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Mechanical and Fatigue behavior of G22NiMoCr5-6 and G18NiMoCr3-6 used in heavy-duty crawler track plates

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Abstract

G22NiMoCr5-6 and G18NiMoCr3-6 steels are commonly used in the manufacturing of crawler track plates of heavy-duty equipment due to their enhanced mechanical properties which allow them to be suitable for this particular application. This research aims to investigate the mechanical and fatigue behavior of both material grades to evaluate their performance in the manufacturing of heavy-duty crawler track plates. In the present work, experimental investigations were carried out including chemical composition, tensile, hardness, Charpy impact, and low-cycle fatigue tests. Also, metallographic examination was conducted to show the microstructure of both materials. Based on the experimental analysis results, the bainitic structure of G18NiMoCr3-6 was found to have longer fatigue life and higher toughness than the tempered-martensitic structure of G22NiMoCr5-6 which qualifies G18NiMoCr3-6 to be more suitable for manufacturing of heavy-duty crawler track plates than G22NiMoCr5-6 steel.

Keywords: G22NiMoCr5-6, G18NiMoCr3-6, Mechanical testing, Microstructure, Fatigue, Crawler track plates

Introduction

There is an increasing demand for high-strength low-alloy (HSLA) steels in the manufacturing of heavy-duty mechanical parts and structural applications. It meets specific mechanical properties such as strength, toughness, formability, ductility, weldability, and corrosion resistance together to be used in specific applications that require all these properties with optimum values [1]. G22NiMoCr5-6 and G18NiMoCr3-6 steels are a sub-category of HSLA steels that are widely used in heavy-duty mechanical and industrial applications for their high wear resistance and ultra-high tensile strength that ranges from 780 to 1200 MPa. These extraordinary mechanical characteristics of G22NiMoCr5-6 and G18NiMoCr3-6 steels make them a very suitable choice for applications that are exposed to heavy loads and high stresses such as heavy crane components [2]. In addition, the development of such materials with these characteristics and mechanical properties made it possible to develop the capabilities of heavy cranes and other equipment in the industry of heavy equipment over time.

In this regard, A. Ryzhkov et al. investigated the influence of microstructure on the impact energy of Cr-Ni-Mo alloy that is used in heavily loaded applications. They found that manufacturing this grade of material using carbon content that ranges from 0.10 to 0.15 wt.% and slow cooling rate produces alloy with bainitic structure and high impact energy [3]. Also, V. G. Laz'ko et al. investigated the influence of carbon content on the strength and toughness of steel. They found that the increase of carbon content within the chemical composition increases the strength and decreases the toughness of steel [4, 5].

W. Garrison studied the influence of nickel and silicon content on the strength and impact energy of steels. The strength shows an increase with the increase of silicon, while it decreases with the increase of nickel. And the impact energy increases with the increase of Si and Ni [6]. Also, the influence of nickel on the mechanical properties of steel was studied by H. Y. Dong et al. They found that hardness and elongation increase with the addition of nickel [7]. The effect of molybdenum on the mechanical properties of high-strength steels was studied by Z. Chen et al. With the addition of Mo, the strength shows an increase while the ductility shows a reduction [8].

The effect of chromium content on the tensile properties of steel welds was studied by M. Gharavol et al. The researchers found that when Cr increases, the strength increases while ductility decreases [9]. Also, P. Machmeier et al. studied the effect of chromium content on the impact energy of ultra-high strength steel. They found that with the increase of Cr content, impact energy increases [10].

H. Fan et al. investigated the effect of tempering temperatures on the tensile properties of G18NiMoCr3-6. They found that strength and hardness decrease as the tempering temperature increases. However, ductility and impact energy decrease as the temperature is below 400 ℃ and increase for temperatures that exceed 400 ℃ [11]. Also, Y. Zhu et al. studied the effect of tempering process parameters on and mechanical properties of G18NiMoCr3-6. They found that with the increase of tempering temperature, strength and hardness decreases, while ductility and impact energy increases. Mechanical properties also were found to have the same trending results affected by the tempering time parameter [12]. C. Tang et al. studied the effect of the induction hardening process on G18NiMoCr3-6 steel. The researchers found that the hardening surface depth increases as the moving speed decreases. G18NiMoCr3-6 shows a martensitic microstructure after the hardening process carried out using different moving speeds [13].

