Thermomechanical treatment of austempered ductile iron

***A. A. Nofal, H. Nasr El-din and M. M. Ibrahim**

(Central Metallurgical Research and Development Institute, (CMRDI), Cairo, Egypt)

Abstract: The production of lightweight ferrous castings with increased strength properties became unavoidable facing the serious challenge of lighter aluminum and magnesium castings. The relatively new ferrous casting alloy ADI offers promising strength prospects, and the thermo-mechanical treatment of ductile iron may suggest a new route for production of thin-wall products. This work aims at studying the influence of thermomechanical treatment, either by ausforming just after quenching and before the onset of austempering reaction or by cold rolling after austempering.

In the first part of this work, ausforming of ADI up to 25% reduction in height during a rolling operation was found to add a mechanical processing component compared to the conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to a much finer and more homogeneous ausferrite product. The kinetics of ausferrite formation was studied using both metallographic as well as XRD-techniques. The effect of ausforming on the strength was quite dramatic (up to 70% and 50% increase in the yield and ultimate strength respectively). A mechanism involving both a refined microstructural scale and an elevated dislocation density was suggested. Nickel is added to ADI to increase hardenability of thick section castings, while ausforming to higher degrees of deformation is necessary to alleviate the deleterious effect of alloy segregation on ductility.

In the second part of this work, the influence of cold rolling (CR) on the mechanical properties and structural characteristics of ADI was investigated. The variation in properties was related to the amount of retained austenite (γ_r) and its mechanically induced transformation. In the course of tensile deformation of ADI, transformation induced plasticity (TRIP) takes place, indicated by the increase of the instantaneous value of strain-hardening exponent with tensile strain. The amount of retained austenite was found to decrease due to partial transformation of γ_r to martensite under the CR strain. Such strain-induced transformation resulted in higher amounts of mechanically generated martensite. The strength and hardness properties were therefore increased, while ductility and impact toughness decreased with increasing CR reduction.

Keywords: ADI; ausforming; cold-rolling; thermomechanical treatment; transformation induced plasticity

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Austempered ductile iron (ADI) is a relatively new engineering material with exceptional combination of mechanical properties and marked potential for numerous applications [1]. The attractive properties of ADI return to its distinct and unique microstructure, which consists of fine acicular ferrite within carbon-enriched stabilized austenite (ausferrite). The relationship between microstructure and mechanical properties of this material has been the subject of extensive studies [2, 3]. The morphology of the final two-phase matrix microstructure is determined by the number, shape and size of the initially formed ferrite platelets in the first stage of austempering reaction. The control of this stage of transformation will, therefore, ultimately control the final microstructure and mechanical properties.

It has been shown [4] that the rate of ferrite formation during stage I austempering may be controlled by the following processing variables:

Chemical—including alloy content selection. This may be necessary for hardenability, together with the austenitization temperature selection which controls the matrix carbon content.

Thermal—including austempering temperature and time.

Mechanical—including mechanical deformation before austempering (ausforming).

Naturally, an optimum final microstructure could be produced which includes elements of all three processing variables. It has been shown [4-7] that mechanical processing of ADI can act as a control valve for the stage I austempering reaction. In ausformed austempered ductile iron (AADI), mechanical deformation is utilized to affect microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, refining of the microstructure and increasing of the structural homogeneity. The first objective of this work is

***A. A. Nofal**

Male, professor, former chairman of CMRDI, Egypt. Research interest: metal casting.

E-mail: aanofal@cmrdi.sci.eg

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to study the influence of ausforming with different degrees of deformation on kinetics and mechanical properties of nickel alloyed ductile iron.

