Weldability of ADI and The Applied NDT Methods

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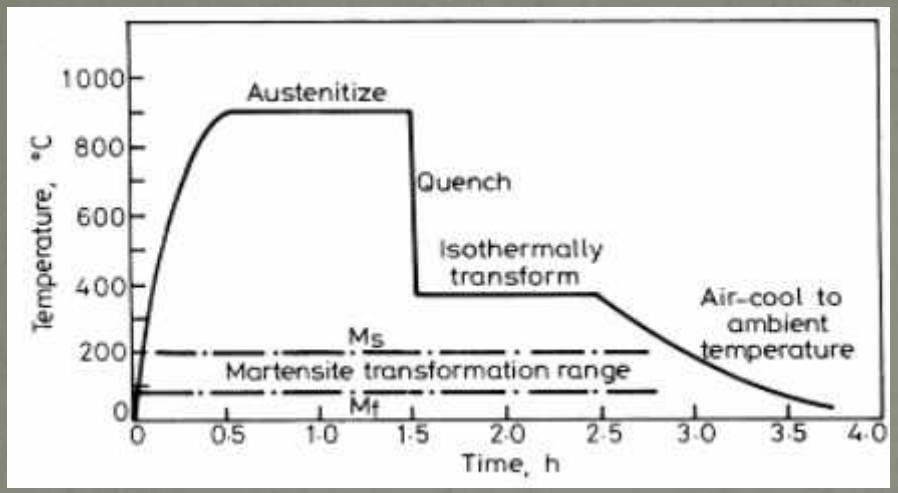
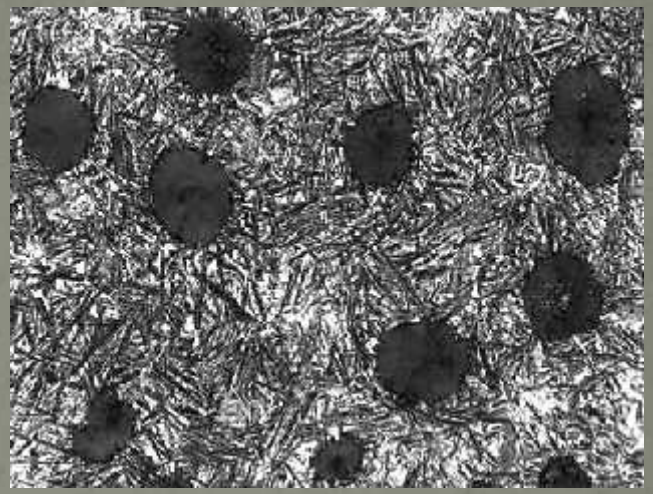
Introduction

- The Austempered Ductile Iron (ADI) is a specialty heat treated material that takes advantage of the near-net shape technology and low cost manufacturability of ductile iron castings to make a high strength, low cost, excellent abrasion-resistant material.

- ADI has gained increasing interests in academic research and industrial application as it can be cast like any other member of the ductile iron family through an austempering transformation process resulting in exceptional combination of tensile strength (800-1600) MPa and ductility (4-10%) that are superior to conventional ductile iron, cast & forged aluminum and many cast & forged steels.

ADI Structure & Mechanical Properties

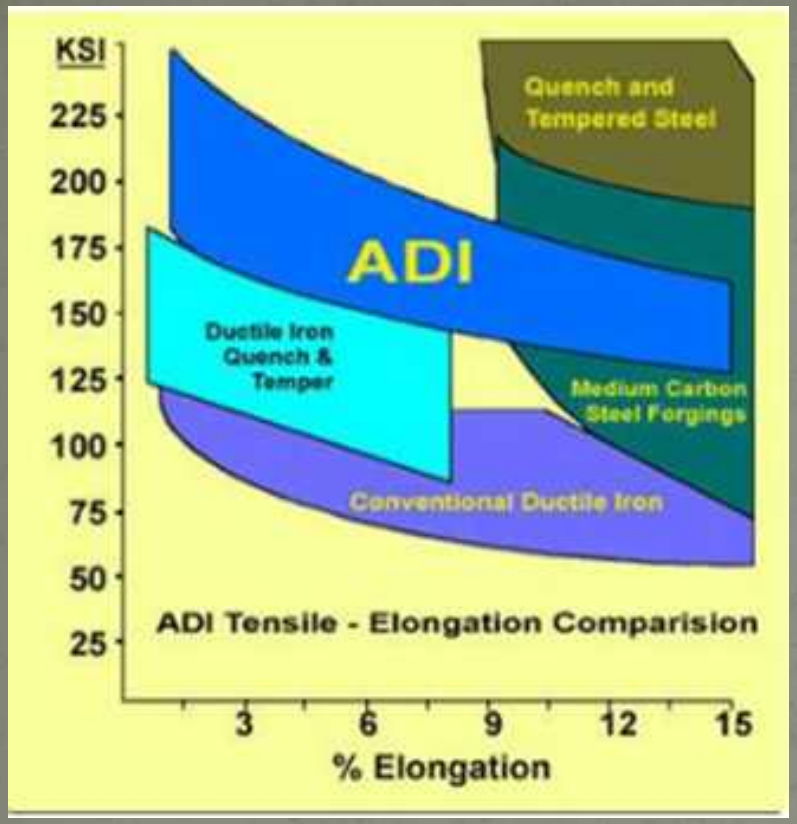




- The attractive properties of ADI return to its distinct and unique microstructure, which consists of fine acicular ferrite within C-enriched stabilized austenite (ausferrite).

- The ADI technology involve the solution heat treatment at the temperature 850-950 °C which is followed by isothermal quenching in the temperature range 250–400 °C.

- Depends on the heat treatment parameters, high strength ADI with Rm=1600MPa or mediate strength ADI with Rm=800MPa & ~ 10% elongation can be obtained. On the other hand the high strength, low ductile ADI is obtained in case of low temperature isothermal quenching. In this case, except carbon stabilized austenite and bainitic ferrite; some amount of martensite forms.



