IRAQI JOURNAL OF APPLIED PHYSICS
Vol. 22, No. 4, October-December 2026, pp. 548-551

Tempering Effects on Hardness and Wear Behaviors of 420 Martensitic Stainless Steel

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This study examined the impact of thermal tempering on the hardness and wear resistance of martensitic stainless steel AISI 420. We used XRD, SEM, and EDS to look at the structure, and Vickers hardness and dry sliding wear tests to look at the mechanical performance. The results showed that tempering at 350 °C for 90 minutes caused carbide precipitation and coarsening, but the martensitic matrix nevertheless stayed the same. After tempering, the hardness went up a little, but the wear resistance went down a lot, as shown by the increased material loss under frictional loading. This apparent disparity highlights the intricate interplay between hardness and wear behaviour in martensitic stainless steels, where microstructural changes and carbide dispersion are crucial factors.

Keywords: Martensitic stainless steel; Tempering; Hardness; Wear resistance

1. Introduction

Stainless Steel 420 is a martensitic grade that can harden at high temperatures and is very hard and strong. Commonly referred to as "cutlery grade," this steel is utilized in knives and medical equipment. It has more carbon than austenitic steels (304, 316), which makes it stronger but less resistant to corrosion [1]. Researchers discovered that heat treatments (tempering and annealing) at 250-450°C enhance wear resistance under dry friction by converting martensite to retained austenite and improving the microstructure [2].

If 420 steel is tempered correctly, it can reach a tensile strength of about 1100 MPa and a hardness of 50-56 HRC, depending on how it is heated. These qualities are important for equipment that need to be very hard and not wear down easily, like surgical tools and industrial parts with sharp edges [3].

To make alloy 420 less brittle and more ductile, it is first heated to 980-1035°C and then rapidly cooled. After that, it is tempered to make it less brittle and more ductile. Annealing may also be used to make it easier to work with before tempering [4]. The 420 alloy is harder and can be hardened by heat treatment better than other stainless steels like 304 and 316. However, it is less resistant to corrosion and easier to weld. Steels 304 and 316 are great for damp or chemical conditions, but they can't be toughened by heat treatment, which limits their usage in sharp cutting applications [5]. Experimental findings on AISI 420 alloy indicated a progressive reduction in hardness with increasing tempering temperature, alongside enhanced toughness and microstructural stabilization. However, secondary hardening was observed between 450-550°C due to carbide precipitation, succeeded by a significant hardness decline above 550°C resulting from martensite decomposition into softer phases [6].

After tempering, grades 410 and 420 were compared. The findings indicated that carbides (Cr_3C_2, Mo_2C) were generated in AISI 420 during tempering at approximately 450°C, enhancing wear resistance. Nonetheless, there is no direct correlation between overall hardness and wear resistance, as the latter is contingent upon the distribution of carbides rather than only the overall hardness value [7]. AISI 420 alloy tempered at 245-445°C exhibited diminished wear rates relative to the untreated condition, with mass loss falling from 15.62 to 13.88 mm³; while a little reduction in hardness, higher ductility improved surface wear resistance [8]. Kumar et al. (2021) stated that heat treatments that include rapid cooling and mild annealing make steel harder and more resistant to wear. On the other hand, high-temperature annealing makes steel softer and more prone to wear because of changes in its microstructure and the movement of carbides [9]. Hardness is an important characteristic for testing materials for wear and deformation resistance, and it is also an important factor in engineering applications [10]. It is usually measured in thin or fine materials [11].

