Effect of progressive solid-solution treatment on microstructures, mechanical properties and impact abrasive wear behavior of alloyed high manganese steel

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Abstract
Alloyed high manganese steel is a general type of wear-resistant steel, and its precipitates and austenite matrix grain sizes play an important role in impact abrasive wear behavior. Solid-solution treatment is an effective method to balance the size of the austenite grains and precipitates. This work attempts to find a new progressive solid-solution treatment to make alloyed high manganese steel castings refine the microstructure and balance the wear resistance under impact abrasive wear conditions. Compared with traditional solid-solution treatment, the MC- and M23C6-type carbide precipitates resulting from progressive solid-solution treatment decrease, and the tensile strength and impact toughness of steel are significantly increased. After the solid-solution treatment at different heating rates, the grain refinement effect is remarkable after shortening the holding time at 1100 °C and increasing the heating rate to 150 °C h⁻¹. The impact abrasive wear test results show that, compared with the traditional solid-solution treatment at 1100 °C for 4 h, the wear resistance of high manganese steel has a 23.1% improvement after progressive solution treatment at 1100 °C for 2 h, and the wear failure forms of all the experimental steels are microcutting, oxidation wear and plastic deformation.

1. Introduction
As a traditional wear-resistant material, high manganese steel was invented by Hadfield more than 130 years ago. Because of its excellent work hardening ability and good wear resistance, it has been widely used in high-wear industrial fields such as railways, mining, and impact hammers [1–5]. However, the development of industry over time has produced more complicated application conditions with higher service performance requirements for high manganese steel, such as strength and wear resistance. Therefore, some scholars have extensively studied improvement of the service performance of high manganese steel, mainly including its modification treatment and prehardening treatment [6–9]. Various new types of high manganese steel have been developed rapidly. Studies have pointed out that the good wear resistance of high manganese steel is due to its high hardness [10]. Pei et al [11] studied the wear mechanism of high manganese steel and pointed out that due to low initial hardness and yield strength, high manganese steel is easily pressed into abrasives to produce grooves, cutting and delamination pits, which cause more serious wear. In recent years, some researchers have demonstrated that adding hard particles (TiC, NbC and VC) to steel can strengthen the metal matrix, thereby improving the wear resistance of steel [12–14]. With the rapid development of controlled rolling and controlled cooling processes, some researchers have focused on the study of microalloyed high-strength steels [15]. The precipitation of nano-TiC increases the yield stress of steel [16]. The wear resistance of high manganese steel is improved by introducing V, and when Ti and V are introduced together, the wear resistance of steel is
2. Materials and methods

2.1. Materials and heat treatment

The test steel ingot was prepared by the traditional melting and casting process. Vacuum melting is carried out according to the chemical composition of alloy high manganese steel shown in table 1, and the casting temperature is 1530°C–1550°C. The size of as-cast ingot is Φ300 mm × 800 mm and the weight is 50 kg. In this study, the introduction of a small amount of Ti, V and Nb alloying elements can precipitate M(C, N) carbides, thereby pinning the grain boundaries, delaying the growth of austenite grains and significantly improving the mechanical properties of the steel [23]. The phase equilibrium diagrams were calculated with JMatPro (General Steel database) and Thermo-Calc (TCFE7 database) software, as shown in figures 1(a), (b). M(C, N) carbides are precipitated at 1290°C. Due to the excessive thickness of austenite steel castings and poor thermal conductivity, a four-stage solid solution process has been designed to avoid the occurrence of hot cracks [24]. MC and $M_{23}C_6$ carbides are produced when the casting is cooled to approximately 650°C and 350°C, respectively. The stability of austenite decreases, and then pearlite is formed. With increasing temperature, the pearlite clusters recrystallize as austenite. The austenite grains are refined. One report [25] pointed out that carbides are basically

| C  | Si  | Mn  | Cr  | Ti  | V  | Nb  | Cu  | Mo  | Ni  | P  | S  |
|----|-----|-----|-----|-----|----|-----|-----|-----|-----|----|----|
| 0.976 | 0.998 | 19.860 | 1.890 | 0.091 | 0.582 | 0.180 | 0.590 | 0.923 | 0.180 | 0.01 | 0.02 |

Table 1. Chemical composition of alloyed high manganese steel (wt.%)

significantly improved [17, 18]. However, less attention has been given to the role of alloyed high manganese steel in impact abrasive wear through appropriate heat treatment processes.