Transformation of austenite to martensite by deformation has been extensively studied in austenitic stainless steels, whereas very little has been reported [4] on the martensite transformation induced by cold rolling and its effect on microstructure and hardness of low alloy ADI. In the course of fracture toughness tests of ADI in the upper bainite region, which containing high volume fraction of retained austenite, $\gamma_r \rightarrow \alpha'$(martensite) transformation induced plasticity (TRIP) has been reported to occur [8], leading to superior toughness compared to conventional cast iron. Another objective of the present work is to study the influence of the generated microstructure on the tensile properties of the unalloyed ADI taking into consideration the TRIP effect. The influence of cold rolling on the tensile properties, impact toughness and hardness has been as well investigated.

1 Experimental method

Table 1 shows the chemical analysis of irons investigated. Alloys I and II were subjected to ausforming, whereas cold rolling was limited to alloy I. Ausforming was performed in the following sequence: austenitizing at 900℃ for 60 minutes – quenching into a salt bath to the austempering temperature T_A of 375℃ for one minute, rolling to height reductions (RH) of 12.5% and 25% through one or two passes and then austempering in the same salt bath at T_A for different time (0.03-120 min) followed by water quenching to room temperature.

Table 1 Chemical composition of the investigated alloys

Alloy No	Chemical composition, wt%						
	C	Si	Mn	P	S	Mg	Ni
I	3.52	2.80	0.310	0.035	0.0060	0.060	-
II	3.30	2.60	0.270	0.027	0.0053	0.045	2.0

The unalloyed irons were austenitized as mentioned before and then subjected to rapid quenching into the salt bath at 400℃ for 60 min, followed by water quenching. Rectangular blanks of 8 mm × 20 mm × 220 mm were then cold rolled to different reductions in height of 7%, 13%, 19% and 25%. Standard flat tensile specimens, DIN 50125 E5 with 16 mm × 50 mm gauge section were prepared along the rolling direction. The specimens were submitted to uniaxial tensile test on Instron 4112 tensile testing machine at constant cross head speed of 0.5 mm/min.

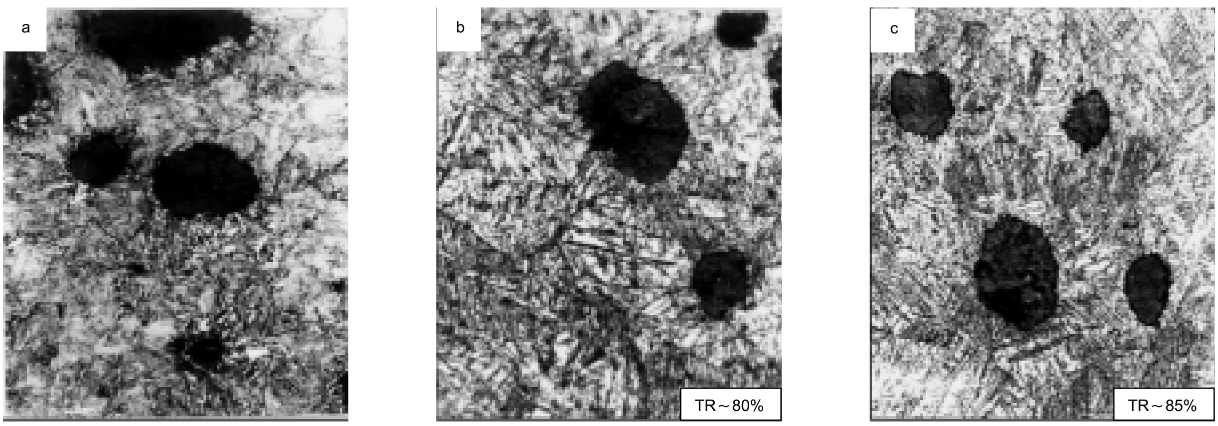
The percentage of the matrix transformed to ausferrite was determined using the point counting technique. The volume fraction of the retained austenite (X_γ) and its carbon content (C_γ) were determined using X-ray diffraction analysis.

