Review Article

A review: phase transformation and wear mechanisms of single-step and dual-step austempered ductile irons

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Austempered ductile iron (ADI) is a type of graphite cast iron produced by an isothermal heat treatment process. It is an alternative to traditional steel castings and forgings and even aluminum due to the exceptional mechanical properties such as high strength, good toughness and excellent machinability. In the matrix, the uniqueausferritic structure consists of graphite nodules uniformly surrounded by acicular ferrite and carbon saturated austenite. In the automotive industry, ADI has been commonly applied in the manufacturing of camshafts, crankshafts, gears and engine valves. These components are frequently subjected to surface contact with relative motion and external load. Therefore, it is necessary to understand the wear behavior of ADI in order to solve the tribological issues in existing ADI applications and utilize ADI into future designs appropriately. This paper was aimed at reviewing the fabrication processes of single-step and dual-step ADIs. The corresponding microstructure and mechanical properties were also briefly discussed. The studies on wear performance of ADI and potential mechanisms have been systematically reviewed.

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1. Introduction

Austempered ductile iron (ADI) is a type of graphite ductile iron produced through an isothermal heat treatment process. It has competitive mechanical properties as compared with conventional cast irons, steel castings, steel forgings, aluminum and even titanium alloys [1–5]. As shown in Fig. 1, yield strength of ADI can be at least twice higher than as-cast ductile iron and three times higher than cast and wrought aluminum with acceptable deformations on ductility. Even though the maximum yield strength and elongation achieved on hardened steels would be higher than ADI, it is clear to see the weight per unit of yield strength of ADI is lower than that of various aluminum and steels due to the presence of graphite nodules in the matrix. Also, the cost per unit of yield strength of ADI is only 20% of steel castings and almost same as steel forgings and heat treated steels [4]. Additionally, titanium alloys have larger range of elongation under acceptable yield strength than ADI, but it is well-known that titanium alloys has high cost on production and poor moldability which cannot be commonly utilized in industries. Except these, ADI also has excellent toughness and good machinability [6,7]. The exceptional mechanical properties can be attributed to its unique ausferritic structure, which consists of acicular ferrite and carbon saturated austenite. In the past decades, many research studies have been conducted to investigate the phase transformation and mechanical properties of ADI using different chemical compositions and various heat treatment parameters and establishing the computational models [8–12].

ADI had been utilized to substitute for some conventional steel and aluminum in the manufacturing of components for commercial trucks and cars since 1970s such as camshafts, cranksshafts, gears and engine valves [13–19], see Fig. 2. Most of these parts commonly experienced surface contact with relative motion and external load. Thereby, the outstanding wear resistance of ADI was required to ensure the trouble-free operation with a long service life. Based on such background, the investigations on the wear performance of ADI became critical for the employment of ADI material in current and future applications.

There are several publications which reviewed and summarized the characteristics of phase transformations and mechanical properties of ADI [20–25]. However, there is still lack of a systematic review on wear behavior of ADI. In the present work, the heat treatment methods including single-step and dual-step austempering processes are provided. Next, the typical ausferritic microstructure and mechanical properties are briefly discussed. Then, the tribological research studies conducted to study the wear resistance of ADI and potential mechanisms are thoroughly reviewed.