THE FIVE STANDARD ADI GRADES PER ASTM A897/A897M-16

GRADE	TENSILE* STRENGTH (MPA)	YIELD* STRENGTH (MPA)	ELONGATION* (%)	TYPICAL HARDNESS (HBW)
Grade 1 900-650-09	900	650	9	269-341
Grade 2 1050-750-07	1050	750	7	302-375
Grade 3 1200-850-04	1200	850	4	341-444
Grade 4 1400-1100-02	1400	1100	2	388-477
Grade 5 1600-1300-01	1600	1300	1	402-512

*MINIMUM VALUES

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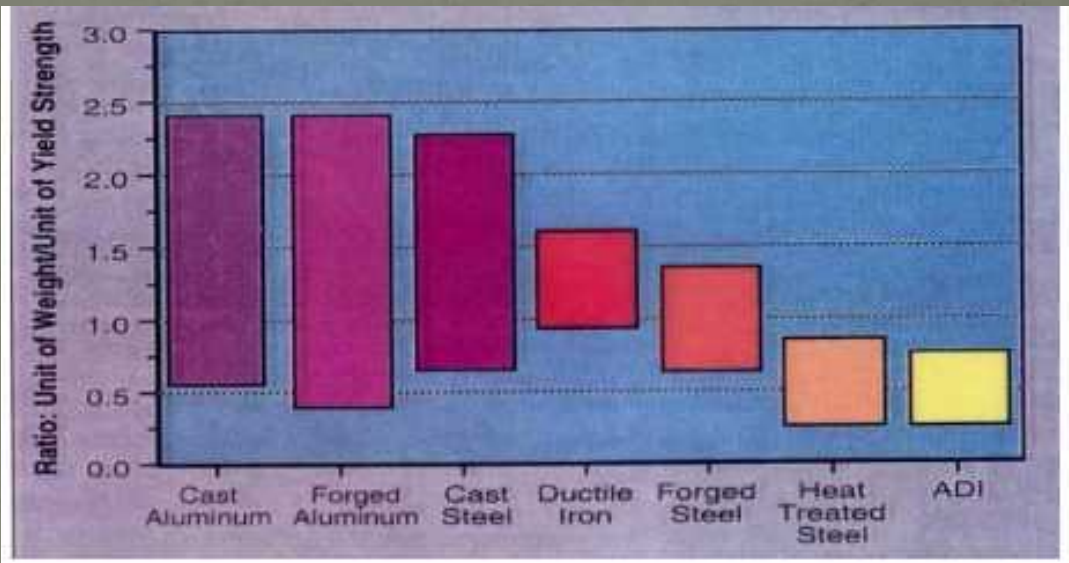
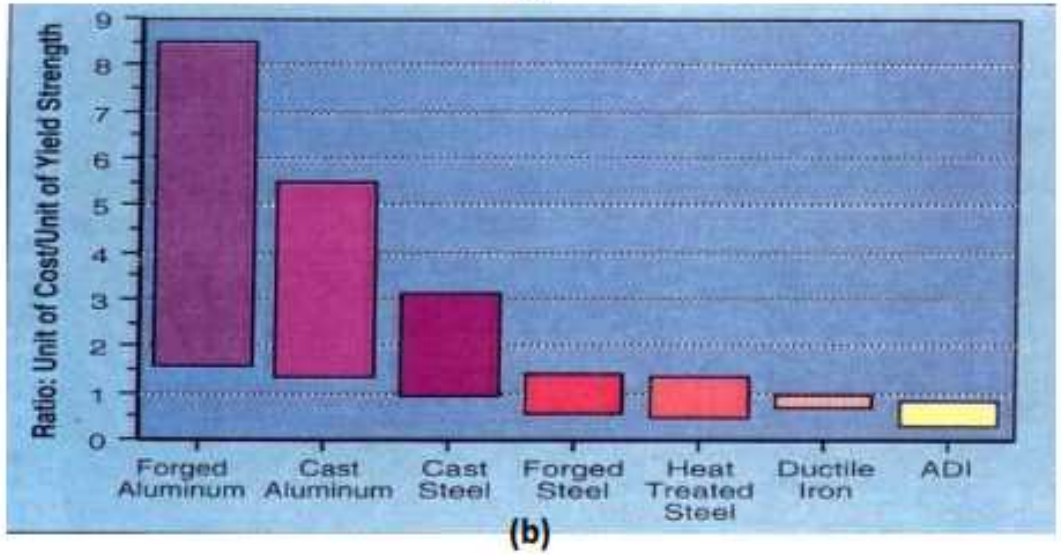
Reference Document: ASTM A897/897M-16 Standard Specification for Austempered Ductile Iron

ADI components are very competitive with steel forgings, castings, weldments, aluminum forgings and castings as five grades of ADI are available to address property combinations of high strength, abrasion resistance and toughness for converting from costly forgings, weldments and assemblies.



(a)



(b)

Comparison of the (a) weight and (b) Cost per unit of yield strength for different engineering alloys.

ADI at CMRDI

Experimental Foundry at CMRDI

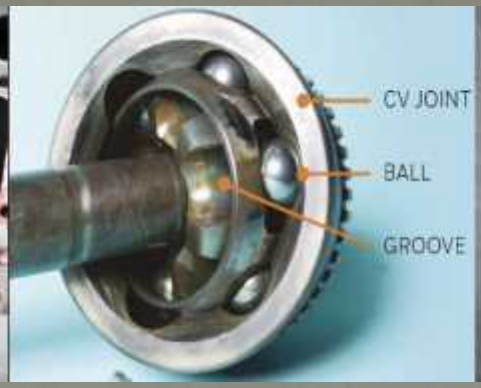
Austempering Plant

Austempered Ductile Iron (ADI) has found successful applications across many industries, including Agriculture, Automotive, Heavy Truck and Railroad. Most of them are already produced in CMRDI.