The microstructure of as-cast high manganese steel is generally composed of austenite and some network carbides at and near the grain boundary. The appearance of such network carbides when subjected to external forces can significantly reduce the toughness of the steel and then affect the overall mechanical properties of high manganese steel [19, 20]. Traditional high manganese steel castings are treated by water toughening to dissolve a large number of network carbides distributed in and near the grain boundaries, thereby obtaining a complete austenite microstructure and improving the mechanical properties of the steel. Similar to the solid-solution annealing and quenching of high-gap CrMnCN austenitic stainless steel, the precipitation of carbonitrides is avoided and a uniform microstructure is obtained [21]. However, in addition to the network carbides distributed in the as-cast microstructure of the high manganese steel after alloying treatment, some large-sized block or polygonal carbonitride precipitated phases will also be generated in situ, which contain more types of alloying elements. The microstructure of high manganese steel is complex and its distribution uniformity is poor, seriously affecting its mechanical properties. High manganese steel also has the characteristics of poor thermal conductivity and a high coefficient of thermal expansion. This results in thermal cracks due to internal stress if the temperature difference in different parts of the steel is large during heating. The traditional water toughening treatment process adopts the solid-solution method of continuous heating, which will easily cause austenite grains to coarsen. However, the large precipitated phase formed in situ is not easy to dissolve, and thermal cracks will occur when the casting is too thick. Therefore, it is particularly important to select an appropriate heat treatment process to dissolve the carbides precipitated in situ in the alloyed high manganese steel matrix and to improve the size and distribution of the second phase. Bandanadjaja et al [22] formulated two progressive solid-solution treatment processes for high manganese austenitic steel, each of which has two steps. One process is to heat it to 700°C for 3 h and then heat it to 1000°C for 1.5 h. The other involves heating to 600°C for 10 h, then heating to 980°C for 2 h, with a final water quench and cooling to room temperature. The results show that the grain refinement is remarkable, and the toughness is increased by more than 25% compared with the traditional solid-solution treatment. However, there are few reports on the heat treatment process of alloyed high manganese steel; the number of heat preservation steps in the heat treatment process has less influence on the microstructure, mechanical properties and wear resistance of alloyed high manganese steel.

In this study, alloyed high manganese steel was prepared using a traditional casting process. The traditional solid-solution treatment and a new progressive solid-solution treatment process were carried out on the castings. The mechanical properties of the steel were characterized by room temperature tensile tests, impact toughness tests and Brinell hardness tests. The wear resistance of the high manganese steel was studied by an impact abrasive wear test. The main purpose of the work reported in this paper is to eliminate a large number of toughness tests and Brinell hardness tests. The wear resistance of the high manganese steel was studied by an impact abrasive wear test. The main purpose of the work reported in this paper is to eliminate a large number of toughness tests and Brinell hardness tests. The wear resistance of the high manganese steel was studied by an impact abrasive wear test.
dissolved in the austenite matrix when the temperature is approximately 950 °C. Figures 1(a), (b) shows that holding at 950 °C for a period of time can ensure the dissolution of M7C3 carbides. To prevent the coarsening of crystal grains, the temperature of the highest holding stage is set at 1100 °C, and the progressive solid-solution treatment route is shown in figure 1(c). The specimen is cut from the cylindrical ingot away from the riser. The specimen size for heat treatment is 100 mm × 25 mm × 25 mm. The heat treatment process and nomenclatures of the steel are shown in table 2.

| No. | Holding temperature | Heating rate | 1100 °C holding time |
|-----|----------------------|--------------|----------------------|
| USS | —                    | —            | —                    |
| S75 | 1100 °C              | 75 °C h⁻¹    | 4 h                  |
| G75 | 550 °C–650 °C–950 °C–1100 °C | 75 °C h⁻¹ | 4 h                  |
| G150| 550 °C–650 °C–950 °C–1100 °C | 150 °C h⁻¹ | 2 h                  |

Figure 1. (a) Phase diagram of alloyed high manganese steel; (b) Thermodynamic equilibrium phase diagram; (c) Route map of progressive solid-solution treatment.