2. Isothermal heat treatment

2.1. Single-step austempering process

Single-step austempering process is a conventional method, and widely used to produce ADI material in industry. This isothermal heat treatment process is initiated by an austenitizing step above the Acm temperature or austenite transformation temperature. Appropriate austenitizing temperature and austenitizing time to achieve full austenite without any coarse grains are strongly dependent on the specific chemical compositions, section size and hardenability of the original ductile iron. In the austenitizing step, the pearlitic structure is transformed into unstable austenite. Meanwhile, the alloy elements would be distributed uniformly, and some carbon atoms would be dissolved from graphite nodules into
surrounding austenite. Some research studies have reported that the austenitizing process plays a vital role on the final microstructure and mechanical properties of single-step ADI [26–30]. Delia et al. [26] found that the austenitizing temperature and austenitizing time had significant influence on the impact toughness of single-step ADI. It was found that the austenitization reaction could not be completed at the austenitizing temperature of 850 °C since the pro-eutectoid ferrite still existed in the matrix. The austenitizing temperature of 1000 °C was likely to result in large grains which could reduce the carbon percentage in austenite. In this case, more martensite was formed after the cooling step with an increase of brittleness. The optimal impact toughness was obtained while using austenitizing temperatures between 900 °C and 950 °C with the austenitizing time from 120 min to 180 min.

In the austempering step, the austenitized ductile iron is quickly transferred to another pre-heated furnace, and quenched to a low temperature between pearlite formation temperature and martensite formation temperature and then held for a certain period, see Fig. 3. During this isothermal process, tiny acicular ferrite is apt to nucleate around the graphite nodules due to high potential energy, see Fig. 4(a). Then, the ferritic platelets would grow and the carbon saturated austenite would be formed as the diffusion of carbon atoms, see Fig. 4(c)–(e). Finally, the ideal ADI microstructure should contain acicular ferrite and carbon saturated austenite, which is
called as ausferrite, see Fig. 4(b). In the austempering step, a salt bath furnace is used to eliminate or minimize the effects of surface carburization and oxidation. A complete production process of single-step ADI is shown in Fig. 5. The morphology of acicular ferrite, volume fraction of stable austenite and carbon content in austenite are strongly dependent on the austempering temperature and austempering time. Also, the final mechanical properties of ADI are effectively controlled by these two austempering parameters [31–34,10,35–37]. Thin needle-like ferrite is generated while using low austempering temperature and short holding time. However, needle-like ferrite becomes coarse and feather-like after increasing the austempering temperature or extending the holding time, see Fig. 6. This is the result of more carbon atoms diffused out of crystal structure with a high rate. In addition to changing the morphology of ferrite platelets, the mechanical properties of single-step ADI can also be modified by varying the austempering temperature and austempering time. According to the related studies, it can be summarized that the hardness and tensile strength of single-step ADI decreased, and ductility increased with increasing austempering temperature or extension of holding time. This could be interpreted as more unstable austenite is transformed into acicular ferrite and austenite with high carbon content during the isothermal heat treatment process, and less martensite is formed in the final ADI matrix [32,10].

Two issues should be addressed in the austempering step. First, the transfer of fully austenitized ductile iron between two furnaces should be carried out as fast as possible to avoid the formation of pearlite from unstable austenite. The
presence of pearlite would degrade the excellent mechanical properties of single-step ADI. Some researchers have advised to add some alloy elements to improve the hardenability or inhibit the formation of pearlitic structure such as Mo, B and Mn [38–40]. Second, the austempering step could be divided into two separated and consistent stages in terms of holding time [41–43]. In the first stage, the unstable austenite would be transformed into acicular ferrite and carbon saturated austenite, see Eq. (1). However, the carbon saturated austenite would be decomposed into equilibrium ferrite and carbide, which is bainite, see Eq. (2). The formation of bainite should be prevented in the production of single-step ADI since bainitic structure has remarkable degradation on the mechanical properties of single-step ADI.

\[
\gamma \rightarrow \alpha + \gamma_{HC} \tag{1}
\]

\[
\gamma_{HC} \rightarrow \alpha_{eq} + \text{carbide} \tag{2}
\]