Applications

Timing Gears

CV Joints



Steering Knuckles

Sprockets

Wheel Hubs

Rollers

Control Arms

Connecting Rods

Plough blades

Flanged shafts

Crankshafts

Hitches

Weldability of ADI

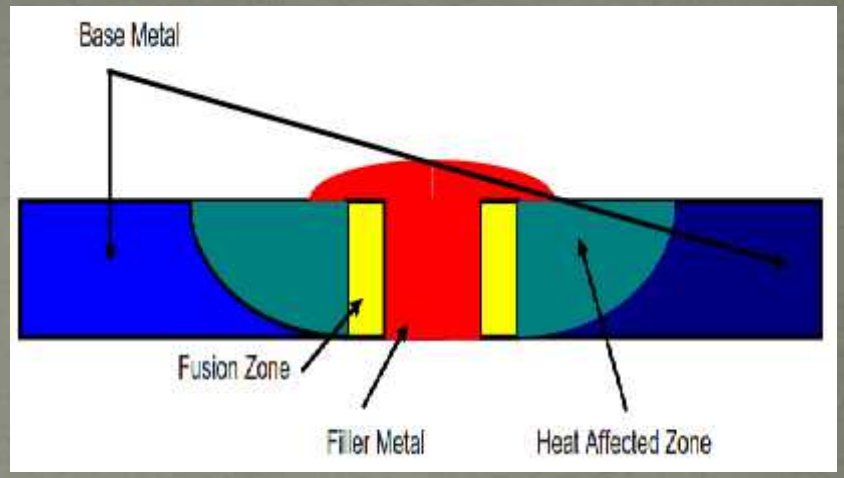
Such wide applications as a result, there is an urgent need for welding of ADI.
But In fact, welding of ADI parts remains a great problem during and after manufacturing.

There are two main problems during welding of ADI:

- First : The formation of carbides in the as-welded ductile iron as well as the partial fusion zone due to fast cooling rate leading to cracking.
- Second: The properties of ADI weld should match those of ADI however the welding temperature would necessarily damage the structure of ADI.

- Studies were reported earlier about the influence of thermal treatments and welding techniques of ADI using different filler materials .
- In ADI welding techniques, some advances have been done in either applying welding processes on ADI plates directly or applying welding processes on ductile cast iron plates then the whole sample is austempered.
- The next review is an attempt to compile the results of recent researches and advances in mechanical properties improvement through the modification in welding techniques, heat treatment, filler materials, and surface alloying to produce a successful welding properties for ADI parts during and after manufacturing.

Welding Technique



- Welding of ADI was investigated using SMAW (Shielded Metal Arc Welding) and GTAW (Gas Tungsten Arc Welding) methods with Nickel base filler materials: ENi-Cl and ENiFe-Cl-A.

- Using filler material based on Ni; prevents the formation of a brittle area (carbides and martensite) in the fusion zone. During the welding process; the carbon of the base material is diluted with filler material in the fusion zone and the excess carbon is precipitated as graphite during the solidification of fusion zone. Before Post Weld Heat Treatment (PWHT); the (HAZ) exhibited martensitic structure and partially melted zone exhibited white cast iron structure plus martensite. Applied PWHT resulted in the dissolution of martensite in HAZ and the reduction of partially melted zone hardness.

- When ENiFe-Cl-A filler metal has been used with GTAW and SMAW process for ADI; the mechanical properties were that tensile test and impact properties of the welded joint are lower than mechanical properties of the ADI base material. That's why this type of filler metal ENiFe-Cl-A can be applied successfully only for repair by welding of ADI parts.

- Buttering with AWS-ENiCI followed by welding with E11018-G electrode leading to a tensile strength higher than that of ADI plates using AWS-ENiFeCI electrode However, the tensile test result is still lower than that of ADI base metal.

Chemical composition of weld metal, mass%

Electrode	C	Si	Mn	Cr	Ni	Mo	Fe
AWS- E11018-G	0.06	0.5	1.8	0.35	2.2	0.4	Bal.
AWS- ENiFeCI	0.5	-	-	-	53	-	Bal.
AWS- ENiCI	0.5	-	-	-	97.5	-	2

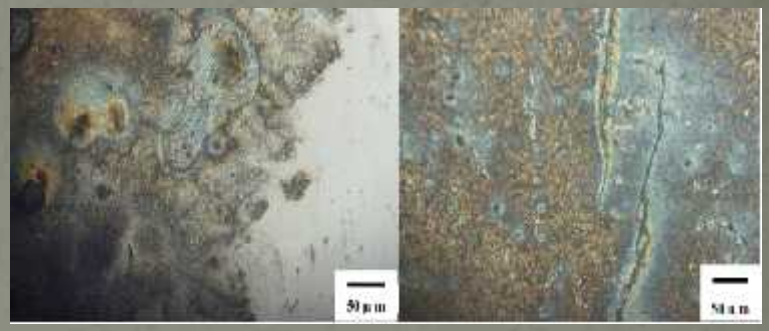
Tensile test results using different SMAW electrodes

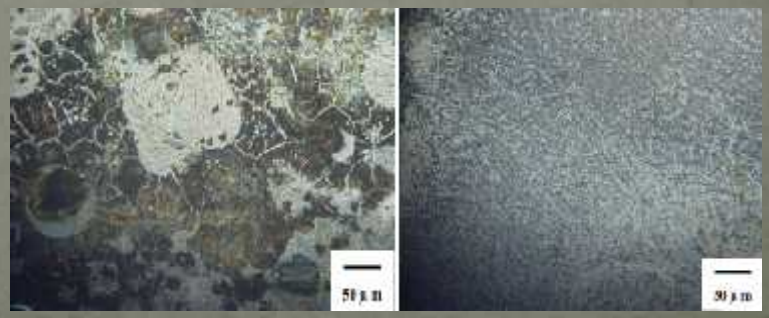
Electrode type	UTS, MPa	YS, MPa
AWS-ENiFeCI	450	300
Buttering with AWS-ENiCI followed by welding using AWS- E11018-G	500	300