S. Nagel et al. investigated the fatigue behavior of G22NiMoCr5-6 steels with internal defects. They found that the number of cycles until fracture was plotted between $1 \bullet 10^4$ and $1 \bullet 10^7$ cycles versus stress level that ranges from 150 to 570 MPa [14].

In manufacturing of crawler track plates, fatigue behavior is a very important factor to consider. Track plates are exposed to fluctuating tension/loose cyclic loading as shown in Fig. 1 with a magnitude between minimum and maximum values every cycle which is the total length of the chain track. In addition, another fatigue fluctuation resulting from the rotation of the sprocket with an angle equal to the pitch angle exposes the track plates to fluctuating loads that range from the maximum tension and a little lower than the maximum value.

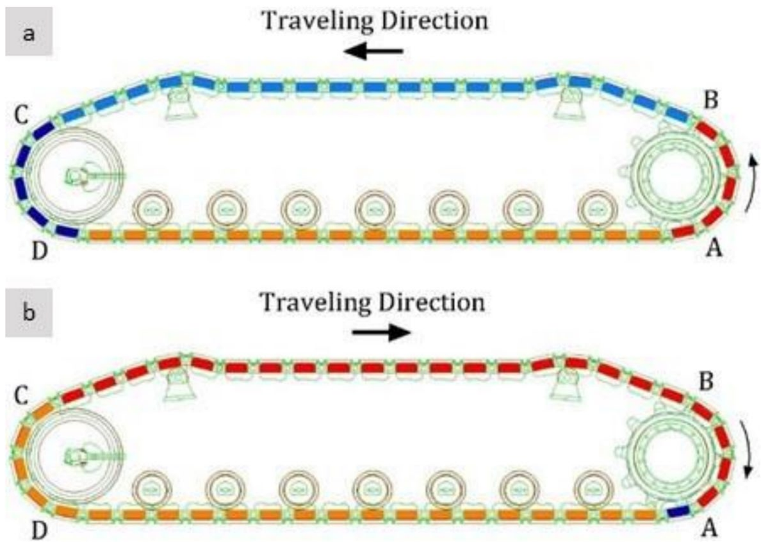

Fig. 1 Loading on crawler tracks traveling **a** forward and **b** backward

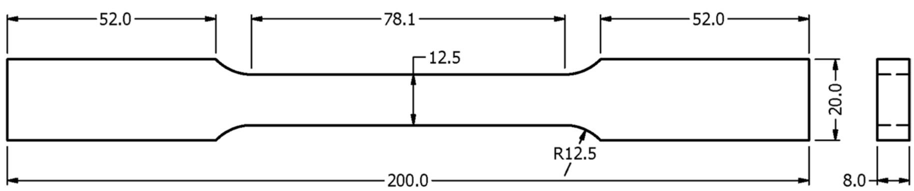

Fig. 2 Geometry of tensile test specimens

This research aims to investigate the mechanical and fatigue behavior of G22NiMoCr5-6 and G18NiMoCr3-6 steels to evaluate their performance in heavy equipment industry applications, especially in the manufacturing of heavy-duty crawler track plates.

Methods

Samples extracted from crawler track plates made of G22NiMoCr5-6 and G18NiMoCr3-6 were used to implement the experimental methodology within this research. Chemical composition was investigated by an optical emission spectrometer instrument according to ASTM A751 [15]. Also, scanning electron microscopy (SEM) was used to examine the microstructure according to ASTM E3 [16]. Specimens were grinded and polished, then they were etched in 2% nital solution.

A tensile test was conducted according to ASTM E8/E8M standard [17]. The test was done using a 600-kN universal testing machine (model 602, Tinius-Olsen TMC, USA). Figure 2 shows the dimensions of specimens used to conduct the tensile test.

V-notch Charpy impact test at room temperature was implemented according to ASTM E23 standard [18] using a Zwick/Roell pendulum impact tester (model RKP 450, Zwick/Roell Amsler, Germany). Figure 3 shows the dimensions of specimens used to conduct the V-notch charpy impact test.