In this study, a tetrahedral pyramid indenter was used to assess Vickers hardness. A Vickers hardness tester was employed in this study. It works by putting a tetrahedral pyramid into the material. The hardness was figured out by utilizing the following formula:

$$HV = \frac{1.8544F}{d^2} \qquad (1)$$

where F is the load applied to the specimen in N units, d is the diameter of the resulting dent by mm

When choosing materials for high-friction applications, wear resistance is very important. Knowing how wear occurs and how to measure it can help improve performance and reduce losses. Also, thermal and surface treatments, along with choosing the right material, can greatly improve wear resistance and make the system more reliable [12,13]. The following equation gives the wear resistance rate:

$$Wear\ Rate = \frac{\Delta w}{s} \quad (2)$$

where Δw is the sample weight difference, s is the total sliding distance equal to $\pi D_S N t$ and measured in cm

This study examines the influence of tempering temperature and duration on the hardness and wear resistance of 420 martensitic stainless steel, seeking to determine optimal parameters that harmonize both attributes and improve performance in high-load and friction applications.

2. Experimental Procedures

In this study, stainless steel 420 from Baosteel Stainless Company in China was utilized to look at how the structure changed and how well two bodies resisted corrosion before and after thermal review. The composition of stainless steel 420 was examined by the State Company for Inspection and Engineering Rehabilitation (SIER), Engineering Inspection & Labs Department, as indicated in table (1).

Type 420 stainless steel was tempered at 350°C for 90 minutes and then polished with sandpaper, Al_2O_3 paste, and diamond paste to make it harder, wear-resistant, and structurally sound. The X-ray diffraction (XRD), field-emission scanning electron microscopy (FE-SEM), and energy-dispersive X-ray spectroscopy (EDS) were used to characterize the samples and compare the results of heat treatment on hardness and wear resistance to those of untreated samples.

A TR20-LE pin-on-disc tester (Ducom, India) was used to test the wear resistance of 420 martensitic stainless steel under a 2000 g load and a controlled speed. Tests were done at room temperature for 10, 15, and 20 minutes. The wear rates were found by measuring the weight loss using a high-precision scale and averaging the results over three readings for accuracy.

A Vickers hardness tester with a load of 500 kg and a holding time of 10 seconds was used to determine the overall hardness. For each sample, the average of four readings was calculated.

3. Results and Discussion

A Philips PAN-analytical X'Pert XRD system was used to record the XRD patterns of the samples. The device used Cu-Kα radiation in an angular range of 10°-80°, a scan rate of 0.1°, and a wavelength of 1.5404 Å, with an accelerating voltage of 40 kV. All the tests were performed at room temperature and then the diffraction patterns were compared according to the JCPDS card, as shown in Fig. (1) and table (2).

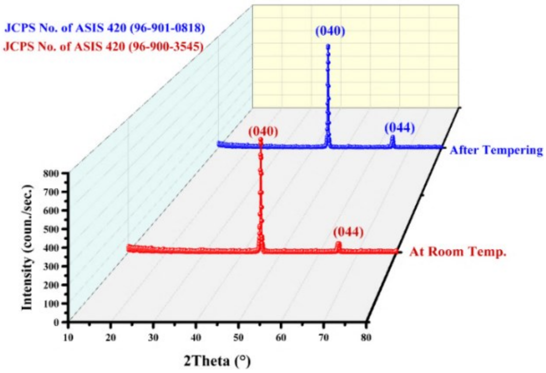

Fig. (1) XRD analysis of ASIS 420 samples at room temperature and after tempering

The FE-SEM micrographs in Figs. (2) and (3) demonstrate what AISI 420 steel looks like at normal temperature and after tempering. The findings demonstrate that undissolved carbides persisted post-tempering. These carbides tended to become coarser and bigger when new carbide phases formed. Microscopic investigations demonstrated the significant influence of carbon concentration on the carbide precipitation mechanism, as evidenced by the FE-SEM results. The microstructure of AISI 420 steel was predominantly martensitic, which confirms that this type of stainless steel is unique after being heat treated.