Preheating Effect:

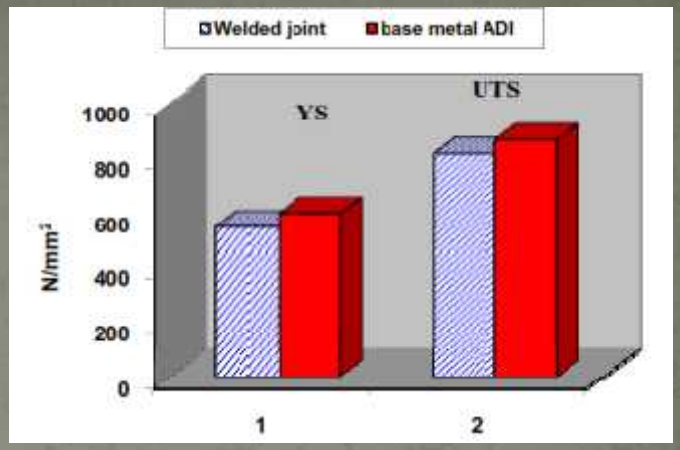
The microstructure analysis of the joint welded at room temperature (without preheat) using AWS-ENiFeCI electrode showed that HAZ has a martensitic structure & the fusion zone has a carbide structure but the joints buttered with AWS-ENiCI included some cracks at the weld metal due to the increase in hardenability of the weld metal resulted from the deposition of AWS-E11018-G electrode.

Preheating at 400°C temperature resulted in the disappearance of the martensite in (HAZ), the coarsening of carbides and the elimination of such cracks.





- For the sake of comparison, GTAW process was also applied using slides of GGG-40 ductile iron as a filler metal. Preheated at 400°C for 20 min. After welding; the welded specimens were austempered in an electric furnace at 400°C for 2 hours and then furnace cooled to room temperature. The resulted weld metal has microstructure and tensile properties which is comparable to that of ADI base metal as well.



Preheating Time:

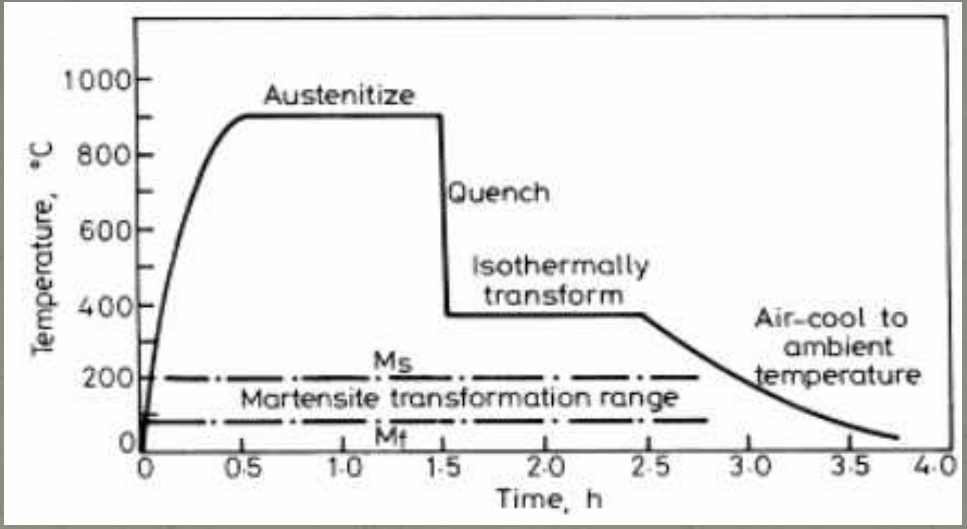
In the view of crystallography and its dynamics, only when the alloy elements dissolve into the grain, they can stabilize the austenite, otherwise they cannot have any obvious stabilization effect , based on this theory and when the cooling rate is very rapid, the weld metal will solidify under a non-equilibrium condition as the stabilization effect of Ni or Mo atoms is relatively weak as only part of them has enough time to dissolve into the grain of austenite so that the austenite becomes easy to transform may be to martensite or other forms. That's why it shall undergo a long time preheating during the austenitizing heat treatment (about 30 min. at 900° C) and the atoms of Ni, Mo at the grain boundary get chance to diffuse and homogenize at the time so that the austenite will become more stable.

- A new challenge has been set for the development of new welding electrodes for arc welding (with preheat) and arc cold-welding (without preheat) of ADI in addition to the determination of optimum composition and heat treatment process to produce a successful ADI weld metal.

Heat Treatment

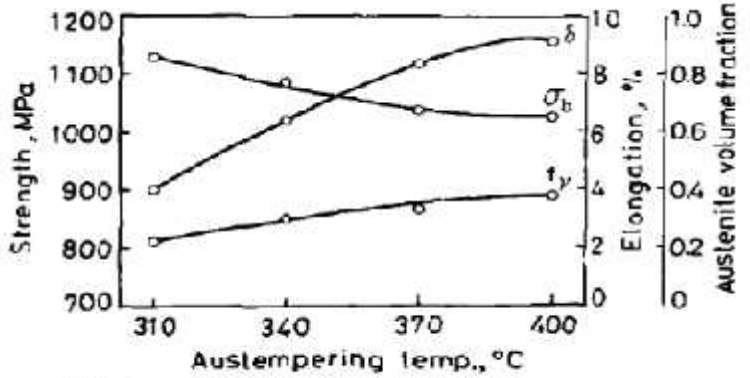
As the heat treatment process has obvious effects on the microstructure and mechanical properties of ADI weld metals, some weld metals were austempered by different austenitizing temperature, austempering temperature & austempering time to study the optimum heat treatment conditions.

