Influence of Cr element on impact fracture process of ductile Ni-resistant alloyed iron at low temperature

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Abstract: In this study, in order to investigate the influence of Cr element on the impact fracture process of ductile Ni-resistant alloyed iron at low temperature, different contents of Cr element were added to ductile Ni-resistant (DNR) austenitic alloyed iron. The experimental results show that Cr addition can increase the hardness of the DNR alloyed iron, but it has a destructive effect on low-temperature impact properties. Through the analysis of the dynamic load and absorbed energy of samples with different Cr contents in the impact fracture process, and the comparison of the impact fracture process at room and low temperatures, it reveals that Cr addition into the DNR alloyed iron can facilitate the formation of the carbide mixture in $Mn_{23}C_6$ and $Cr_{23}C_6$ with homogeneous and discontinuous distribution. Meanwhile, Cr addition also can improve the the maximum dynamic load and crack initiation energy at low temperature, but has no obvious effect on the yield behavior of the DNR alloyed iron in the impact fracture process. Compared with the impact crack propagation process at room temperature, the metastable propagation energy at low temperature declines significantly with an increase in Cr content. This is because the micro-cracks that caused by the carbides weaken the matrix, resulting in the decline of impact crack propagation resistance. The fracture analysis results also show that the impact fracture mechanism gradually transforms from ductile to brittle with an increase in Cr content at low temperature. It explains that too much Cr addition can lead to brittle fracture even though the austenitic matrix has a good toughness at low temperature.

Key words: Ni-resistant alloyed iron; carbide; impact fracture; low temperature; Cr addition

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Commonly, conventional ductile cast irons all have a ductile-brittle transition temperature at low temperature, which is determined by the properties of the matrix. Ductile Ni-resistant (DNR) alloyed iron with a stable austenitic matrix does not have the ductile-brittle transition phenomenon, so it can still retain good impact properties even at quite a low temperature. Additionally, DNR alloyed iron has superior machinability and castability. Therefore, it is widely applied in the manufacture of low temperature mechanical equipment parts^[1-4]. However, as an austenitic matrix alloy, it has relatively low hardness, so it cannot meet the design requirements in specific conditions such as in a high frictional wear environment. It is stated clearly that Cr

element addition can promote the formation of carbides in the DNR alloyed iron, and can also improve its hardness. However, the related studies all focused on the tensile properties at room and high temperatures, and there is little in the literature concerning the influence of Cr element addition on the impact fracture process at low temperature and no explanation about the phenomenon from the aspects of force and energy^[5-8]. Therefore, in this study, the dynamic load and absorbed energy of different Cr contents in the DNR alloyed iron during the impact fracture process were analyzed, and the impact fractures at room and low temperatures were compared. Finally, the influence of Cr element addition on the impact fracture process of ductile Ni-resistant alloyed iron was discussed.

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1 Experimental procedure

In this study, there were three kinds of DNR iron: (a) 0.1Cr-4Mn-23Ni; (b) 0.5Cr-4Mn-23Ni and (c) 0.9Cr-4Mn-23Ni. Carbon and silicon were controlled in the

range of 2.7wt.% to 2.9wt.% and 1.8wt.% to 2.0wt.%, respectively.

Y-block castings with a 25-mm thickness were prepared according to ASTM A571/A 571M^[9]. With the pendulum impact tester (MTS ZCJ1000), V-notched bar impact tests were carried out at room and low temperatures, following ASTM E 23^[10]. The Vickers hardness was tested following ASTM E384^[11].

Metallographic samples were cut from the broken half of the impact test specimens for microstructural observation using optical microscopy (OM) OLYMPUS BX60F5, and the other broken half of the impact test specimen was used for fractographic analysis using scanning electron microscopy SEM Hitachi S-3400N. In addition, the amount of graphite spheroid, carbide and austenitic matrix in the microstructure was measured according to ASTM A247^[12].

2 Results and discussions

The impact values and hardness of the DNR alloyed iron in this experiment are shown in Table 1. With an increase in the Cr content, the hardness has a steady increase, and the impact values present a decreasing trend. It can be seen from the impact values of samples with the same Cr content at room and low temperatures (-196 °C) that when the Cr content is 0.1wt.% and 0.5wt.%, the impact values differences are 1.78 J and 5.78 J, respectively, while it achieves 7.76 J at 0.9wt.% Cr. This shows the Cr content in the DNR alloyed iron has a strong sensitivity to low temperature.

