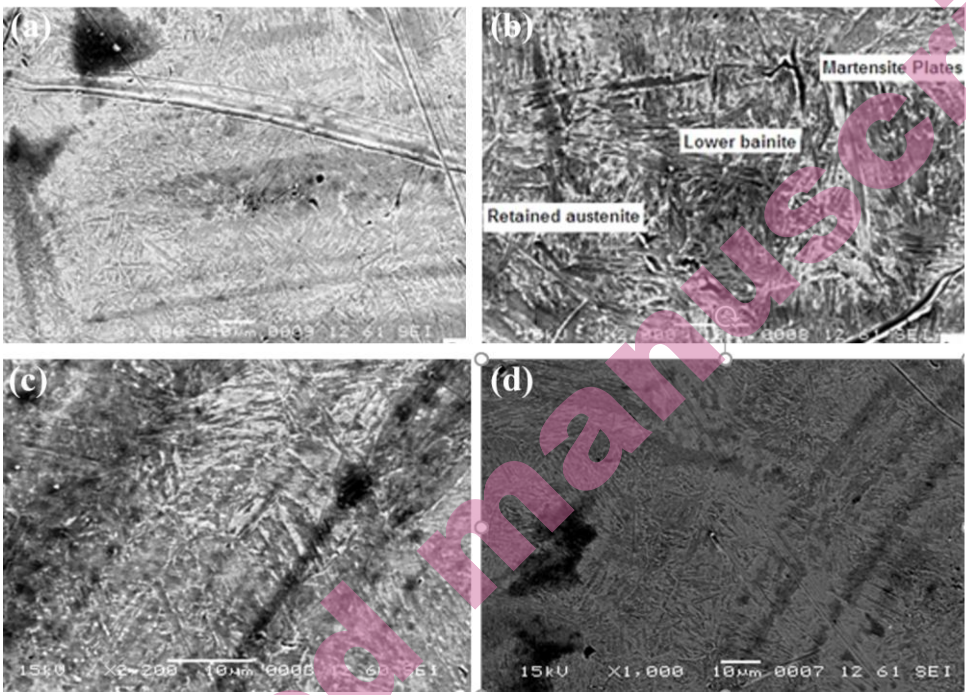

Fig 3. SEM micrograph of AISI 4340 Steel (a) tempered at 350 °C (b) tempered at 450 °C (c) Comparative topography at 450 °C (d) Comparative analysis at 550 °C.

In this contemporary study a steel grade was hardened and tempered to reduce the hardness as being of martensitic structure and enhance the high-energy region. It has been testified by numerous investigators.[42] that P, S and Sn and antimony have adverse effect on steel showing brittle appearance once tempered. Impurities present in the steel caused to segregate near the austenitic region and decohesion across the border line which eventually outcomes will be inter granular brittle failure. These consequences in shape of impurities and discrimination have raised by tempered treatment of steel at elevated temperature. While similar steel grade when quenched from elevated temperature, irregularities within the material does not activate during cooling and therefore rejecting embrittlement mechanism of fracture. As is evident from reported results, tempered specimen failure via tensile test were studied using scanning electron microscope. Micrograph showed in Fig. 4(a) fractured surface of a work piece was tempered at 350 ºC, scrutinized under scanning electronic microscope and conforming stress-strain photograph. AISI 4340 sectioned pieces contained of inter granular fracture, which comes in categories of brittle fracture. Illustration of stress-strain diagram did not present any yielding and elongation all through the tensile test. These values indications of brittle fracture material. Fracture along the grain boundaries of tempered martensitic phase structure is good agreement with discoveries conferred previously. New findings quantified in Table III. signifies the tempering temperature at 350 ºC. The hardness values are comparatively higher and impact energy is relatively lower than the finding of hardness and impact energy noted when tempered at 450 ºC. Illustration of Table III. also indication of increased in tensile strength of work material. Therefore, advancement of impact energy reduces considerably the hardness and strength of specimens.[43] Micrographs were recorded for AISI 4340 steel tempered at 350, 450, and 550 °C, as presented in Fig. 4(a–c). As the tempering temperature rises, the fracture morphology exhibits a distinct change in failure mode, which is directly correlated with modifications in mechanical behavior. The fracture surface primarily displays intergranular and quasi-cleavage features in Fig. 4(a), which corresponds to tempering at 350 °C. This suggests a relatively brittle fracture mechanism. Tempered martensite with high residual stresses and fine ε-carbides, which restrict plastic deformation and encourage crack initiation along previous austenite grain boundaries, is linked to this behaviour. As a result, this condition is usually characterized by increased strength and hardness but decreased toughness. As seen in Fig. 4(b), the fracture mode changes towards ductile fracture when the tempering temperature is raised to 450 °C. Microvoid nucleation, growth, and coalescence produce uniformly distributed dimples on the fracture surface. This transition shows increased plasticity as a result of controlled cementite (Fe_3C) precipitation and partial martensitic structure recovery. Strength and toughness are better balanced at this tempering condition, which is frequently regarded as ideal for AISI 4340 steel. The fracture surface exhibits deeper and larger dimples at the maximum tempering temperature of 550 °C (Fig. 4(c)), indicating a fully ductile fracture mechanism. Carbide coarsening and spheroidisation, as well as substantial stress relief and martensite breakdown into a ferrite–carbide matrix are responsible for the increase in dimple size. This microstructural evolution leads to increased ductility and impact toughness but decreased hardness and strength. The evolution of carbide precipitation Fe_3C and the transformation of the martensitic phase are reflected in the progressive increase in dimple size with tempering temperature. The observed trends in the mechanical properties of tempered and hardened AISI 4340 steel are strongly supported by these morphological changes seen in SEM fractography.