2.2. Microstructural characterization

The microstructure of as-cast and heat treated steels were studied by scanning electron microscopy (SEM, ZEISS EVO18-21-57) and electron backscatter diffraction (EBSD, OXFORD SYMMETRY). The specimen sizes for SEM and EBSD are 10 mm × 10 mm × 10 mm. The SEM specimens were ground on 2500 mesh SiC sandpaper and then corroded with a solution of 4% nitric acid in ethanol. The EBSD specimens were ground with water on 2500 mesh SiC sandpaper, polished with different micron-range diamond suspensions, and finally polished with silica polishing compounds for 20 min EBSD and Energy Dispersive Spectroscopy (EDS, ULTIM MAX170) were used to characterize the carbides in the as-cast microstructure of the test steel. The sizes
of grains and precipitates were calculated by Image-Pro Plus (version 6.0). To ensure the accuracy and reliability of the experiments, ten images were used in each process condition.

2.3. Mechanical properties tests
The specimen size for Brinell hardness test (HBE-3000A) is 15 mm × 15 mm × 10 mm, five points are randomly selected to measure the hardness on each specimen, and the average value is the final hardness value. The tensile test (AG-X 100kN) is carried out on a universal testing machine, and the tensile rate is 5 mm min⁻¹. To ensure the accuracy and reliability of the experiment, the specimens of each process are tested three times. The impact toughness test (JB-30B) specimen adopts the V-notch impact specimen size of the ASTM E23 metal Charpy (V-notch) standard. A fully automatic micro Vickers hardness tester (HMV-G-FA) was used to obtain the hardness distribution of the specimen after impact abrasive wear. The load was 0.1 kg and the pressure holding time was 10 s.

2.4. Impact abrasive wear test
The upper specimen size of the impact abrasive wear test (MLD-10) is 10 mm × 10 mm × 30 mm, as shown in figure 2(a). The hardness of the lower specimen is 45 HRC, and the speed is 200 r min⁻¹. Quartz sand is 40–70 mesh (figure 2(b)). The whole test is carried out under an impact energy of 4 J, the test time of each specimen is 240 min, each cycle is 30 min, and the preimpact wear of each specimen is 10 min before the formal impact test (to avoid the influence of the specimen itself on the result). After abrasion, an electronic balance (BSM-520 g/1 mg) is used to measure the weight loss of the specimen with an accuracy of 0.001 g. Three tests are performed on the specimen from each process. Finally, the surface morphology of the specimen after wear was observed via SEM.

3. Result and discussion

3.1. Microstructural characterization
Figure 3 shows the microstructure of USS (as-cast) steel. There are some irregular block and strip micron-sized precipitates and granular submicron precipitates in the microstructure. These precipitated phases are unevenly distributed in austenite, as shown in figures 3(a), (b). According to the EDS analysis of spectrum 1 in figure 3(a), it is mainly composed of C, Ti, V and Nb, as shown in figure 3(k). The size of this massive precipitate is approximately 15–25 μm and we speculate that it is MC type carbide. Such large-sized and unevenly distributed carbides may easily cause stress concentration during the drawing process of steel and reduce elongation. For strip precipitates with a size of approximately 25 μm, we have carried out EBSD phase identification, as shown in figures 3(c)–(j). The results show that this precipitated phase on the grain boundary is M23C6 type carbide rich in Cr, which seriously affects the toughness of steel. During tension, cracks preferentially initiate and expand along the M23C6/austenite interface [19, 20, 26]. In addition, there is a very fine granular precipitate near the grain boundary. According to figures 3(c)–(j), the submicron precipitate is VC. Therefore, it is very important to improve the mechanical properties of alloyed high manganese steel by dissolving carbides in austenite through appropriate heat treatment process.

Figure 4 shows the microstructure after different heat treatment processes. Ti-V-Nb precipitates exist in these three kinds of steels, and S75 steel has more precipitates (indicated by black circles). Compared with the
as-cast microstructure, the size of the precipitated phase after heat treatment is significantly reduced, which shows that low-temperature insulation at 550 °C, 650 °C and 950 °C can effectively provide enthalpy for carbide dissolution, to improve the dissolution rate of the precipitated phase in steel and make the distribution of precipitated phase in the matrix more uniform. This greatly improves the properties of the steels after heat treatment, which will be further discussed later.

Figure 5 shows the size distribution and average size of precipitates in different steels. Compared with G150 steel, S75 and G75 steels have longer holding time and more dissolved precipitates, therefore, the size of precipitates is smaller. There are no particles of particularly large size in G150 steel, the average size being 5.3 μm. Figure 5(b) shows the statistical results of the grain size and precipitates in steel. The average grain sizes of USS, S75, G75, and G150 are 160.9 μm, 233.9 μm, 226.2 μm, 207.5 μm, respectively, indicating that the grains have grown to a certain extent after heat treatment, but compared with the traditional solid-solution treatment, the austenite grains after progressive solid-solution treatment are smaller; shortening the holding time at 1100 °C
Figure 4. Scanning electron microscope microstructure and energy spectrum analysis of steel after heat treatment (a) S75; (b) G75; (c) G150; (d) EDS analysis of spectra 1–4.