2 Experimental results

2.1 Ausforming

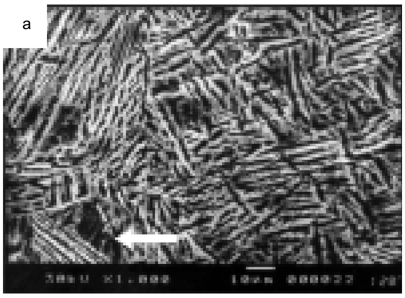
Ausforming to 12.5% and 25% thickness reduction was found to have a significant refinement effect on the microstructure of 2.0% Ni alloyed iron austempered for 10 minutes (Fig. 1). Figure 2 illustrates the effect of ausforming to 25% RH on the refinement of the microstructure. Nickel promotes free austenite and after austempering for very short times, the residual unreacted austenite transforms to martensite on cooling to room temperature (Fig. 3). The rate of stage I transformation was found to be higher in the unalloyed ADI compared to the 2% Ni-alloyed irons. For a given short austempering time, the ausferrite transformation in the alloyed iron was markedly accelerated due to the driving force introduced by deformation (Fig. 4). Ausforming to 25% reduction followed by austempering for short times of one minute resulted in extremely high volume fractions of ausferrite of more than 80% and Fig. 4 shows that the transformation in these specimens has almost gone to completion.

Analysis of the XRD results (Fig. 5) of the austempering reaction kinetics of ADI alloyed with 2% Ni indicates that in the conventionally processed irons, total of the saturated austenite carbon content $C_{\gamma'}$ remarkably increases only after 10 minutes austempering. Ausforming resulted in faster progress of the stage I reaction at short austempering times and this effect may be noticed even at a short time of 2 seconds. The $C_{\gamma'}$ in the ausformed

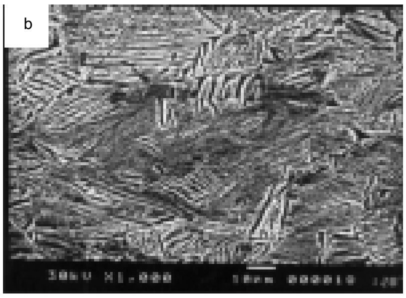


(a) Conventionally processed (b) Ausformed to 12.5% reduction (c) Ausformed to 25% reduction

Fig. 1 Photomicrographs of ADI alloyed with 2%Ni austempered at 375℃ for 10 minutes after different ausforming reductions



(a) conventionally processed



(b) ausformed to 25% reduction

Fig. 2 SEM micrographs of ADI alloyed with 2% Ni austempered at 375˚C for 1 minute. Arrows indicate the brittle martensite formed in many zones in the conventionally processed ADI.

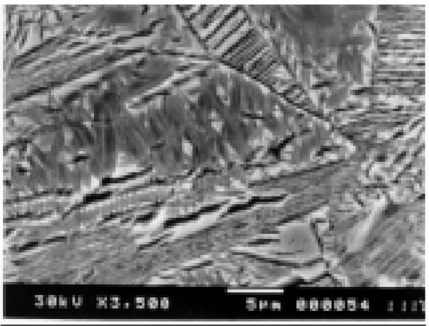


Fig. 3 Martensite formed in austenite zones between ausferrite platelets in 2%Ni alloyed ADI, ausformed to 25% reduction and austempered at 375˚C for 1 min

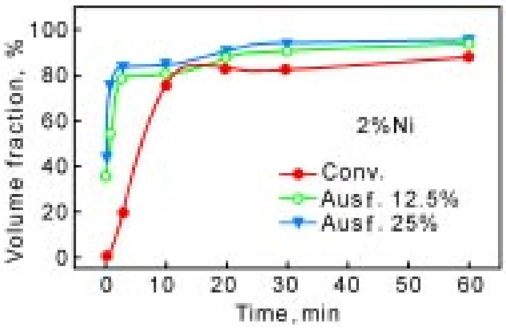


Fig. 4 Volume fraction of transformation versus austempering time for 2% Ni alloyed ADI

irons undergoes a slight decrease after about 100 minutes austempering which may indicate the onset of stage II austempering transformation. Both the yield and ultimate tensile strength values of AADI were found to be superior to those of the conventionally processed ones. Figure 6 shows the dramatic increase in strength of 2% Ni ADI ausformed to 25% reduction and austempered for 10 minutes, where 70% and 50% increase in the yield and ultimate tensile strength respectively may be noticed.