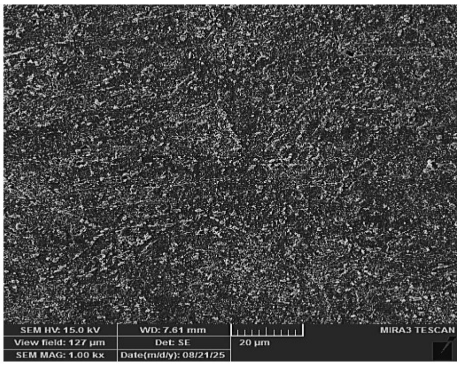

Fig. (2) FE-SEM micrograph of AISI 420 at room temperature

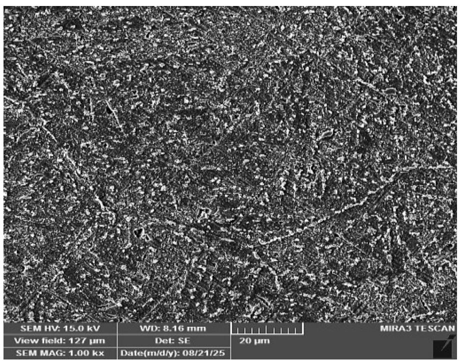

Fig. (3) FE-SEM micrograph of AISI 420 after tempering

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The EDS test verifies the existence of Fe, Cr, C, and O, which are the primary constituents of AISI steel. The EDS measurements were concentrated on distinct regions, with the corresponding peaks illustrated in Figs. (4) and (5), as well as tables (3) and (4).

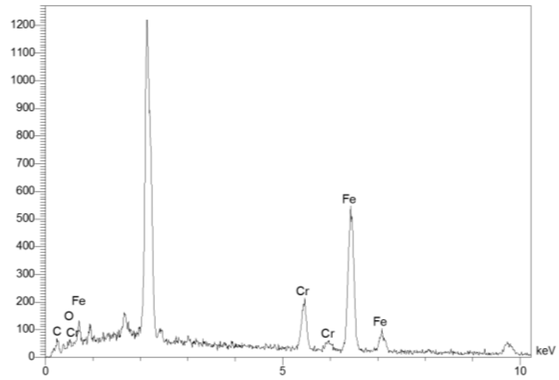

Fig. (4) EDS spectrum of AISI 420 at room temperature

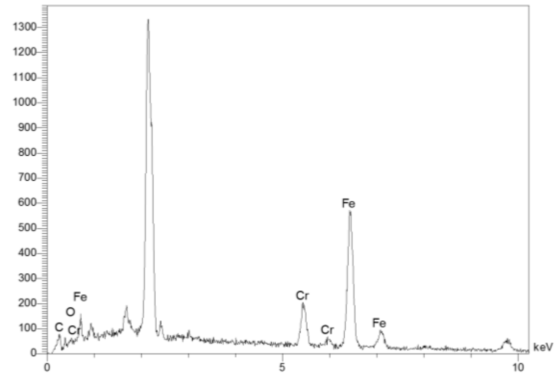

Fig. (5) EDS spectrum of AISI 420 after tempering

We looked at how well AISI 420 martensitic steel held up to wear before and after annealing heat treatment by measuring the frictional mass loss over longer and longer periods of time (10-20 min), as shown in Fig. (6). The results revealed a surprising paradox: despite a minor increase in hardness after annealing (from 221.1 Hv to 226.1 Hv), wear resistance dramatically deteriorated, with the mass loss increasing to roughly 11 g after 20 min compared to 6 g in the untreated sample.

This apparent contradiction suggests that the correlation between hardness and wear resistance in martensitic steels is not merely a straightforward direct relationship, but is significantly affected by the microstructure produced during tempering. It is widely known that tempering breaks down the martensitic phase and makes carbides grow at grain boundaries. This makes the structure less homogeneous and creates brittle zones in some areas [7]. These areas make it easier for corrosion to start and spread when loads are applied repeatedly. This is why the mass loss is so much greater than the tiny increase in nominal hardness [9]. These findings are consistent with the current results, indicating that the tempering technique performed to the sample likely facilitated the development of carbides with a non-uniform functional distribution. This may have made the nominal hardness go up a little, but it also weakened the microstructural integrity, which made the material less resistant to wear. So, the fact that the surface hardness has improved doesn't mean that the mechanical performance has really gotten better when there is actual friction [14].