Figure 5. (a) Statistics of precipitates; (b) Statistics of grain size.
and increasing the heating rate to refine the grains are both significant. The effect of precipitate size on properties will be discussed later.

### 3.2. Mechanical properties

After the solid-solution treatment, most of the brittle carbides of the steel are redissolved in the austenite matrix. When impacted, the steel after solid-solution treatment has higher impact toughness because it contains less brittle precipitated phase. Although the solid-solution process enhances the impact toughness, it also reduces the Brinell hardness value of the steel to a certain extent, as shown in Table 3. Although the solid-solution process enhances the impact toughness, it also reduces the hardness of the steel to a certain extent. This is because although the large-size precipitates in the as-cast microstructure destroy the continuity of the austenite matrix, the hardness value and modulus of these particles are much higher than that of the austenitic matrix, which can effectively protect the matrix. Therefore, the hardness of the as-cast microstructure is higher.

Figure 6 (a) shows the engineering stress-strain curves of USS, S75, G75, and G150 steels. The four specimens show continuous yield characteristics. When the strain of the specimen reaches its peak, the specimen will first neck and then fracture rapidly. The fracture of USS (as-cast) steel occurs at very small strain values, and the larger precipitated phase particles in the alloyed high manganese steel matrix are the main cause of cracks [27]. The progressive solid-solution treatment can dissolve the carbides in the matrix and improve the microstructure, so that a small amount of fine carbides distributed near the austenite grain boundaries during tension will hinder the grain boundary movement, play the role of pinning the grain boundary, and significantly improve the yield strength, tensile strength and elongation. Therefore, the tensile properties resulting from the progressive solid-solution treatment process are better than those from the traditional solid-solution process. In the progressive solution treatment process, the grain is refined by increasing the heating rate and shortening the holding time. When stretched by external force, the austenite grain produces plastic deformation, and the dislocation source will move first in the grain with a large Schmidt factor. The sliding direction is the crystal plane direction, and the dislocations will continue to proliferate in the sliding process. When the dislocations continue to slip, they will be hindered by the grain boundaries, so even if the plastic deformation is limited to the interior of one grain, it will not migrate to the surrounding grains, improving the yield strength, and tensile strength, and greatly improving the elongation of G150 steel. Figure 6(b) shows the microhardness change curve from the impact surface after impact wear. The subsurface hardness of specimens S75, G75, and G150 are 508 HV, 533 HV, and 556 HV, respectively. The thickness of the work hardening layer can better reflect the work hardening ability of the alloyed high manganese steel. After solution treatment, the hardness value is increased because large-size carbides gradually dissolve in the austenite matrix, the precipitates of some small particles effectively hinder the

| No. | TS (MPa) | YS (MPa) | Elongation (%) | HB (HBW) | Impact toughness (J) |
|-----|----------|----------|----------------|----------|----------------------|
| USS | 440      | 390      | 9.2            | 244      | 17                   |
| S75 | 480      | 395      | 13.6           | 209      | 54.4                 |
| G75 | 578      | 395      | 24.8           | 225      | 97.2                 |
| G150| 667      | 407      | 38.3           | 239      | 124                  |

Figure 6. (a) Engineering stress-strain curve; (b) Microhardness curve.
movement of dislocations, and the dislocations will gather around the precipitates due to the pinning effect of the precipitates. The G150 steel refines the size of the precipitated phase particles to a certain extent, and its distribution is more uniform. By shortening the holding time at 1100 °C and increasing the heating rate, the growth and coarsening of the grains can be significantly inhibited, which causes the G150 steel specimen to have the strongest ability to hinder dislocation slip and strongest work hardening ability. Specifically, the thickest work hardening layer of this specimen is 4100 μm. Although the G75 steel can effectively dissolve carbides, the longer holding time coarsens the grains, so its work hardening ability is weaker than that of G150 steel, and the thickness of the work hardening layer is 3400 μm. The work hardening ability of S75 steel is the worst, with a thickness of the work hardening layer of only 2300 μm.