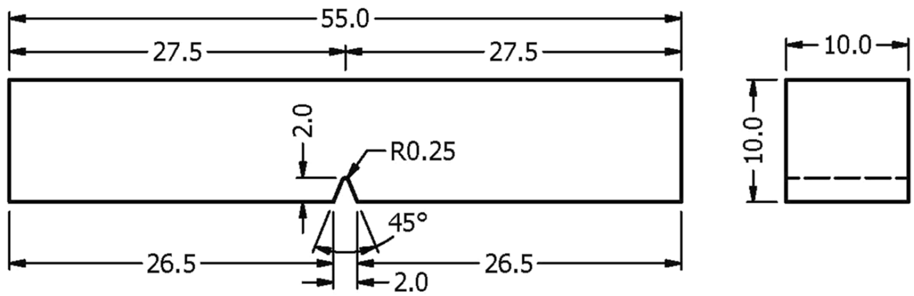

Fig. 3 Geometry of Charpy-impact test specimens

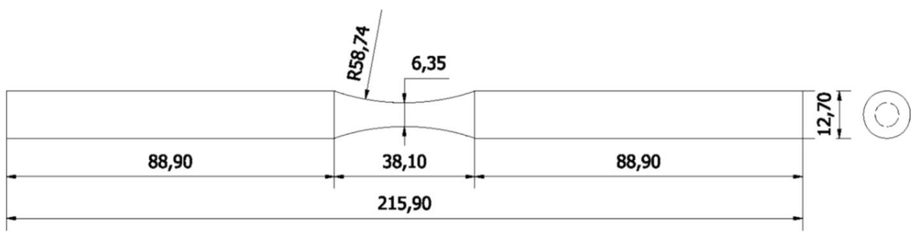

Fig. 4 Geometry of fatigue test specimens

Rockwell hardness was measured as well according to ASTM E18 [19]. In addition, the rotating beam bending fatigue testing machine model RBF-200 HT (System Integrator LLC, USA) was used to conduct fatigue test according to ASTM E606/E606M [20]. The geometry of the recommended hourglass round test specimen is shown in Fig. 4 according to instructions illustrated in the operation manual of the bending fatigue testing machine [21].

A fatigue test was done on 8 specimens of each material at a stress level of 625 MPa. For steels, the endurance limit (σe) can be estimated to be half of the ultimate tensile strength (UTS) according to the formula σe = 0.5*UTS [22], it is very important that the selected stress value for the implementation of the fatigue test to be higher than the endurance limit. Otherwise, the test will take a long time to be completed and the specimen may not fracture. On the other hand, the selected stress value shall be less than the value of yield stress to avoid static fracture as possible. So, the stress value of 625 MPa is selected for the implementation of the fatigue test as an approximate median value between the estimated endurance limit and yield strength.

Results and discussion

Chemical analysis

The results of the chemical composition of both G22NiMoCr5-6 and G18NiMoCr3-6 are shown in Table 1, along with the specified chemical composition recommended by relevant standard. It shows an average of 48% excess in carbon content and a 29% reduction in molybdenum content for G22NiMoCr5-6 samples. Also, a relatively high content of nickel is found. Nickel improves the fracture toughness of the alloy. In addition, wear resistance, ductility, hardness, and fatigue resistance are expected to be enhanced by the contribution of chromium with nickel [23, 24].

Table 1 Results of chemical composition analysis of G22NiMoCr5-6 and G18NiMoCr3-6

Material	Sample	Element content (%)						
		C	Si	Mn	Ni	Mo	Cr	P
G22NiMoCr5-6	S-1	0.38	0.45	0.97	1.32	0.33	1.02	0.014
	S-2	0.33	0.43	0.82	0.92	0.38	0.97	0.008
	Specified	0.18–0.24	≤ 0.6	0.8–1.2	0.8–1.3	0.5–0.7	0.5–1.0	≤ 0.015
G18NiMoCr3-6	S-1	0.18	0.33	1.06	0.95	0.60	0.85	0.011
	S-2	0.17	0.41	0.86	0.62	0.65	0.76	0.007
	Specified	0.17–0.22	≤ 0.6	0.8–1.2	0.6–1.0	0.4–0.7	0.4–0.9	≤ 0.020