Austenitizing & Austemperting Temperature :

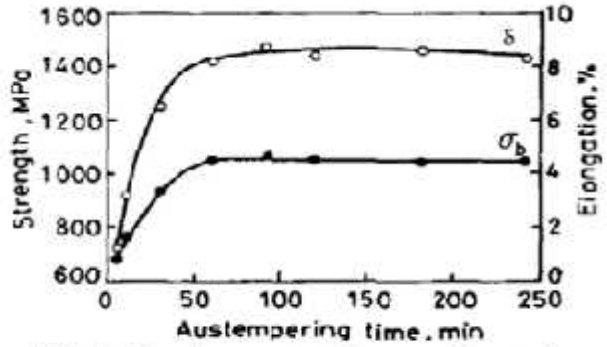


- Increasing the austenitizing temperature from 860°C to 900°C resulted in slight increase in the strength of ADI weld metal from 1024 to 1040 MPa, while the elongation decreases slightly from 8.8 to 8.3%. When austenitizing temperature exceeds 900°C, both the strength and elongation decrease to 950 MPa and 6.1% respectively at 980 °C and the retained austenite volume fraction (*fγ*) in ADI weld metals increases almost linearly from 0.272 to 0.441 with increasing austenitizing temperature from 860 to 960°C. Therefore the proper austenitizing temperature should be selected at about 900 °C, and the proper combination of strength and elongation of ADI weld metal can be obtained when the austempering temperature is 370°C.

Austempering Time:



Effect of austempering temperature on microstructure and mechanical properties



Effect of austempering time on the mechanical properties

- For studying the effect of austempering time, we have to know that the bainitic transformation in ADI weld metal involves two stages.
- In the initial part of stage I some austenite transforms into bainitic ferrite and carbon atoms are rejected from the ferrite into the surrounding austenite. On the other hand, the untransformed austenite turns into martensite, which results in the reduction of retained austenite volume fraction (*fγ*) and mechanical properties. As austempering time increases, the (*fγ*), the strength and the elongation increase greatly. In the later part of stage I because the bainitic transformation tends to end, the (*fγ*), the strength and the elongation remain respectively at a plateau. The strength and elongation are 1040-1060 MPa and 8.3-8.7% in the range of 1 h to 4 h.
- In stage II, austenite volume fraction (*fγ*) and austenite carbon continent (*Cγ*) decrease obviously. Since there is no other convenient place for carbon to go, it follows then that iron carbide is present.

- Experimentally Ductile iron welds with 3.7%C, 3.4%Si, O.4%Mn, 0.004%Mg, 0.12%RE and tiny amount of Ca, Ba, Al and Bi were austenitized at 900°C for 60 min followed by austempering at 370° C from 1 to 1440 min.
- The ADI welds had high mechanical properties (the strength of 1040~1050 MPa, the elongation of 7.8%~8.2% and the impact toughness of 95~105 J/cm2) in the austempering time range from 15 to 240 min. With further increasing austempering time from 240 to 1440 min, carbides precipitated in the austenite and at the bainitic ferrite/austenite interface, the amount of carbides increased and the retained austenite volume fraction decreased.

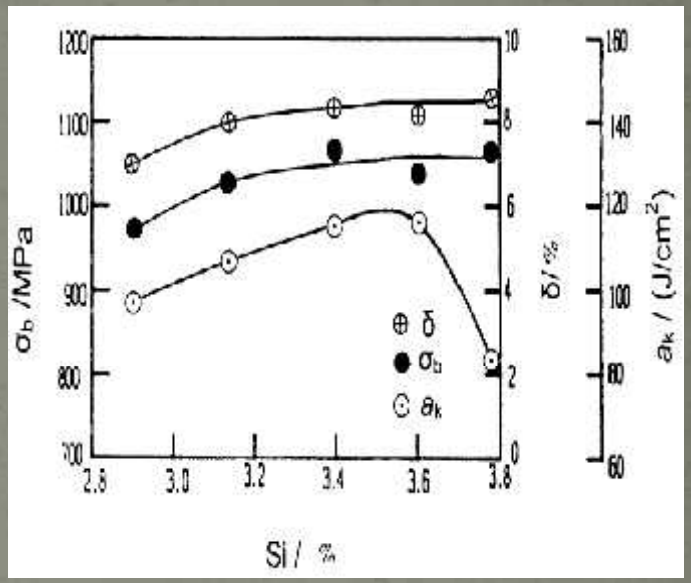
- The mechanical properties of welded joints can match the requirement of ADI but during arc cold-welding of ADI; the carbide formed from weld pool under extremely rapid cooling, which is one of the main problems that will seriously increase the tendency of cracking of weld metal before austempering.
- Such problem can be controlled by the determination of optimum composition.

Filler Material

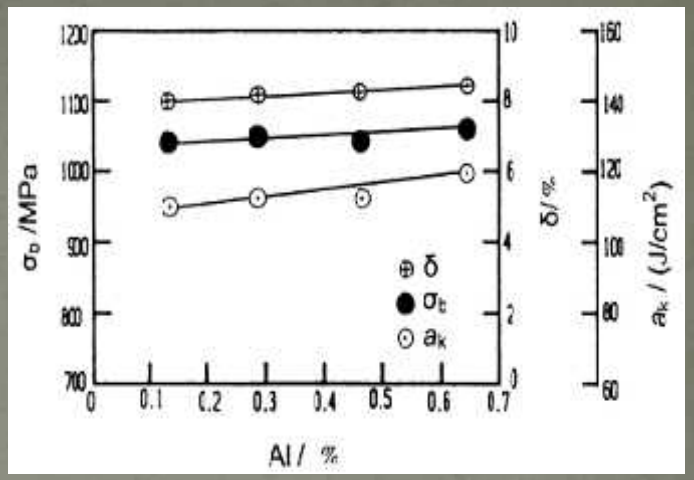
In the way of getting the optimum composition Some studies were focused on developing better welding electrodes through some investigations about the effect of various elements on the mechanical properties of the weld metal.