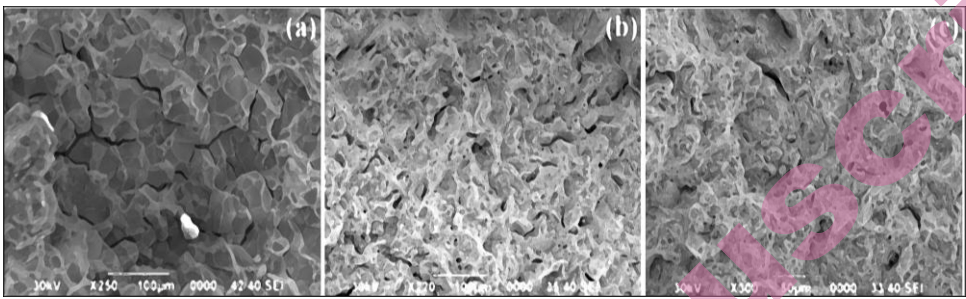

Fig.4. SEM Analysis of samples after tempering at (a) 350 °C (b)450 °C (c) 550 °C.

TABLE IV. Tensile properties of AISI 4340 steel at various tempering temperatures.

Samples	Tempering temp. (˚C)	Diameter (d_0) (mm)	L_0 (mm)	Fmax N/mm^2	F_{Break} %	eBreak %	e-Fmax %
(a)	350	12.5	35.08	1400.09	1400.09	22.59	22.59
(b)	450	12.5	35.14	1456.96	1186.72	36.53	29.32
(c)	550	12.5	30.07	1255.02	980.52	41.47	30.99

The table IV presents the tensile properties of three samples subjected to different tempering temperatures (350 °C, 450 °C and 550 °C), has been fixed by chamber oven UF160-Memmeryt GmbH+Co. Kg, Germany, highlighting the influence of heat treatment on tensile behavior. At 350 °C, the sample exhibits a maximum stress of 1400.09 N/mm², which increases to 1456.96 N/mm² at 450 °C, indicating enhanced strength due to the tempering-induced micro structural changes, such as stress relief and carbide precipitation. However, a further increase in tempering temperature to 550 °C results in a reduction to 1255.02 N/mm², suggesting over-tempering, where coarsening of the micro structure and reduction in dislocation density lead to decreased strength. A similar trend is observed in the fracture strength, which drops significantly from 1400.09% at 350 °C to 980.52% at 550 °C, reflecting a loss in the material's ability to withstand stress before failure as it becomes more ductile. Meanwhile, the elongation at break (eBreak) and at maximum stress (e-Fmax) increase progressively with tempering temperature, rising from 22.59% at 350 °C to 41.47% and 30.99%, respectively, at 550 °C. This indicates a clear enhancement in ductility due to the transformation of the brittle martensitic structure into a more plastic and deformable phase. The results revealed a classic trade-off between strength and ductility with increasing tempering temperature. The sample tempered at 450 °C demonstrates an optimal combination of high tensile strength and improved elongation, suggesting it may offer the best mechanical performance among the three for applications requiring both durability and formability.