2.2. Dual-step austempering process

The mechanical properties of ADI are dominated by the following three factors: the fraction of carbon saturated austenite, carbon content in stable austenite and the morphology of acicular ferrite [44,45]. Since the nucleation rate of ferrite is controlled by the degree of supercooling. More ferrite platelets would nucleate at high energy regions under high supercooling condition. In addition, the carbon percentage in austenite is mainly dependent on the diffusion rate of carbon atoms, which is promoted by high austempering temperature. Therefore, the dual-step austempering process was proposed to produce fine needle-like ferrite and more stable austenite with higher carbon content in the ADI matrix to enhance the mechanical properties [46–55]. In the dual-step austempering process, the fully austenitized ductile iron was first quenched to a low austempering temperature for nucleation of ferritic platelets. Then the austempering temperature was increased with a constant heating rate or moved to another pre-heated furnace with higher austempering temperature for

\[
\gamma \rightarrow \alpha + \gamma_{HC} \tag{1}
\]

\[
\gamma_{HC} \rightarrow \alpha_{eq} + \text{carbide} \tag{2}
\]

Fig. 6 – Morphological evolution of ausferrite with increasing the austempering temperature (austenitizing temperature: 910 ℃, holding time: 90 min). (a) Austempering temperature: 350 ℃, holding time: 90 min, (b) austempering temperature: 370 ℃, holding time: 90 min, (c) austempering temperature: 390 ℃, holding time: 90 min and (d) austempering temperature: 410 ℃, holding time: 90 min.

Source: (Reproduced with Permission of Ref. [9]. Copyright (2008), Elsevier).
the growth of ferritic platelets and facilitation of the carbon diffusion into austenite. The complete production process of dual-step ADI is shown in Fig. 7. For instance, Dakre et al. [47] initially quenched austenitized ductile iron specimens to a low temperature of 250 °C and held for 10 min, then the furnace was gradually heated to 350 °C at a constant heating rate of 1.7 °C/min. After that, the ductile iron specimens were soaked at a high austempering temperature of 350 °C for 120 min.

As compared with single-step ADI, the ferritic platelets in the matrix of dual-step ADI become finer, see Fig. 8. The differences in the size of ferritic platelets between the two kinds of ADI became significant when decreasing the first austempering temperature in the dual-step isothermal heat treatment process. It is known that the fineness of ferritic platelets is more sensitive to the nucleation rather than the growth [55]. In addition, the volume fraction of high carbon content austenite was higher in dual-step ADI due to the finer ferrite would occupy less area in the matrix and leave more space for austenite [53,55]. Furthermore, Dakre et al. [48] observed some carbide precipitation in the matrix of dual-step ADI, which was not detectable in the matrix of single-step ADI. This phenomenon can be explained using the conclusion drawn by Yang et al. [55]. The carbon content of stable austenite in dual-step ADI was found to be higher than that in single-step ADI as determined by X-ray diffraction (XRD), see Fig. 9. In order words, the first stage with the formation of ausferritic structure would be completed earlier in the dual-step austempering process. For this case, the carbon saturated austenite might have been decomposed into bainitic structure in the matrix of dual-step ADI while carbon content in the austenite of single-step ADI was still increasing.

By studying the mechanical properties of dual-step ADI, it has been reported that the hardness, yield strength and tensile strength of dual-step ADI decreased when increasing the second austempering temperature [47,56]. This was because more carbon saturated austenite was formed in the matrix due to high diffusion rate of carbon atoms. As compared with conventional single-step ADI, higher macro hardness and tensile strength was found in the dual-step ADI while using similar austempering temperature and holding time [50,57,58]. The better performance was due to the finer ferrite and austenite in the matrix. However, Yang et al. [50] found that the ductility of dual-step ADI was lower than single-step ADI, and further decreased under high austempering temperature. Based on the general relationship between tensile strength and ductility, ductility would be reduced with increasing tensile strength. Also, it is possible that the alloyed carbide structure was precipitated in the matrix of dual-step ADI when using the high second austempering temperature. The presence of carbide particles or islands had negative effects on the ductility of ADI.

In the single-step austempering process, austenitized ductile iron was only held at a constant temperature for a certain period. Dual-step austempering process seemed to be more complicated since the austenitized ductile iron needed to be quenched to a low temperature first, and then heated up. A relative stable heating rate was highly required for the homogeneous ausferritic structure. Even though dual-step ADI showed better mechanical properties than single-step ADI, further considerations were still necessary to determine single-step or dual-step austempering process in terms of specific application, process cost and equipment capability.