Table 1: Impact value and hardness of DNR alloyed iron

Alloyed iron	Impact value (J) RT	Impact value (J) -196 °C	Hardness (HV)
0.1Cr-4Mn-23Ni	25.28	23.50	139
0.5Cr-4Mn-23Ni	22.94	17.16	151
0.9Cr-4Mn-23Ni	21.66	13.90	176

Figure 1 shows the microstructures of the DNR alloyed iron containing different amounts of Cr element. X-ray diffraction analysis (Fig. 2) and microstructural analyses verified that the microstructure is composed of the mixture of austenite, carbides and graphite, and the carbides are in the mixture of $Mn_{23}C_6$ and $Cr_{23}C_6$. The amount of each of constituents in the microstructures is listed in Table 2. The result shows that when Cr element is added in the

Fig. 1: Microstructure of DNR alloys:
(a) 0.1Cr-4Mn-23Ni,
(b) 0.5Cr-4Mn-23Ni and (c) 0.9Cr-4Mn-23Ni

Fig. 2: X-ray diffraction pattern of DNR alloyed iron (0.9Cr-4Mn-23Ni)

DNR alloyed iron, the graphite spheroid count has a decreasing trend and the number of carbides has an increasing trend. The microstructure observation shows that the morphology of the carbides presents irregular strip, which are located at the interfaces of austenitic grains, and the distribution of carbides is homogeneous and discontinuous. This fully corresponds to the solidification characteristic of Cr and Mn element in the DNR alloyed iron^[13].

SEM micrographs taken from the broken halves of impact test specimens at room temperature and low temperature (-196 °C) are shown in Fig. 3. At room temperature [Fig. 3(a, b and c)] a large number of dimples around the graphite spheroid or broken graphite spheroid craters appear on the fracture surface, and the dimension of dimples is between 100 μm to 300 μm . It presents a ductile fracture pattern. With an increase in Cr content, a few micro-cracks can be found on the interface between the austenitic grains rather than the interface between the matrix and graphite spheroids. It shows that the micro-cracks are caused by the carbides located at the grain interfaces rather than the deformation of forced graphite spheroids in the impact process. Also it is observed that this kind of micro-crack cannot

generally extend to the dimples on the impact fracture surface, so it only has limited destruction effect on the impact fracture process. At low temperature, the number of micro-cracks is obviously more than that at room temperature. Generally, the austenite has good toughness, therefore, when the Cr content is 0.1wt.% and 0.5wt.%, the fracture way is still ductile fracture at low temperature [Fig. 3(d and e)]. However, too much Cr addition into the DNR alloyed iron will leads to brittle fracture. This is decided by the different deformation characteristics between austenite and carbides at low temperature^[14]. When the forced matrix begins the plastic deformation, the austenite with a fcc structure still has a good plasticity, while M_{23}C_6 type carbide with a complex cubic structure is relatively weak in this situation^[15]. This is because of their differences in the plastic deformation that produced the internal stress on the interface between the austenite and carbide, which leads to the final decline of plastic property in the matrix. The austenitic matrix is cut off by the reticular distribution of micro-cracks and the impact fracture crack can pass through the dimples easily and only small amount of energy can hinder the crack propagation in the impact process. When Cr addition reaches 0.9wt.%, it only has few dimples on the fracture surface (Fig. 3f), and the carbides have a great destruction effect on the impact fracture process^[16].

The data of dynamic load and absorbed energy were recorded in the impact fracture process. Figure 4 shows the curves of the dynamic load and absorbed energy with the deflection in the impact fracture process. The yield load (F_y), elastic deflection (D_e), yield energy (E_y), maximum dynamic load (F_m), maximum dynamic load deflection (D_m), initiation energy (E_i), propagation energy (E_p), metastable propagation energy (E_{mp}), unstable

Table 2: Amounts of constituents in microstructures of DNR alloyed iron with different Cr contents

Materials	$\gamma\text{-Fe}$ (%)	Carbide (%)	Nodule count (no. $\cdot\text{mm}^{-2}$)
0.1Cr-4Mn-23Ni	99.13	0.42	68
0.5Cr-4Mn-23Ni	97.91	1.33	53
0.9Cr-4Mn-23Ni	96.62	2.71	44

Fig. 3: SEM micrographs of DNR alloyed irons after impact test: (a) (d) 0.1Cr-4Mn-23Ni, (b) (e) 0.5Cr-4Mn-23Ni, (c) (f) 0.9Cr-4Mn-23Ni, and (a)–(c) at room temperature, (d)–(f) at low temperature (-196 °C)

propagation energy (E_{up}) and total energy (E_t) in the impact fracture process are listed in Table 3.

There are several peaks in the dynamic load curve. The distance between the adjacent peaks is in the range of 0.3 mm to 0.4 mm, which is close to the size of dimple layers. It is known that the plastic deformation of the interlaced austenitic grains hinders the impact crack propagation, and ultimately facilitates the formation of dimple layers. The dynamic load peaks are formed in the impact fracture process. All the yield loads (F_y) and yield energy (E_y) are almost the same. It is confirmed that the changes in temperature and Cr addition have no obvious effect on the yield behavior of the DNR alloyed iron.

At room temperature, the dynamic loads present several similar peaks, and their decreasing trend is quite gradual. The maximum dynamic loads (F_m) and the initiation energy (E_i) can remain relatively stable with an increase in Cr content. It suggested that Cr addition into the DNR alloyed iron does not accelerate the crack initiation in the plastic deformation zone. The ratios of the propagation energy and the total energy (E_p/E_t) in the three alloyed irons are 89.32%, 87.80% and 87.49%, respectively. The metastable propagation energy in the impact crack propagation process slightly decreases from 13.98 J to 11.77 J with the increase in the Cr content, and the ratios of the metastable propagation energy and the propagation energy (E_{mp}/E_p) in the three alloyed irons are 55.3%, 54.5% and 54.3%, respectively. Fracture analysis results also show that a large number of dimples present on the fracture and the micro-cracks cannot extend through the dimples.