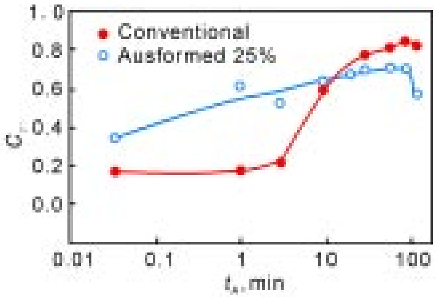


Fig. 5 Variation of total carbon content of saturated austenite C_γ, with austempering time for conventional and ausformed to 25% ADI alloyed with 2% Ni

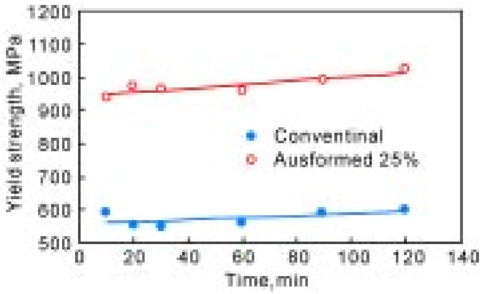


Fig. 6 Yield strength vs austempering time and ausforming reduction for ADIs alloyed with 2% Ni

Figure 7 shows that the ductility of the conventionally austempered irons alloyed with 2% Ni is rather low at short austempering time, whereas prolonged holding time at the austempering temperature improves ductility. Ausforming of this alloy to 12.5% leads to a significant improvement of ductility at austempering times less than 60 minutes. The increased ausforming to 25% results in a slight decrease in the ductility over the entire range of the austempering time.

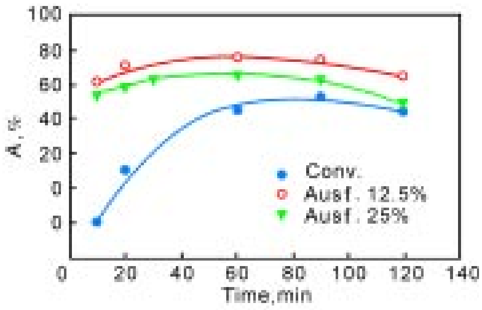


Fig. 7 Total elongation *vs* austempering time and ausforming reduction for ADI alloyed with 2% Ni

Results of tensile tests are given in Fig. 8. Each data point represents the average of typically four tensile specimens austempered for a given time. The austempering time in minutes is indicated to each data point. Ultimate tensile strength is plotted against ductility and a curve generated from the minimum specifications for ADI (ASTM standard A897-90) is superimposed on the plot for comparison. Both the UTS and ductilities of

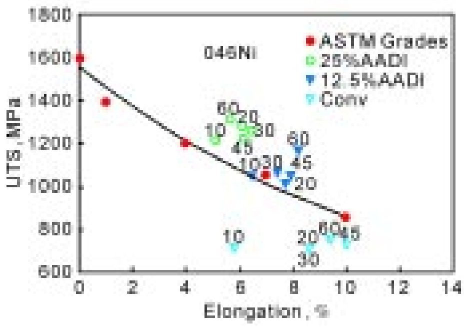


Fig. 8 Ultimate tensile strength versus ductility for 12.5% and 25% ausformed and conventionally austempered specimens along with ASTM minimum requirements for ADI. The austempering time specified (in min) adjacent of the point

ausformed ADIs are superior to those of conventionally processed ones, regardless of the austempering times. The improved ductility in ausformed specimens is only shown for the alloyed ADI.