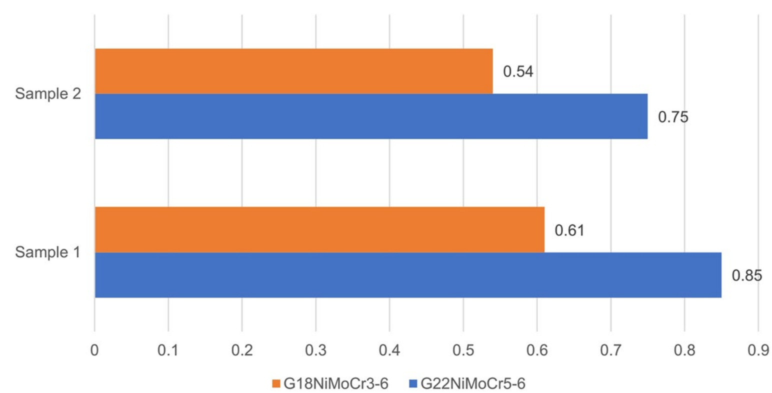

Fig. 5 Carbon equivalent of G22NiMoCr5-6 and G18NiMoCr3-6

On the other hand, G18NiMoCr3-6 results show a perfect alignment with the standard. G18NiMoCr3-6 steel samples maintain a reasonable carbon content while relying on the content of the molybdenum and manganese, which solutes harden ferrite to enhance the ultimate tensile strength while maintaining a good weldability and fracture toughness.

To obtain high-strength steel with good weldability and fracture toughness, the minimum carbon content is used as possible, while enhancing the strength by the addition of a small amount of other alloying elements to the composition. For this reason, it is appropriate to use the concept of carbon equivalent (CE) when dealing with iron-carbon alloys to figure out the influence of alloying elements' content on strength, fracture behavior, and weldability. Various formulas have been proposed to calculate the carbon content in steels. In this paper, carbon content is calculated and plotted in Fig. 5 using the results shown in Table 1 and the formula $CE = C + Si/24 + Mn/6 + Ni/40 + Cr/4 + V/14$ [25].

G22NiMoCr5-6 shows an average carbon equivalent of 0.8 which is approximately 40% higher than that of G18NiMoCr3-6 which records an average of 0.58. Increasing in carbon equivalent means that weldability and impact energy decrease [26, 27].

Microstructure

The microstructure was observed by SEM. The observation results reveal that the microstructure of G22NiMoCr5-6 is a tempered-martensitic structure as shown in