2.3. Additional tempering process on ADI

The transformation curve (TTT-curve) has been frequently used to determine the phase transformation under specific temperatures and times for ferrous materials, but no feasible transformation curves for graphite ductile iron with various chemical compositions have been developed to determine the specific time interval in the austempering step. Because of this issue, the isothermal heat treatment has to be interrupted conservatively before the ending point of the first stage in case of the decomposition of carbon saturated austenite. Therefore, there is always a fraction of unstable austenite which will be transformed into martensite in the final cooling step, which is accompanied with an increase of residual stress. Residual stress will promote the initiation and propagation of internal cracks. Also, the brittleness would increase significantly. The tempering process is one of the most effective methods to alleviate these problems. However, only a few research studies focused on the phase transformation of ausferrite under different tempering temperatures. Wen et al. [59] found that ausferritic structure could still be observed after receiving a tempering process around 200 °C. The martensite was transformed into tempered martensite. The strength and toughness could be enhanced after a tempering process as compared with ductile iron which was austempered only. Cui et al. [60] and our previous research [61] found that the carbon
saturated austenite would be decomposed, and a significant number of dispersive cementite particles were formed in the matrix while using high tempering temperatures, see Fig. 10. The hardness and compressive strength became lower when increasing the tempering temperatures. In terms of these studies, it could be seen that the ausferrite was able to survive under low tempering temperatures. Also, the martensite and retained austenite would be converted into tempered martensite and martensite during the tempering process [59,62]. Some of mechanical properties would be improved somehow.

Fig. 8 – Comparison of ferritic platelets between single-step ADI and dual-step ADI. 

Fig. 9 – (a) Content in stable austenite in single-step ADI and dual-step ADI, (b) single-step austempering design and (c) dual-step austempering design.
3. Wear performance of ADI

ADI is an alternative for traditional steel forgings and castings and even aluminum in the manufacturing of automotive components such as crankshafts, camshafts and gears due to the excellent mechanical properties. These parts commonly experience the surface contacts under relative motion and external loads in a mechanical system. This led to great interest in understanding the wear performance of ADI produced through various heat treatment designs. The following sections mainly introduce the characteristics of wear behavior of single-step ADI and dual-step ADI in different test configurations and the potential mechanisms.

3.1. Wear behavior for single-step ADI

Similar to the studies on mechanical properties of ADI, many researchers have focused their attentions on the effects of austempering temperature and holding time on the wear resistance of single-step ADI [63–71]. Pin-on-disk and block-on-ring test rigs were normally employed to examine the wear performance of ADI in the laboratory experiments. Seliamuthu et al. [63] found that increasing the austempering temperatures could result in significantly high wear loss on single-step ADI specimens in rotational ball-on-disk sliding tests. Extending the holding duration in austempering process would also result in lower wear resistance [65]. Similar results were also obtained by Batra et al. [64] and Sharma et al. [69]. The incremental wear loss on single-step ADI under high austempering temperature or long holding time was associated with the decrease in hardness. Even though the fracture toughness of ADI could be improved somehow through austempering step, it seemed to not compensate for the influences of hardness reduction on wear resistance. Therefore, it was concluded that the wear resistance of single-step ADI was primarily dominated by the hardness.

In addition to the austempering parameters, the addition of alloy elements also plays an important role in the wear resistance of single-step ADI [72–74]. It was found that addition of boron would increase the wear rate of single-step ADI in a pin-on-ring sliding wear tests since formation of more ausferrite would result in softer surface [72]. Han et al. [73] showed that the molybdenum could provide benefits on wear resistance since the acicular ferrite became finer and percentage of carbon saturated austenite became higher after increasing the content of molybdenum. Similar results were reported by Lee et al. [74] in dry rolling wear tests.