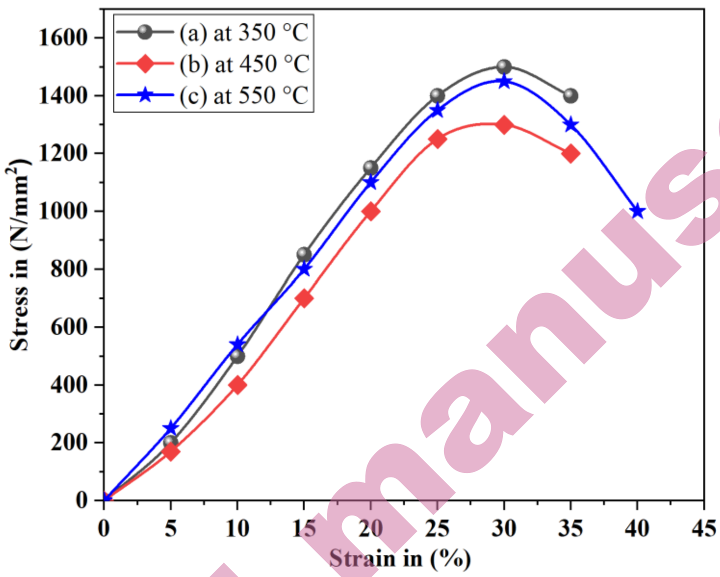

Fig 5. Illustration of the tensile properties of AISI 4340 steel at different tempering temperatures.

CONCLUSIONS

This study investigated the tempering of AISI 4340 steel to optimize its mechanical properties, finding that different tempering temperatures yield distinct results. Tempering at 350 °C primarily enhances tensile strength without significantly improving ductility or impact energy, while a higher temperature of 450 °C for 45 minutes provides an optimal balance, effectively increasing both toughness and ductility while maintaining acceptable levels of strength and hardness. Conversely, tempering at 550 °C leads to a further increase in impact energy and ductility but results in a more significant reduction in strength and hardness. This observed behavior is directly linked to the formation of tempered martensite within the steel's microstructure, as confirmed by microstructural analysis. Therefore, the findings suggest that a tempering treatment of 450 °C for 45 minutes is the most effective approach for achieving a desirable combination of mechanical properties for a wide range of engineering applications.

И З В О Д

ИСПИТИВАЊЕ МОРФОЛОШКИХ И МЕХАНИЧКИХ СВОЈСТАВА КАЉЕНОГ И ОТПУШТЕНОГ ЧЕЛИКА AISI 4340

SUBHAN ALI[1], ABDUL QADEER LAGHARI[2], ARSHAD IQBAL[3], GHULAM MUSTAFA MEMON[4], IFITKHAR AHMED MEMON[1], FIDA HUSSAIN CHANNA[5], ABDUL SAMI CHANNA[6], MASROOR ABRO[2], KHAN MUHAMMAD[3], SHOUKAT ALI NOONARI[7]

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Челик AISI 4340 се због своје изврсне механичке чврстоће и отпорности на удар широко користи у индустријама високог ризика. Механичка својства овог челика могу се значајно побољшати термичком обрадом, нарочито отпуштањем на контролисаним температурама. Ова студија истражује утицај отпуштања на микроструктуру и механичка својства челика AISI 4340. Експериментална анализа обухвата карактеризацију пре и после термичке обраде како би се процениле промене у чврстоћи, жилавости и дуктилности. Резултати испитивања показују да отпуштање на 450 °C (45 минута) оптимално побољшава енергију удара и дуктилност, уз благо смањење тврдоће и чврстоће, док отпуштање на 550 °C доводи до израженијег повећања енергије удара и дуктилности, али по цену већег смањења тврдоће и чврстоће. Микроструктурна испитивања потврђују формирање отпуштеног мартензита, што доприноси уоченом механичком понашању. Ови налази пружају драгоцен увид у оптимизацију параметара термичке обраде челика AISI 4340 ради постизања баланса чврстоће, жилавости и дуктилности за индустријску примену.

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