3.3. Analysis of strengthening and toughening mechanism

The dispersed precipitated phase particles will have a certain impact on the mechanical properties of the alloyed high manganese steel. To further explore the influence of the precipitated phase particles on the mechanical properties of the alloyed high manganese steel, this section will analyze the strengthening and toughening mechanism of three steels. In S75, G75 and G150 steels, there are many strengthening mechanisms and a synergy between them. These strengthening and toughening mechanisms mainly include fine-grain strengthening, precipitation strengthening and solid-solution strengthening. Considering these strengthening and toughening mechanisms, the yield strength increment of alloyed high manganese steel can be expressed by the following formula [28]:

$$\sigma_y = \sigma_0 + \sigma_s + \sigma_d + \sigma_p + \sigma_{sa} + \sigma_f + \sigma_{ia}$$

(1)

Among them, \(\sigma_0\) is the Peierls friction force with a value of 215 MPa, \(\sigma_s\) is the fine grain strengthening increment, \(\sigma_d\) is the increment of solid-solution strengthening, \(\sigma_p\) is the dislocation strengthening increment, and \(\sigma_s, \sigma_d, \sigma_{sa}, \sigma_f, \sigma_{ia}\) are the precipitation phase strengthening increment, submicrostructure strengthening increment, texture strengthening increment and strain aging strengthening increment, respectively.

Based on the microstructure analysis of S75, G75 and G150 steels, the strengthening mechanism of formula (1) can be simplified. The yield strength increment of alloyed high manganese steel can be approximately regarded as the comprehensive effect of fine grain strengthening, precipitation phase strengthening and solid-solution strengthening, which can be expressed as:

$$\sigma_y = \sigma_s + \sigma_p + \sigma_f$$

(2)

Among them, the value of \(\sigma_s\) can be described by the Hall–Petch equation [29]:

$$\sigma_s = Kd^{-1/2}$$

(3)

Where \(K\) is a constant with the value of 11.3 MPa·mm\(^{1/2}\) and \(d\) is the average grain size of alloyed high manganese steel. According to the grain statistical results, the \(d\) values of the S75, G75 and G150 steels are 233.9 μm, 226.2 μm and 207.5 μm, respectively. Calculated according to formula (3) \(\sigma_s\) is 23.36 MPa (S75), 23.76 MPa (G75) and 24.81 MPa (G150), respectively, and the differences between these \(\sigma_s\) values can be ignored.

The precipitation phase strengthening increment \(\sigma_p\) can be expressed by the Ashby–Orowan equation [28]:

$$\sigma_p = 9.549 \times 10^8 (f^{1/3}/d) \ln(20.417d)$$

(4)

Where \(d\) is the average size of the carbide precipitated phase particles in alloyed high manganese steel, and \(f\) is its volume fraction. According to the statistical results of particle size distribution of the precipitation phase in the S75, G75 and G150 steels as shown in figure 5(b), when \(d\) is 4.2 μm (S75), 2.9 μm (G75) and 5.3 μm (G150) and \(f\) is 0.8% (S75), 0.66% (G75) and 0.83% (G150), substitution into Formula (4) results in calculated values for \(\sigma_p\) of 23.10 MPa (S75), 29.40 MPa (G75) and 19.03 MPa (G150), respectively, and these differences can also be ignored.

According to the statistical results of grain size and size distribution, the difference in average grain size of S75, G75 and G150 steels is not large. Moreover, for austenitic steel, the effect of grain boundary strengthening is not very obvious when compared with ferritic steel [30]. This is also due to the grain size of S75, G75 and G150 steels being different, but the final calculated fine grain strengthening increment \(\sigma_f\) is the reason for the small difference.

Compared with the traditional ZGMn13 high manganese steel, the yield strength of S75, G75 and G150 steels increased to a certain extent, and the comparative hardness value also increased to a certain extent. In addition, the abovementioned fine grain strengthening increment and the precipitation phase strengthening increment contribute approximately 45 MPa strength increment to the steel. Since the three steels have not been subjected to deformation pretreatment, the dislocation strengthening increment cannot be considered. The large-size particles in the matrix of alloyed high manganese steel after solid-solution treatment will dissolve, because during the heating and holding process, a part of the coarse precipitated phase particles that are present
in the austenite matrix during the transformation of the molten steel from solid to liquid are re-dissolved into the austenite matrix. In addition, the part of the alloy elements that do not precipitate and exist in the austenite in a solid-solution state lead to serious lattice distortion, which improves the solid-solution strengthening increment of alloyed high manganese steel. Therefore, it can be deduced that the remaining yield strength increment is provided by solid-solution strengthening.