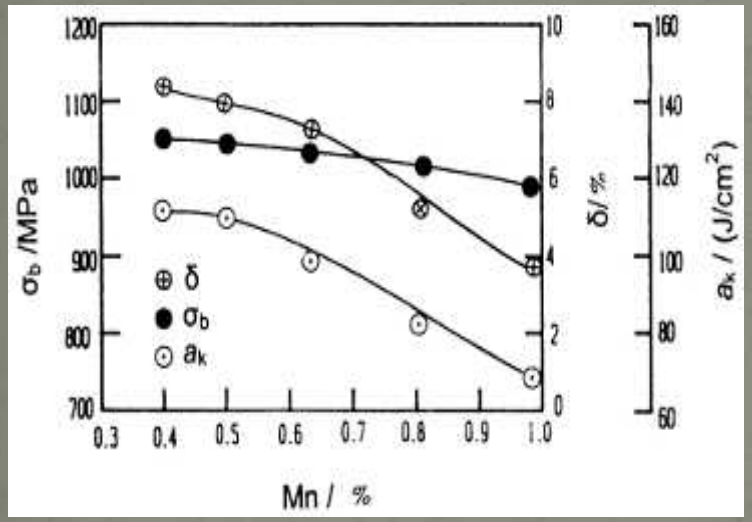
- **Study about the effect of Si, Mn and Al on the microstructure and mechanical properties of ADI weld has been developed.**

The tensile strength & elongation increased from 960 to 1060 MPa and 7.0% to 8.5% with increasing Si content from 2.90% to 3.79% due to the solid strengthen effect of Si and the increased retained austenite having high ductility. But an excess of **Si** (3.79%) results in decreasing the impact toughness and the austemperability owing to decreasing the carbon content of the matrix austenite, thus it is suitable that the Si content is not more than 3.60% to improve the mechanical properties of ADI weld.



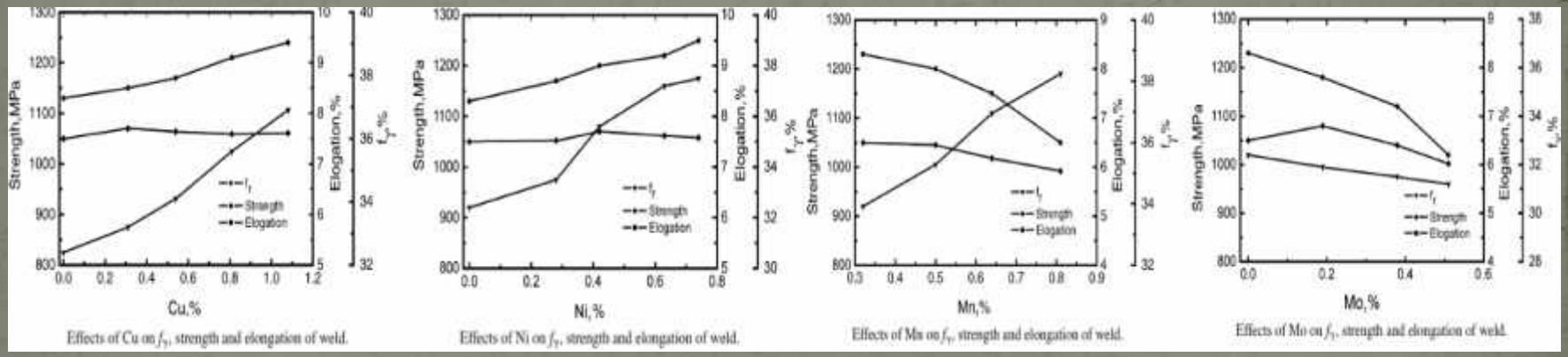
- The effect of **Al** was similar to that of Si. The addition of Al in ADI weld results in increasing the retained austenite volume, which can be explained by Al suppressing carbide formation and making more carbon-enriched stabilized austenite. Increasing Al in the range of 0.13%-0.64% favors improving the mechanical properties of ADI weld.





Mn increases the retained austenite volume fraction but the ductility and impact toughness of weld obviously decrease with increasing Mn content (above 0.50%) because of increased amount of martensite. Further the higher weld Mn content, the longer austempering time necessary. Therefore it is suitable to select low Mn content (<0.50%) to improve the mechanical properties of ADI weld.

- **Cu, Ni, Mn and Mo effects have been studied as they are all have favorable effect on austemperability of the ADI weld.**
- As for example the most pronounced increasing in the austemperability is brought by Mo.
- Both Cu and Ni have little effect on the tensile strength, but they can improve the ductility of ADI weld due to increased retained austenite volume fraction.
- Increasing weld Mn or Mo content results in impairing the ductility of ADI weld, which is mainly attributed to the formation of martensite or carbide enriched with Mo in eutectic cell boundary region.
- The weld alloyed with 0.54% Cu, 0.71% Ni, 0.32% Mn and 0.19% Mo has not only high austemperability but also exceptional combination of the mechanical properties, the critical bar diameter (*D*c), tensile strength and elongation being 42 mm, 1142 MPa and 9.5%, respectively. They can match those of low-alloy ADI



Effects of Cu on f_γ, strength and elongation of weld.

Effects of Ni on f_γ, strength and elongation of weld.

Effects of Mn on f_γ, strength and elongation of weld.

Effects of Mo on f_γ, strength and elongation of weld.

- **Additional studies were done about the effect of C, Si, Al, Ca, Ba and Bi on the WCL in the PFZ, then the effect of C, Co, Ti and Nb on the strength and elongation of ductile iron weld metal before austempering into ADI.**

- It was found that increasing weld C, Si, Al and Bi continent decreasing WCL in PFZ but it may decrease the hot cracking resistance of Ni weld metal, thus the suitable weld content should be in the range of 1.49-1.92% C , 0.27-0.47 % Si , 0.4-0.8% Al & 0.0087-0.017% Bi . The main reason of reducing the WCL in PFZ by increasing such elements is that they are graphitizing elements which by the weld heat input will defuse from the weld to the PFZ to promote the graphitization of PFZ reducing the WCL.