In the comparison with some other ferrous materials, single-step ADI can produce excellent wear resistance [75–77]. Ghaderi et al. [75] found the single-step ADI produced higher wear resistance than pearlitic gray cast iron in block-on-ring sliding wear tests, especially under low sliding speed. Further, Ahmadabadi et al. [76] proposed that single-step ADI would be a potential substitute for pearlitic gray cast iron in railway braking applications. Also, single-step ADI was demonstrated to be a possible replacement of manganese steel under heavy load conditions [77]. Nevertheless, only a few papers compared the wear performance of single-step ADI with others under
equivalent hardness [78–80]. We tested the wear resistance of ADI prepared by single austempering process using ball-on-disk rotational sliding tests with PAO4 (Poly-Alpha-Olefin) lubricant [78]. Quenched and tempered ductile iron specimens were produced to match the hardness of single-step ADI specimens. The single-step ADI had lower wear volume loss than quenched and tempered specimens with the same hardness. Haseeb et al. [79] slid cylindrical ADI and quenched and tempered ductile iron pins against rotating disks made up of hardened medium carbon steel without lubricant respectively. Under the same experimental conditions, the wear resistance of single-step ADI was far better than quenched and tempered ductile iron under similar hardness. Better wear resistance became significant under higher applied load and longer sliding distance, see Fig. 11. In these studies, it has been mentioned that the exceptional wear resistance of single-step ADI was mostly attributed to the stress-induced transformation into martensite from residual austenite. The wear resistance would be promoted because the contact surface or subsurface became harder after the formation of martensite. This will be discussed further in Section 3.2.

Some researchers tried to understand the effects of surface hardening technologies on the wear resistance of single-step ADI [81–84]. Zammit et al. [81] examined the wear performance of single-step ADI after receiving shot-peening treatment. It was found that the surface hardness of single-step ADI was enhanced after shot-peening treatment. However, no noticeable reduction in wear loss was found on shot-peened ADI samples. This might be because the increase in surface hardness and residual compressive stress was counterbalanced by the significant increase in surface roughness. More peak interaction between two contact surfaces could cause localized cold welding, which could produce more wear debris to induce severe abrasive wear. In addition, effects of laser surface hardening method on the wear resistance of single-step ADI were studied by Soriano et al. [82]. The laser hardening could cause the self-quenching mechanism to form martensitic layer and residual compressive stress. Both were beneficial to retard the formation of cracks on the wear track. Moreover, similar as the role of nano-scale particles in composite materials [85,86], hard nanoparticles were proposed to be added into single-step ADI to improve its wear resistance [87–89]. Kaleicheva et al. [87] added cBN nano-size additives into single-step ADI. The wear resistance of single-step ADI could be improved by approximately 34% as compared with specimens without nanoparticles. In addition to cBN nanoparticles, TiN and TiN + TiC nano-sized additives were also used to strengthen the wear resistance of single-step ADI [88].