3.4. Wear resistance

Figure 7 shows the cumulative mass loss data of steels with different heat treatment processes under an impact energy of 4 J for 4 h of cumulative impact. The wear of S75 steel, G75 steel and G150 steel are 2.94 g, 2.51 g and 2.26 g, respectively. Compared with S75 steel, the wear resistance of G150 steel has a 23.1% improvement. It shows that compared with the traditional solid-solution process, the progressive solid-solution treatment process can effectively increase the wear resistance of the material. At the same time, shortening the holding time at 1100 °C and increasing the heating rate can significantly enhance the impact and abrasive wear resistance of steel. This is because the grain coarsening can be effectively restrained by appropriately reducing the holding time at high temperature during solid-solution treatment, and the progressive solid-solution treatment process can dissolve the carbides in the matrix and improve the microstructure, so that a small amount of fine carbides distributed near the austenite grain boundary during stretching will hinder the movement of the grain boundary, pinning the grain boundaries and then reducing the mass loss when subjected to impact abrasive wear.

Figure 8 shows the SEM wear morphology of S75, G75 and G150 steels, and a partial enlarged view on the right. It can be seen from figures 8(a)–(f) that the wear types of alloyed high manganese steel mainly include the following categories: microcutting, oxidative wear and plastic deformation wedge formed by microplowing. S75 steel has large and deep grooves with a certain degree of plastic deformation. There are some pits distributed in these grooves, and there are some obvious tissue separation areas at the grooves, which are called fatigue stripping zones. This is because the steel is subjected to impact abrasive wear for a long time and the toughness of the matrix is poor, as shown in figures 8(a), (b). Compared with the wear morphology of S75 steel, it can be found that the groove depth of the wear surface of G75 steel is significantly shallower, the fatigue stripping zone barely exists, the number of pits distributed in the groove is greatly reduced, and a large number of plastic deformation wedges are obvious in its impact abrasive wear surface, as shown in figures 8(c), (d). The wear surface morphology of G150 steel has small and shallow grooves, and it can be seen that the number of plastic deformation wedges is far more than that of S75 and G75 steel, as shown in figures 8(e), (f). This shows that shortening the holding time at 1100 °C and increasing the heating rate can reduce the wear loss and improve the wear resistance. The wear mechanism changes from micro cutting to plastic deformation.
4. Conclusions

In this paper, different alloyed high manganese steels were prepared by different heat treatment processes, and their microstructure and properties were studied. The following conclusions can be drawn:

(1) The average grain sizes of USS, S75, G75, and G150 are 160.9 μm, 233.9 μm, 226.2 μm, and 207.5 μm, respectively. Compared with traditional solid-solution treatment, in the progressive solid-solution process, more MC- and M23C6-type carbide precipitates in the steel can be dissolved, resulting in a significant solid-solution strengthening effect and refined austenite grains.

(2) Compared with S75 steel, the tensile strength of G150 steel is increased by 187 MPa, the elongation is increased by 24.47%, and the impact toughness is increased by 69.6 J. The progressive solid-solution treatment can dissolve the carbides in the matrix and improve the microstructure, so that a small amount of fine carbides distributed near the austenite grain boundaries hinder the grain boundary movement by pinning the grain boundary, and significantly improve the strength and toughness of the steel.

Figure 8. Surface morphology after wear (a), (b) S75; (c), (d) G75; (e), (f) G150.
The progressive solid-solution treatment has excellent wear resistance under high impact abrasive wear. The wear of S75 steel, G75 steel and G150 steel are 2.94 g, 2.51 g and 2.26 g, respectively. Compared with S75 steel, the wear resistance of G150 steel has a 23.1% improvement. The impact surface microhardness of G150 steel is 556 HV, and the thickness of the work hardening layer is 4100 μm. This is mainly the result of solid-solution strengthening, compared with precipitation strengthening and grain boundary strengthening. The wear mechanism is microcutting, oxidation wear and plastic deformation.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Contribution

The experiments were designed by Zulai Li and Quan Shan, and carried out by Haibin Wang and Lei Wu. The steel was fabricated by Haibin Wang, Yuelin Zhao and Lei Wu. The characterization and properties tests were performed by Haibin Wang and Lei Wu. The manuscript was written by Haibin Wang, Zulai Li and Quan Shan, supervised by Fei Zhang. Quan Shan are the corresponding authors.

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