2.2 Cold rolling

The austempering conditions of the unalloyed specimens resulted in complete transformation of austenite to fine ausferrite matrix of X_γ= 39% and C_γ = 1.8%. The austempering treatment results in 1 065 MPa tensile strength and 7.75% elongation. In Fig. 9 ln true stress versus ln true strain is illustrated. The data are fitted by two intersecting straight lines over the entire range of strain. At plastic strain ε = 0.0094, there is a clear increase in slope of the straight line fitting the data corresponding to the strain hardening exponent "n", which is determined from the true stress-true strain curve.

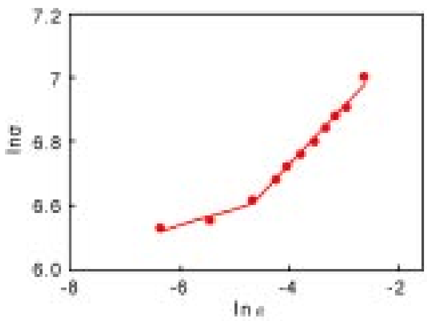


Fig.9 ln true stress versus ln true strain

Increasing cold rolling CR reductions of ADI to 19%, the amount of γ_r decreased due to partial transformation of γ_r mechanically generated martensite (Fig. 10). The volume fraction of martensite induced by cold deformation was calculated as the difference between the original austenite content and that measured after deformation. The metallographic results were confirmed by X-ray diffraction. Figure 11 shows the variation of peak intensity for austenite and (ferrite + martensite) phases in the unalloyed ADI. It is evident that the intensity of (111) decreases with cold deformation. Figures 12 and 13 illustrate that the cold deformation results in marked increase of ultimate tensile strength and hardness, whereas elongation and impact toughness decrease.

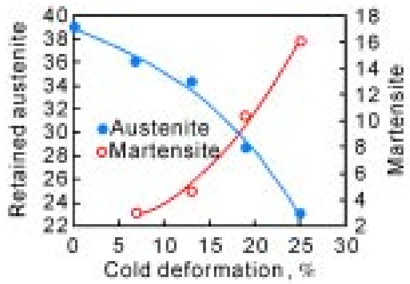


Fig. 10 Variation of volume fractions of retained austenite and mechanically formed martensite with cold reduction pct

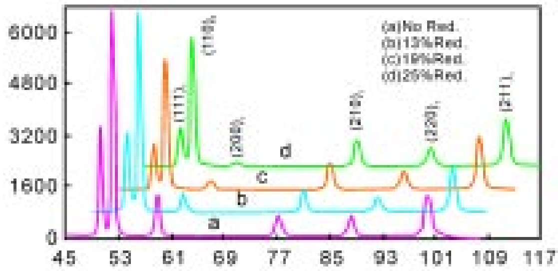


Fig. 11 Variation of peak intensity for γ- and α+α' phases in unalloyed ADI

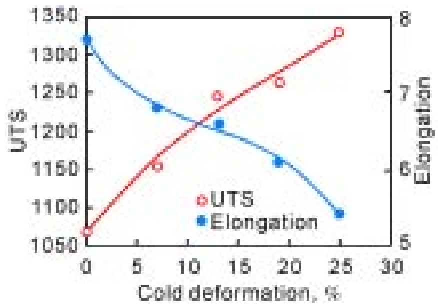


Fig. 12 Variation of elongation and ultimate tensile strength with cold reduction pct

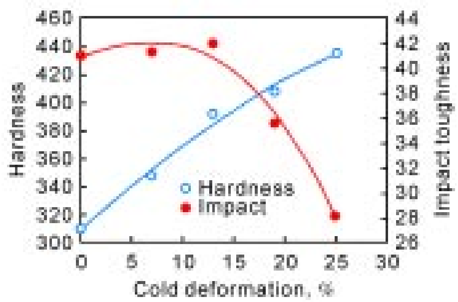


Fig. 13 Variation of Vickers hardness and impact toughness with cold reduction pct

3 Discussion

3.1 Ausformed ADI

The properties of ADI depend on the ratio of saturated austenite to ferrite as well as the morphology of ferrite in the ausferrite mixture. The remarkable accelerated transformation kinetics of the ausformed austempered irons indicate that the additional energy supplied by deformation adds significantly to the driving forces for nucleation of bainite ferrite. Many more ferrite particles, accordingly, nucleate preferentially on slip bands and at grain boundaries. Ausforming results in the elimination of large volumes of austenite, referred to as type II and/or type III, known to reduce the microstructural uniformity of conventionally austempered iron.