3.2 Stress-induced transformation reaction during wear tests

It is evident that the single-step ADI had good performance in wear tests with various configurations. Most of the studies declared that the excellent wear resistance was associated with stress-induced transformation of residual austenite into martensite due to the high localized strain or plastic deformation [64,70,90–93]. Batra et al. [64] examined the wear behavior of ADI by using a pin-on-disk rotational test rig. It was found that the wear resistance could be improved by increasing the austempering temperature. The wear loss could be reduced up to 38% of that in original ductile iron without any heat treatments. External force applied on the interface between pin and disk produced sufficient stress to induce the transformation of residual austenite into martensite. Also, no significant temperature jump could be found around the contact surface, so the transformation reaction was unlikely to be produced by temperature. The residual austenite was described as blocky austenite in the vicinity of martensite plates. Wen et al. [90] applied ball-on-block reciprocating
sliding wear tests on ADI with two different normal loads of 25 N and 100 N. The formation of martensite from residual austenite was found in the matrix to improve the micro-hardness of surface and sub-surface, and the increase in micro-hardness became remarkable under 100 N, see Fig. 12. The residual austenite in the transformation reaction was not clearly confirmed in this research. Balos et al. [91] expressly stated that the good wear resistance of ADI was attributed to the induced transformation of residual austenite into martensite due to high local stress. The induced transformation reaction could only occur if the required amount of low carbon enriched austenite and local pressure were fulfilled. Zhang et al. [94] thought the surface hardening layer could be explained as the phase transformation of austenite with high carbon percentage into martensite. Kumari et al. [70] clearly found the dark etching lenticular martensitic phase below the worn surface of ADI specimens, see Fig. 13. However, the definition of residual austenite involved in this strengthening mechanism was not explicit. Residual austenite involved in this induced transformation reaction was believed to include carbon saturated austenite if 100% completion of first stage in the austempering process was achieved and both carbon saturated austenite and low carbon content austenite if some martensite was formed in the final matrix. Under high localized stress or plastic deformation, residual austenite with low carbon content would be transformed into martensite first since it is metastable, and then the high carbon content austenite. The wear resistance would be improved owing to the surface hardness increase [91,94,95].

3.3. Wear mechanisms on single-step ADI

During wear tests, the graphite nodules could be broken up and spread off the wear track. The small graphite particles would act as dry lubricant to lower the coefficient of friction, which was favorable in the reduction of wear loss. In the wear tests without addition of fluid lubricant, oxidative wear was mostly reported as one of the main wear mechanisms [64,79,95]. The oxidative layer would be easily broken during the sliding motion due to high brittleness. Also, some oxidative wear debris (Fe₂O₃ and FeO) with high hardness might scratch the surface or even tear up the base material [64,96]. Under this case, three-body abrasive wear became another main wear mechanism, see Fig. 14(a). Since the specimens made up of single-step ADI always ran against the counterpart made of steel or other ferrous materials with high hardness, the asperities on the hard surface would penetrate and plough the grooves on the relative soft ADI surface, which was two-body abrasive wear [79]. In addition, severe plastic flow and delamination were commonly observed on the wear track which represented the adhesive wear became significant during the wear tests [64,91,94,95], see Fig. 14(b). Beyond these,
Prado et al. [97] and Chiniforush et al. [98] suggested subsurface fatigue might be also a potential wear mechanism in the development of material delamination and removal. The cracks tended to nucleate around the graphite nodules in the matrix, and a tough-like chip was formed above the graphite nodules, see Fig. 14(c). Also, the ferrite platelets were deformed and graphite nodules were squeezed by high shearing force, see Fig. 14(d). Our previous study [99] and Stocks et al. [100] concluded that the graphite nodules could be considered as stress concentration spots. The cracks were apt to propagate from one graphite nodule on the subsurface to adjacent graphite nodules or outer surface to form small-scale pits or large-scale spalls, see Fig. 14(e). The cracks could be also generated by repeatable sliding of wear debris and contaminants or scraping of hard asperities on contact surface. Under high localized strain or plastic deformation, residual austenite would be transformed into martensite on the surface or subsurface. However, the brittleness of the contact surface would be increased as well. Some micro-cracks were more likely initiated and grew to promote the wear loss under high brittleness. In the preparation of ADI specimens, some void spots on the surface due to the removal of graphite nodules in the grinding and polishing steps would also accelerate the formation of cracks, see Fig. 14(f). According to the analysis on worn surface of single-step ADI, it was apparent that wear of single-step ADI had multiple potential mechanisms which might include oxidative wear, two-body abrasive wear, three-body abrasive wear, adhesive wear, delamination and fatigue wear.