All the results verify the ductile fracture mechanism at this time.

At low temperature, the maximum dynamic loads (F_m) and the initiation energy (E_i) all are significantly higher than those at room temperature. The dynamic loads also present absolutely different peaks, and the decline of the peaks is very steep. When the Cr content is 0.1wt.%, the metastable propagation energy still reaches 12.42 J and the ratio of the metastable propagation energy and the propagation energy (E_{mp}/E_p) can also remain above 50%. It shows the same ductile fracture mechanism as at room temperature. With an increase in Cr content, the impact crack propagation process shows a significant difference, and the metastable propagation energy has a drastic decline. When the Cr content is 0.9wt.%, the E_{mp} falls to 4.94 J, and the ratio of E_{mp} and E_p is only 35.5%. The ratios of propagation energy and total energy (E_p/E_t) in the three alloyed irons also drop to 80.73%, 75.47% and 76.91%, respectively. Fracture analysis results show that a large number of micro-cracks present on the boundaries of the austenitic grains, which are prone to accelerate the impact crack propagation. Although the crack initiation energy at low temperature is higher than that at room temperature, the impact crack has less resistance in the impact crack propagation process. The impact crack can pass through the matrix more easily at low temperature, and the impact fracture mechanism gradually transforms from ductile to brittle at low temperature.

Due to the dimples commonly having a correlation with graphite spheroids in the DNR alloyed iron, the number of graphite spheroids and broken graphite spheroid craters on the impact

Fig. 4: Curves of dynamic load and absorbed energy: (a) at room temperature and (b) at low temperature (-196 °C)

Table 3: Data of dynamic load and absorbed energy in impact fracture process

Materials	T (°C)	$F_y/D_e/E_y$ (kN/mm/J)	$F_m/D_m/E_i$ (kN/mm/J)	E_p (J)	E_{mp} (J)	E_{up} (J)	E_t (J)
0.1Cr-23Ni-4Mn	RT	7.41/0.46/0.50	10.50/0.85/2.70	22.58	13.98	8.60	25.28
	-196	7.37/0.43/0.58	18.89/0.88/4.53	18.97	12.42	6.55	23.50
0.5Cr-23Ni-4Mn	RT	7.36/0.47/0.47	10.61/0.92/2.80	20.14	12.51	7.63	22.94
	-196	7.45/0.43/0.45	16.76/0.91/4.21	12.95	7.57	5.38	17.16
0.9Cr-23Ni-4Mn	RT	7.61/0.46/0.50	10.81/0.86/2.71	18.95	11.77	7.18	21.66
	-196	7.79/0.44/0.45	14.46/0.87/3.21	10.69	4.94	5.75	13.90

fracture surface and the amount ratio (on the impact fracture surface/on the microstructure) were counted in order to analyze the main fracture locations on the impact fracture surface. The results are shown in Fig. 5 (a) and (b). It can be found that the 0.1Cr-4Mn-23Ni alloyed iron has the largest number of graphite spheroids and broken graphite spheroid craters on the impact fracture surface at room and low temperature (67 and 64). This suggests that the main fracture is caused by graphite spheroids based on the fragile nature of graphite spheroids. With the increasing of Cr content in the DNR alloyed iron, the amount ratio presents a decreasing trend, and this is more obvious at low temperature. When Cr content reaches 0.9wt.%, it only has 56.8% graphite spheroids on the fracture surface at low temperature. The micro-cracks become the main fracture sources instead of the graphite spheroids. This further explains why the low temperature and the amount of carbides have an important effect on the impact fracture process of the DNR alloyed iron.

Fig. 5: Number of graphite spheroids and broken graphite spheroid craters on the impact fracture surface and the amount ratio (on the impact fracture surface/on the microstructure)

3 Conclusion

In summary, Cr addition into the DNR alloyed iron can facilitate the formation of the carbide mixture of $Mn_{23}C_6$ and $Cr_{23}C_6$ with homogeneous and discontinuous distribution. Therefore, the hardness of the DNR alloyed iron can be significantly improved. Additionally, Cr addition has no obvious effect on the yield behavior of the impact fracture process, but it can improve the maximum dynamic load and the crack initiation energy at low

temperature. Compared with the impact crack propagation process at room temperature, the metastable propagation energy presents an obvious decline with an increase in the Cr content at low temperature. This is because the micro-cracks that caused by the carbides weaken the matrix, resulting in the decline of impact crack propagation resistance. The final fracture analysis results show that the impact fracture mechanism gradually transforms from ductile to brittle with an increase in Cr content at low temperature. It is verified that too much Cr element addition still can lead to brittle fracture even though the austenitic matrix has a good toughness at low temperature.

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