Table 2 shows that the austempering time required to develop, for example 50% and 70% of ausferrite increases in the Ni-alloyed ADI. Such a delay indicates that the chemical driving force for transformation is reduced by alloying. The effect of ausforming on increasing the rate of ausferrite formation was confirmed by the XRD results. About 30% volume fraction of retained austenite could be obtained after austempering for less than 1 minute, whereas in the conventionally processed irons, this fraction could be obtained after austempering for about 8 minutes. A slight decrease of both X_γ and C_γ after austempering for time periods longer than 90 minutes may be attributed to the precipitation of some carbide particles at the expense of the carburized austenite (the onset of stage II transformation).

Table 1 Effect of ausforming deformation on the austempering time for developing 50% and 70% ausferrite fractions

Ausforming Reduction	Unalloyed		2%Ni-alloyed	
%	50%	70%	50%	70%
0	1.5 min	5 min	6 min	8 min
12.5	<2 s	<2 s	42 s	1 min
25	<2 s	<2 s	3 s	4.2 s

Two different mechanisms may attribute to the increased yield and ultimate strengths of AADI. The microstructural refinement resulting from ausforming can contribute to the higher yield strength, whereas the warm working of austenite would increase the dislocation density in the bainitic ferrite, resulting in elevated yield and ultimate strength values [5].

The rather low ductility of this alloy at short austempering time (Fig. 7) is apparently due to the big amounts of martensite generated during cooling. Prolonging holding time at the austempering temperature improves ductility as the austenite carbon content, and, hence austenite stability will decrease, which leading to smaller amounts of martensite. Structural refinement should have little beneficial effect on the material, that cracks initiate at graphite nodules, casting flaws or the untempered martensite, which forms from the unreacted or partially stabilized austenite [5]. The acceleration of the stage I transformation by ausforming promotes the formation of more uniform ausferrite throughout the structure and results in an increase of the austenite stability within the ausferrite leading to an improved ductility. Figure 7 shows that increasing the ausforming reduction from 12.5% to 25% results in a slight decrease in ductility. It is believed that at such rather high degree of warm deformation, the ferrite nucleation in austenite is markedly enhanced. Consequently, a large number of ferrite platelets separated by very thin films of austenite, interspersed with these platelets being formed, such matrix would limit the high plasticity of the retained austenite to be manifested, leading to some decrease in ductility.

3.2 Cold rolled ADI

The increase in slope of the straight line fitting the data corresponding to the strain hardening exponent "n" (Fig. 9) was previously observed [8] in the alloyed ADI, which means that the Holloman equation, relating true stress with true strain ($\delta = k\varepsilon^n$) is not followed. The change in slope of the ln δ-ln ε representation can be associated with the transformation induced plasticity (TRIP) effect. As shown in Fig. 9,"n" increases with the tensile strain. The increase is associated with the strain induced martensitic transformation during the tensile test. The generated strain by the volume expansion accompanying the martensitic transformation stimulates new martensitic transformation resulting in the increase of the instantaneous n-value with strain. As a consequence of changes in the structure in the course of tensile deformation, it is believed that the initial segment of ln stress versus ln strain corresponding to the lower plastic strain (Fig. 9) is characterized by the plastic deformation of the retained austenite. At higher strains as previously reported [2] the deformation process is modified by the formation of strain-induced martensite, which takes place when the deformation of austenite has been exhausted.