3.4. Wear behavior on dual-step ADI

With the development of dual-step ADI, some researchers found that not only did the extra austempering process enhance the mechanical properties, it also had positive effects on the wear resistance of ADI [50,101-106]. Ibrahim et al. [101] found that abrasion wear resistance of ADI could be improved using dual-step austempering treatment in pin-on-ring sliding wear tests, see Fig. 15. The refining effect using dual-step austempering process was one of the causes for the improvement. The finer acicular ferrite would enhance the fracture toughness of ADI. Also, more residual austenite in the matrix of dual-step ADI was transformed into martensite during the wear tests. Another key reason was the higher intrinsic surface hardnass of dual-step ADI as compared with single-step ADI. As was mentioned above, higher surface hardness is able to provide extra protection for ADI specimens. Yang et al. [50] attached dual-step ADI pins on movable abrasive cloths under external normal loads. They found that the contact pressure produced in these wear tests could not activate the transformation reaction from residual austenite into martensite. However, the wear rate of dual-step ADI was still lower than single-step ADI, which was associated with the finer microstructure and higher surface hardness. Similar wear mechanisms such as severe plastic deformation and material delamination with single-step ADI were found on the wear track of dual-step ADI [101,106]. According to the wear studies on dual-step ADI, an additional austempering treatment could provide benefits on wear performance of ADI. This is due to the following aspects. The presence of more residual austenite in ausferritic structure could facilitate

Fig. 14 – Examinations on worn surface of single-step ADI: (a) abrasive grooves and oxidative regions (Reproduced with Permission of Ref. [79]. Copyright (2000), Elsevier), (b) plastic flow and delamination (Reproduced with Permission of Ref. [95]. Copyright (2004), Elsevier), (c) tough-like chip (Reproduced with Permission of Ref. [98]. Copyright (2016), Springer Nature), (d) plastic deformation, micro-cracks and deformed graphite nodules on sub-surface (Reproduced with Permission of Ref. [94]. Copyright (2014), Elsevier), (e) cracks nucleation and propagation around graphite nodules (Reproduced with Permission of Ref. [99]. Copyright (2018), Elsevier) and (f) cracks initiated around surface voids.
the strain-induced transformation reaction. Next, the superior wear resistance of dual-step ADI could be related with higher hardness, tensile strength, yield strength and fracture toughness. Last, finer ferritic platelets and blocky austenite would be beneficial in the reduction of wear rate. However, the stress level required to initiate this induced transformation reaction should be dependent on the carbon percentage in austenite. More carbon content would require additional stress. Hence, mechanical properties and finer microstructure were believed to contribute greatly to the between wear performance of dual-step ADI.

### 3.5 Prediction of wear loss

Except applying laboratory experiments, estimation of wear loss using mathematical models was also important in the understanding on wear behavior of ADI. Yang et al. [103] proposed a formula to quantitatively predict the wear loss of both single-step and dual-step ADIs. In their research, the total wear loss was suggested to be contributed by two portions, basic mechanical properties of material and external loading condition, see Eq. (3). Since the \( Q_{\text{material}} \) was dependent on the material properties such as yield strength, elastic modulus, fracture strain and toughness, it could be further expressed as Eq. (4), and the \( Q_{\text{load}} \) could be represented as Eq. (5). The comparison between the wear loss obtained from wear tests and predicted by derived formula is shown in Fig. 16. It showed that the current mathematical model had a high correlation with real data, which could be used to estimate the wear resistance of ADI beforehand.

\[
Q_t = Q_{\text{material}} + Q_{\text{load}}
\]  

\[
Q_{\text{material}} = \left( \frac{K^* \sigma_{\text{ys}}}{K^*_f} \right) \left( \frac{X_s C_f}{\sqrt{d}} \right)^{n+1} \]  

\[
Q_{\text{load}} = K^* \sigma f L (\mu L)^n
\]

where \( K^* \) is the strength coefficient, \( E \) is the elastic modulus, \( \sigma_{\text{ys}} \) is the yield strength, \( K_f \) is the fracture toughness, \( X_s C_f / \sqrt{d} \) is the control parameter, \( \epsilon_f \) is the true strain at fracture and \( n \) is the strain hardening exponent. 

\[
Q_{\text{load}} = K^* \sigma f L (\mu L)^n
\]

\( K^* \) is the contact area factor, \( \sigma \) is the applied stress, \( \mu \) is the coefficient of friction, \( L \) is the sliding distance, \( H \) is the
material hardness, \( T \) is the austempering temperature and \( m \) is the constant factor.