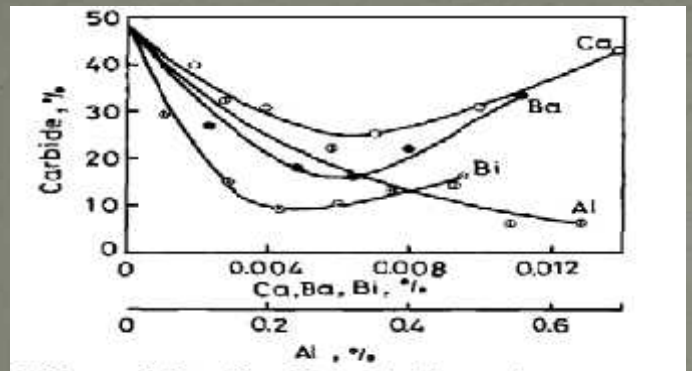
- The strength and elongation of Ni weld metal decrease with increasing weld C continent while for weld Co and Nb contents being 0.77% Co and 0.044% Nb, the weld metal has strength of 511 MPa and elongation of 18.2%. The optimum composition of Ni weld metal is shown on next table.

Tble 2 Composition of weld metal(%)

C	Si	Al	Bi	RE	Co	Nb	Ni
1.49	0.47	0.80	0.0087	0.012	0.77	0.044	bal.

Table 3 Properties of new electrode

Strength /MPa	Elongation /%	WCL /mm	Maximum hardness HB/GPa
511	18.2	0.002	270



Effect of Ca, Ba, Bi and Al on the amount of carbide in welds

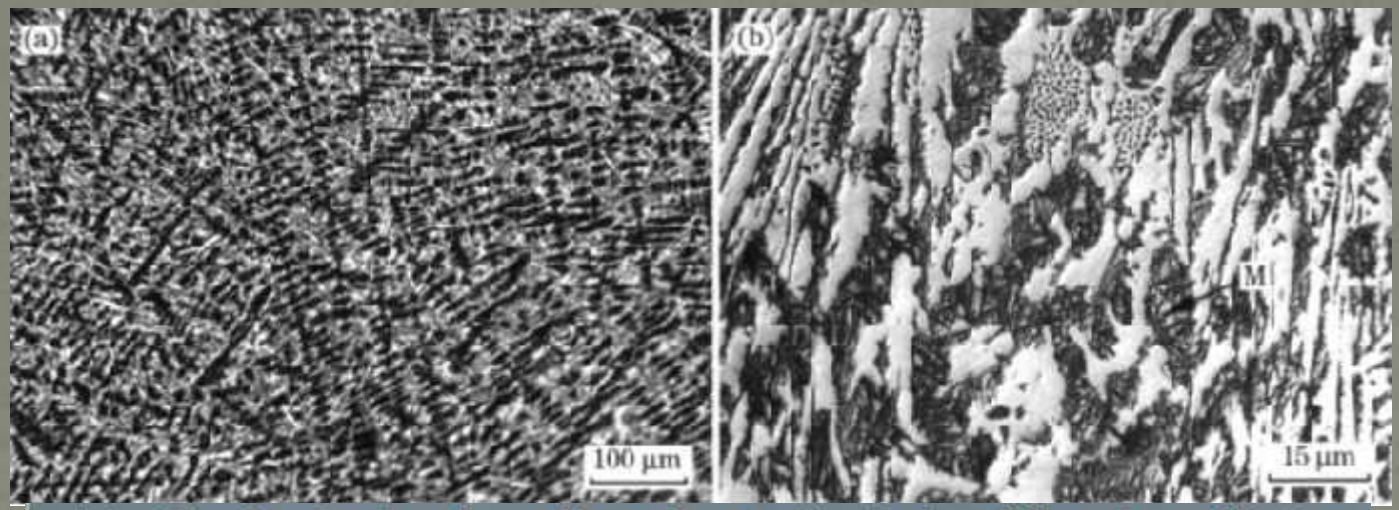
In a previous work; increasing weld C and Si content favors forming graphite and decreasing chilling tendency of weld. It was known that too Ca, Ba, Bi & Al all have a graphitizing effect on ductile iron weld metals but none of them can fully eliminate carbides.

But recently it was found that Ca, Ba, Bi & Al are properly added in combination possess strong graphitizing effect leading to fully elimination of carbide not only in weld but also in partial fusion zone. Best combination is No.3 in the next table.

Base chemical composition, %	C 3.7, Si 3.4, Mn 0.4, Mg 0.034, S<0.015, P<0.015				
Weld specimen	Ca %	Ba %	Bi %	Al %	Matrix structure
1	0.004	0.0064	0.0061	0.46	70%F[1)]+30%P[1)]
2	0.004	0.0064	0.0043	0.54	76%F+24%P
3	0.003	0.0042	0.0045	0.40	80%F+20%P
4	0.007	0.0064	0.0043	0.46	46%F+51%P+3%C[1)]
5	0.008	0.0064	0.0061	0.54	45%F+51%P+4%C
6	0.004	0.0048	0.0061	0.54	72%F+28%P

1) F: ferrite, P: pearlite, C: carbide

Surface Alloying:



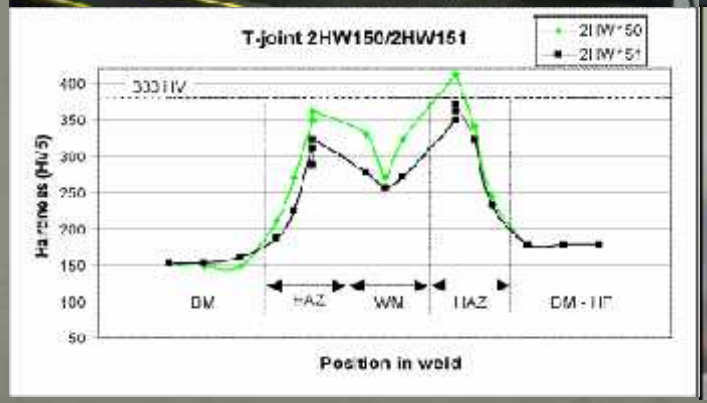
Ledeburitic microstructure formed by surface melting for two different magnifications

TIG welding process was used in surface melting and chromium surface alloying (using ferro-chromium) of ADI samples to study micro-hardness & wear resistance of the resulted microstructures.