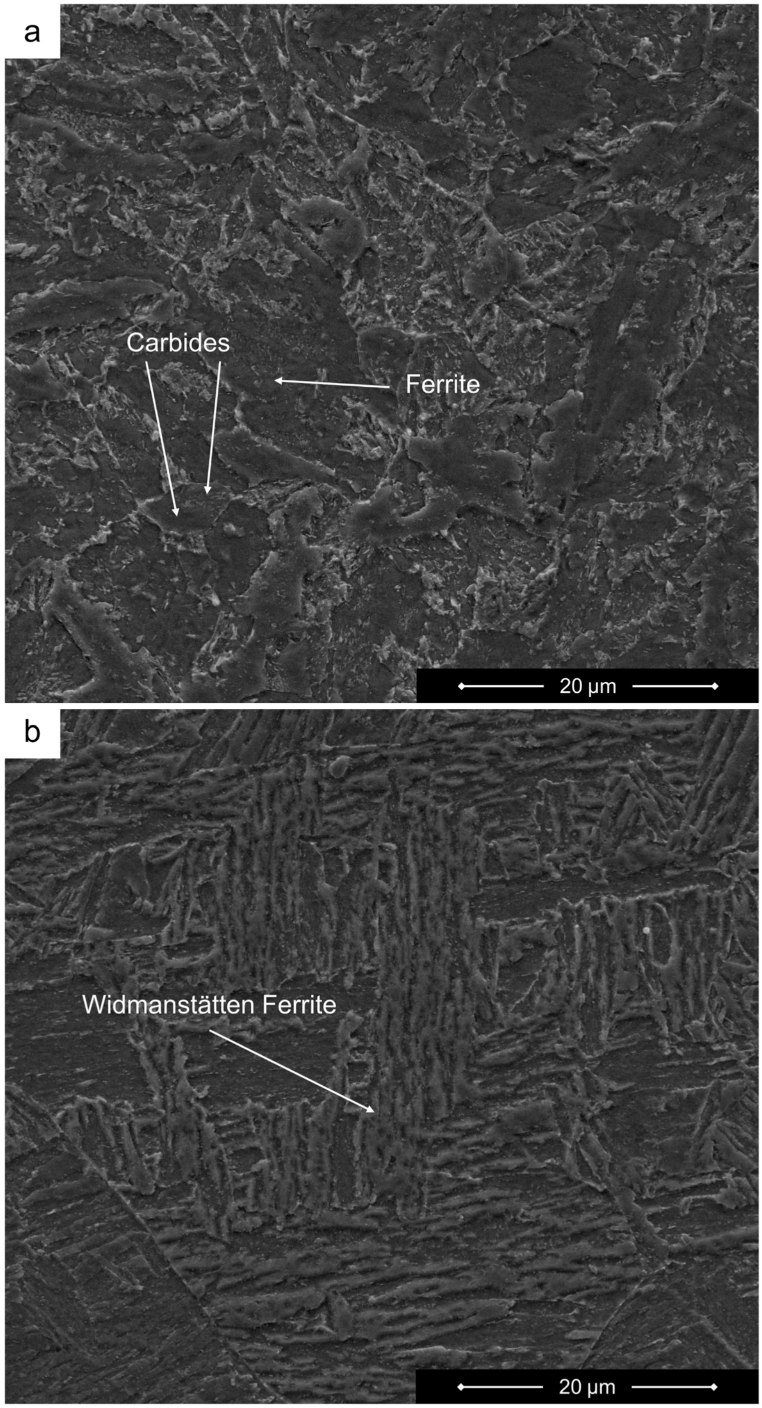

Fig. 6 Microstructure result of **a** G22NiMoCr5-6 and **b** G18NiMoCr3-6

Fig. 6a. Martensite is found in the structure due to the presence of carbon element with high concentration in the chemical composition.

On the other hand, G18NiMoCr3-6 shows a bainitic structure, which is detected due to the formation of a high density of plate-like ferrite in the structure as shown

Table 2 Results of mechanical testing of G22NiMoCr5-6 and G18NiMoCr3-6

	Sample	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Rockwell hardness
G22NiMoCr5-6	T-1	853	949	12.5	35
	T-2	749	896	14.3	30
	T-3	670	893	15.7	25
	Mean	757	913	14.2	30
	Standard error	43.3	14.8	0.8	2.4
	Specified	≥ 825	930–1080	≥ 10	
G18NiMoCr3-6	T-1	868	919	15.5	25
	T-2	781	881	8.6	20
	T-3	755	920	12.8	35
	Mean	801	907	12.3	27
	Standard error	27.9	10.5	1.6	3.6
	Specified	≥ 630	780–930	≥ 12	

Table 3 Results of impact energy test of G22NiMoCr5-6 and G18NiMoCr3-6

	Sample	Impact energy (joules)	Mean (joules)	Standard Deviation	Specified (joules)
G22NiMoCr5-6	I-1	28	30	1.9	≥ 50
	I-2	28			
	I-3	35			
G18NiMoCr3-6	I-1	85	97	5.9	≥ 40
	I-2	95			
	I-3	110			

in Fig. 6b. Bainite is formed at a higher temperature than martensite and the cooling rate is less rapid than that is required to form martensite. This allows for finer grains in the bainite than that of tempered martensite, consequently, producing steel that has better mechanical behavior for heavy-duty applications [28].

Mechanical properties

Tensile, hardness, and Charpy V-notch impact tests were conducted. The mechanical test results for G22NiMoCr5-6 and G18NiMoCr3-6 are presented in Table 2. The tensile test shows a ductile fracture mode which was detected by the presence of necking in the specimens due to applying a tension load beyond the elastic limit and absorption of more energy before fracture. The yield strength of G22NiMoCr5-6 is 8.24% lower than the value specified by the standard, while G18NiMoCr3-6 results show a perfect match to those values specified by the standard.

In addition, the Impact energy of G22NiMoCr5-6 shows a reduction of 40% less than the specified value. While impact energy of G18NiMoCr3-6 is approximately 2.4 times the value specified by the standard. As a comparison between both materials, G18NiMoCr3-6 shows an increase in impact toughness by 223% more than that of G22NiMoCr5-6. Impact energy results are presented in Table 3.

The reduced value of impact energy of G22NiMoCr5-6 steel is due to the excess amount of carbon content in the alloy more than the specified values. Which consequently increases carbide precipitation and raises the equivalent carbon content in the alloy [4, 26]. Otherwise, the results show that the tensile properties are almost the same for both materials, and the tensile test results show a good alignment with hardness test results.

Impact fracture may be brittle or ductile failure mode depending on the temperature environment of the test. This can be detected using a scanning electron microscope to measure the percentage of brittle fracture surface area to the total fracture surface area. Generally, the fracture mode tends to be more brittle failure at lower test temperatures.

Fatigue test

All fatigue specimens of both G22NiMoCr5-6 and G18NiMoCr3-6 steels are subjected to a rotating bending fatigue test at the same stress value equal to 625 MPa rather than to be tested at the same percent of ultimate tensile strength. to give a comparison of performance between the two grades of steel in the same particular application. Fatigue failure is brittle failure mode; this failure can be detected by the presence of striations in the fractography using a scanning electron microscope.