4. Conclusions and expectations

For the single-step ADI, needle-like ferrite platelets can be formed while using low austempering temperature and short holding duration. The ferrite becomes coarse after increasing the austempering temperature or extending the holding time. However, it is possible that the carbon saturated austenite could be decomposed into bainitic ferrite and carbide if the second stage in the austempering process is initiated. For the mechanical properties, the hardness and tensile strength of single-step ADI are reduced with the formation of feathery-like ausferrite. For the dual-step ADI, an additional austempering process could refine the ferritic platelets, increase the percentage of carbon saturated austenite and promote the carbon content in stable austenite. Under this case, the mechanical properties of dual-step ADI are better than single-step ADI. The hardness and tensile strength of dual-step ADI are also degraded when increasing the austempering temperature or holding period. Some carbide precipitations are observed in the matrix of dual-step ADI since the ending point of the first stage occurs earlier than single-step ADI.

The wear performance of ADI becomes worse under high austempering temperature and long holding time due to the reduction of hardness. Compared with steels and cast irons produced by conventional heat treatment process, single-step ADI resulted in lower wear loss under equivalent hardness. The excellent wear resistance is associated with stress-induced transformation from residual austenite into martensite to improve the surface hardness. Also, common surface hardening technology such as shot-peening treatment, laser hardening and addition of nano-size particles can further enhance the wear resistance of single-step ADI. Comprehensive wear mechanisms include abrasive wear, oxidative wear, adhesive wear, delamination and fatigue wear. As expected, dual-step ADI has better wear performance than single-step ADI, which is attributed to the improved stress-induced transformation reaction, better mechanical properties and refinement of ferrite platelets.

It has been confirmed that the single-step ADI could be an alternative to steels and other cast irons using appropriate heat treatment parameters. In the future, single-step ADI would be employed into not only automotive industry, also agriculture tools, shipping and aerospace applications to enhance the reliability and performance of key components. According to the several recent researches, the dual-step ADI has showed improved mechanical and tribological properties as compared with single-step ADI. Hence, dual-step ADI would be a potential substitution to single-step ADI in the existing or future designs to withstand extreme operating conditions. Under this background, further understanding of single-step and dual-step ADIs is still a prospective research topic. On the one hand, the examination on tribological characteristics of single-step ADI needs to be carried out in bench tests or with real working environments rather than laboratory tests only. Also, researches should focus more attentions on the establishment of mathematic models. The microstructure such as morphology and size of ferritic platelets and carbon percentage in stable austenite and mechanical properties such as yield strength, ultimate tensile strength and elongation under different heat treatment parameters can be predicted beforehand. On the other hand, the current review has showed the fundamental studies on dual-step ADI had not been conducted as many as those in single-step ADI. Under this case, other test fixtures and test methodologies are required to discover the wear and fatigue behaviors of dual-step ADI thoroughly. In addition, investigations on the influences of traditional and innovative surface hardening methods on wear performance of dual-step ADI will be helpful to extend its application field. Also, the roles of alloy elements in the ausferritic formation during the two continues austempering steps have to be comprehended clearly. Finally, to meet the growing demands of superior functions of single-step and dual-step ADI, more works should be developed from the aspects of phase transformation, ausferritic morphology, microstructural prediction, alloy elements as well as the examinations on mechanical and tribological properties using basic and advanced test equipments and methodologies.

Conflict of interest

The authors declare no conflicts of interest.

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REFERENCES


[50] Yang J, Putatunda S. Influence of a novel two-step austempering process on the strain hardening behavior of