The increased deformation resulted in a considerable increase in ultimate tensile strength and hardness and decrease in elongation and toughness properties (Figs. 12 and 13). The structural refinement is believed to be the main factor controlling the strength [9]. Hence, the increased strength properties observed after cold rolling can be attributed to the numerous ferrite platelets developed in the matrix. The decreased ductility in the rolled ADI may be related to the morphology of the ausferrite mixture developed in many zones in the matrix structure, which consists of numerous ferrite platelets separated by very thin films of carbon enriched austenite developed after austempering for longer time (60 minutes). As previously reported [2], these ferrite platelets limit the dislocation movement and do not allow the high plasticity of γ_r to be manifested. It should be mentioned that SEM did not reveal any carbide particles, which may have been associated with the onset of stage II austempering and thus contributing to such decrease in ductility.

The increase in strength and hardness with the simultaneous decrease in ductility and impact is attributed to the increase of the hardening of the investigated ADI with cold deformation by both the deformation process (deformation bands and twins) and deformation-induced martensite. It must be mentioned that the observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γ_r. At this light deformation the amount of mechanically formed martensite is very small (Fig. 11).

4 Conclusions

(1) ADI can be thermomechanically treated either by ausforming or cold rolling, both treatments have significant influence on the microstructural features and mechanical properties.

(2) Ausforming refined the ausferritic microstructure which is

consistent with an increased ferrite nucleation rate associated with structural defects such as dislocations introduced by ausforming.

(3) Both metallographic and XRD techniques indicate an enhanced stage I kinetics of the ausferritic formation and the ausferrite was more uniformly formed throughout the structure.

(4) Alloying with 2.0% Ni decreased the rate of ausferrite transformation, particularly in the conventional undeformed ADI. The unreacted retained austenite after short austempering times transformed to martensite on cooling to room temperature.

(5) The influence of ausforming to 12.5% and 25.0% thickness reduction on both the ultimate and yield strength was quite dramatic, strengthening mechanism involving a refined microstructural scale and an elevated dislocation density in both phases of ausferrite was suggested.

(6) Ausforming decreased the ductility of the unalloyed ADI, whereas it significantly improved the ductility of Ni-alloyed iron. Higher degrees of deformation are necessary to alleviate the deleterious effect of alloy segregation on ductility.

(7) In the course of tensile deformation of the investigated ADI, transformation induced plasticity (TRIP) takes place, indicated by the increase of the instantaneous values of 'n' with tensile strain.

(8) Cold rolling reduction of 25% of the unalloyed ADI transformed 41% of retained austenite to martensite and a total of 16% martensite volume fraction was mechanically generated. The yield strength, ultimate strength and hardness were therefore increased whereas elongation and impact toughness decreased.

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Introduction to Shenyang Pump Co. Ltd.

Shenyang Pump Co. Ltd. (Abb. SPC hereinafter), under its previous name of Shenyang Pump Manufactory, was set up in 1932 and has a long history of 75 years until now. It has developed into the biggest pump manufacturer, the leading enterprise and a technical guide company in the pump industry. It became a backbone enterprise of the China National Engineering Industry Bureau, one of the nationally large and first class enterprises and export bases, a base enterprise for significant technology and equipment nationalization, one of the 500 top enterprises of national engineering industries, one of 76 main fostering enterprises in Shenyang, Liaoning Province. It have introduced 7 items of product design and manufacturing technique from Germany, Japan, USA and England as well as corresponding technical standards and quality control standards since the opening up of China.

SPC can provide 50 series of products and spare parts with over 500 types for various applications, such as power plants, petrochemical industry, metallurgy industry, mining, hydraulic engineering, civil constructions, environmental protection, traffic engineering, light industry, national defense. Moreover, SPC can produce new pumps according to the client's requirements whenever necessary.

At present, the pumps offered by SPC have been sold in 31 provinces, autonomous regions, and cities as well as over 40 countries and regions around the world.

SPC won the quality system certification ISO9001 and national military products quality system certification GJB/Z9001 in 1997.