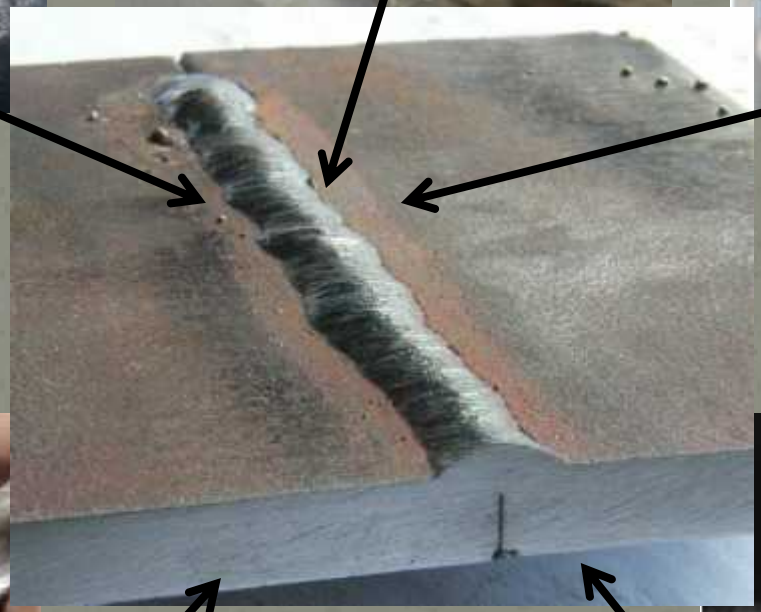
- Surface melting resulted in the formation of a ledeburitic structure in the melted zone with hardness up to 896 HV as compared to 360 HV in ADI. Moreover, chromium surface alloying resulted in the formation of different structures including: (1) hypereutectic structure with a hardness 1078 HV, (2) hypoeutectic structure with a hardness of 755 HV; and (3) ledeburitic structure with hardness of 896 HV.
- The results also indicated that surface melting reduced the wear rate of ADI by approximately 37%. Also, chromium surface alloying yielded a superior wear behavior and reduced the wear rate of the treated specimens by about 38% and 70%, depending on the structures formed.

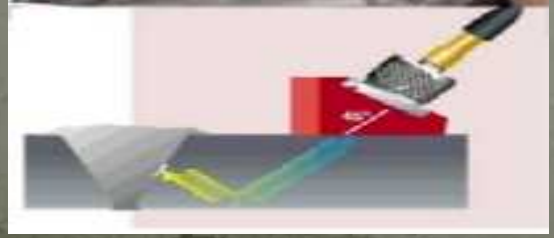
Evaluation:

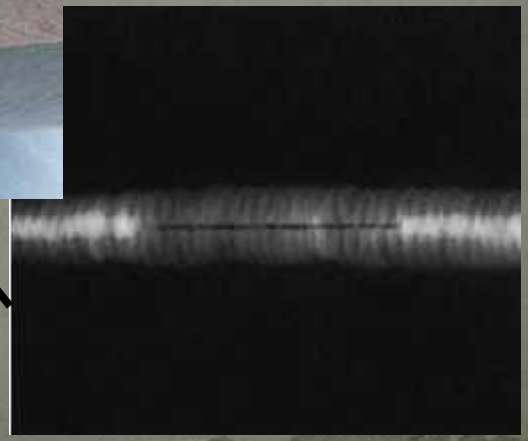
- Mechanical testing, Microstructure evaluation and NDT were applied to determine whether the weld properties are in compliance with the specified requirements.



Non Destructive Testing (NDT):







Concluding Remarks

- The ADI technology involve the solution heat treatment at the temperature 850-950°C then austempering 250–400°C, leading to different grades of ADI with strength 800~1600 MPa & 1~ 10 % elongation for wide range of applications.

- There are two main problems during ADI welding, first : The formation of carbides due to fast cooling rate leading to cracking, Second: The properties of ADI weld didn't match those of ADI base due to weld heat, so that some modifications were done.

A. In welding techniques study; When ENiFe-Cl-A was used with GTAW and SMAW for ADI welding; the mechanical properties & microstructure were lower than whose buttered with AWS-ENiCI followed by E11018-G However, both are still lower than that of ADI base metal. But preheating at 400°C for 20 min resulted in the disappearance of the martensite in (HAZ), the coarsening of carbides and the elimination of cracks. For the sake of comparison, GTAW was also applied using slides of GGG-40 ductile iron as a filler metal. Preheated at 400°C for 20 min. After welding; the welded specimens were austempered at 400°C for 2 hours. The resulted microstructure and tensile properties were comparable to that of ADI base metal as well.

B. In heat treatment study; The proper austenitizing temperature from 860°C to 900°C resulted in slight increase in the strength & elongation of ADI weld metal and when exceeds 900°C, both the strength and elongation decrease. The proper austempering temperature should be selected at about 370°C in the range of 1 h to 4 h.

C. In filler material study; The proper composition for ADI plates welding should be selected as 2.90%-3.60% Si, 0.13%-0.64% Al, (<0.50%) Mn, 0.54% Cu, 0.71% Ni, 0.19% Mo. And the proper composition for DI plates welding before austempering into ADI should be selected as 1.49-1.92% C, 0.27-0.47 % Si, 0.4-0.8% Al, 0.0087-0.017% Bi, 0.77% Co, 0.044% Nb, 0.003% Ca and 0.0042% Ba.

D. In surface alloying study; Surface melting and chromium surface alloying resulted in superior raising in hardness and superior wear rate reduction depending on the different structures formed.

- Mechanical testing, Microstructure evaluation and NDT were applied to determine whether the weld properties are in compliance with the specified requirements.