Fatigue test results are presented in Table 4. G18NiMoCr3-6 shows a mean value approximately 2.55 times greater than that of G22NiMoCr5-6 at the same stress value of 625 MPa. As the fatigue life of G18NiMoCr3-6 is longer than that of G22NiMoCr5-6, this makes it more suitable for use in the application of crawler track plate manufacturing because fatigue behavior is a critical factor in this particular application.

Table 4 Results of fatigue test of G22NiMoCr5-6 and G18NiMoCr3-6

Material	Sample No	Stress level (MPa)	No. of cycles (N) ($\times 10^4$)	Mean value ($\times 10^4$)	Standard deviation
G22NiMoCr5-6	F-1	625	1.47	1.07	0.1
	F-2		0.74		
	F-3		1.45		
	F-4		0.75		
	F-5		1.04		
	F-6		0.98		
	F-7		0.95		
	F-8		1.21		
G18NiMoCr3-6	F-1	625	1.68	2.73	0.3
	F-2		2.39		
	F-3		4.59		
	F-4		3.72		
	F-5		2.04		
	F-6		2.76		
	F-7		1.81		
	F-8		2.86		

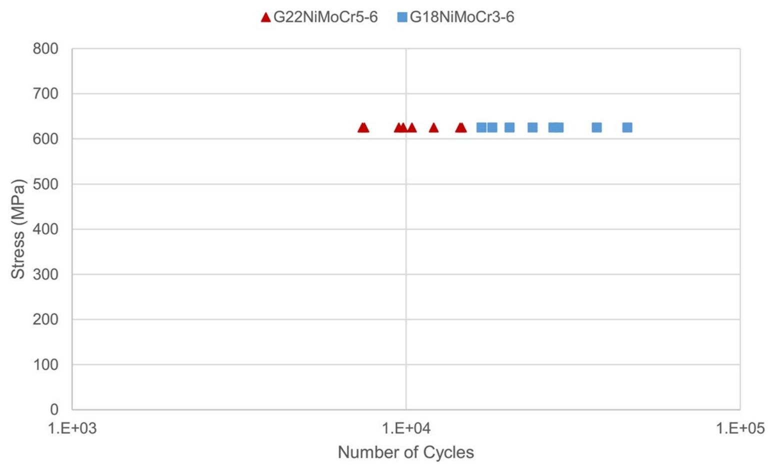

Fig. 7 Logarithmic scale plot of fatigue test results

Figure 7 shows a logarithmic scale plot for the fatigue test results for both materials in means of stress versus the number of cycles until failure.

G18NiMoCr3-6 exhibits a longer fatigue life than G22NiMoCr5-6 due to its bainitic structure. During the tempering process of martensite, carbide films are formed, these films raise the concentration effect which results in a poor fatigue performance of G22NiMoCr5-6 tempered-martensitic steel [29].

Conclusions

In this paper, the mechanical and fatigue behavior of G22NiMoCr5-6 and G18NiMoCr3-6 were studied. This research aims to evaluate the performance of these grades of material in the manufacturing of heavy-duty crawler track plate applications. Based on the experimental analysis results, the following conclusions are presented:

1. G18NiMoCr3-6 steel is more suitable for manufacturing of heavy-duty crawler track plates than G22NiMoCr5-6 steel; G18NiMoCr3-6 steel has a bainitic structure while the structure of G22NiMoCr5-6 is tempered martensitic structure.
2. G18NiMoCr3-6 shows a higher impact toughness of 97 J with an increase of 3.2 times that of G22NiMoCr5-6 which shows only 30 J.
3. Fatigue life at 0.69 of ultimate tensile strength shows 27,300 cycles for G18NiMoCr3-6 with an increase of 2.55 times that of G22NiMoCr5-6 which results in 10,700 cycles while the other tensile properties for both steels are almost the same; this recommends that the bainitic structure has longer fatigue life and higher toughness than the tempered martensite structure under heavy loading.

Abbreviations

HSLA	High-strength low-alloy
SEM	Scanning electron microscope
σe	Endurance limit
UTS	Ultimate tensile strength
CE	Carbon equivalent

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Not applicable

Authors' contributions
AE has conducted the chemical analysis, microstructure, mechanical tests, and fatigue tests and wrote the paper manuscript. EE suggested the research idea, planned the methodology, and explained the microstructure results. SS analyzed test results and explained the mechanical behavior.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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