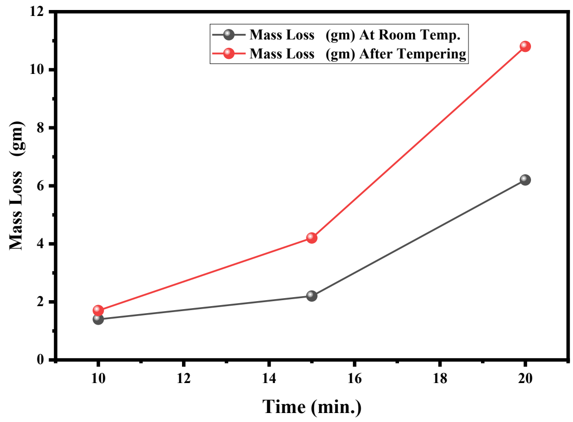

Fig. (6) Wear resistance of AISI at room temperature and after tempering

4. Conclusion

This study demonstrates that tempering AISI 420 martensitic steel results in microstructural alterations, such as carbide precipitation and coarsening, while martensite persists as the predominant phase. Hardness went up a little, from about 221 Hv to 226 Hv, but wear resistance went down, with more mass loss when dry friction was present. This shows that hardness alone does not directly affect wear performance; other parameters, like carbide dispersion, microstructure homogeneity, and residual stresses, are very important. So, tempering conditions need to be carefully optimized to get the right balance between hardness and wear resistance. This will make sure that the material works well in industrial settings where there is a lot of friction and heavy loads.

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Table (1) Chemical composition of the ASIS 420 under study

Samples	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Al%	Cu%	Fe%
	0.15	0.411	0.523	0.038	0.023	12.26	0.0255	0.263	<0.001	0.281	Bal.

Table (2) XRD results of ASIS 420 samples at room temperature and after Tempering

ASIS 420	2θ (deg)	FWHM (deg)	$d_{measured}$ (Å)	$d_{standard}$ (Å)	Rel. Intensity (%)
At Room Temp.	44.4573	0.32510	2.03619	2.07450	100
	64.6843	0.34700	1.43988	1.46689	11
After Tempering	44.6173	0.27300	2.02926	2.07973	100
	64.7828	0.24000	1.43793	1.47061	7

Table (3) Elemental analysis of AISI 420 at room temperature

Element	Line	Intensity	Error	K	Kr	W%	A%	ZAF	Pk/Bg
C	Ka	26.7	6.3470	0.0223	0.0211	6.91	25.47	0.3048	2.59
O	Ka	0.0	0.0000	0.0000	0.0000	0.00	0.00	0.6235	2.00
Cr	Ka	196.6	0.7713	0.1540	0.1455	12.50	10.65	1.1637	5.12
Fe	Ka	727.8	0.7713	0.8237	0.7781	80.59	63.89	0.9655	16.40
				1.0000	**0.9447**	**100.00**	**100.00**		

Table (4) Elemental analysis of AISI 420 after tempering

Element	Line	Intensity	Error	K	Kr	W%	A%	ZAF	Pk/Bg
C	Ka	36.2	9.3027	0.0309	0.0286	9.22	31.83	0.3098	3.91
O	Ka	0.0	0.0000	0.0000	0.0000	0.00	0.00	0.5977	2.12
Cr	Ka	211.6	0.9523	0.1693	0.1563	13.64	10.88	1.1460	6.52
Fe	Ka	692.0	0.9523	0.7998	0.7384	77.14	57.29	0.9572	19.55
				1.0000	**0.9232**	**100.00**	**100.00**		