Environmental Embrittlement of Ductile Iron

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ABSTRACT

When designing mechanical components, engineers take benefit of the many advantages of Ductile Irons over steels, eg. excellent castability, low cost, high machinability and a wide range of achievable mechanical properties. However, to take full advantage of a material, the designer must also know the limitations of this material in a given environment. Certain grades of Ductile Irons have been recently reported to be prone to environmentally assisted embrittlement when exposed to liquids. This article reviews the data published on the subject, with a particular emphasis on austempered Ductile Irons. The published information is complemented by the results of a recent study carried out on the ADI behavior.

INTRODUCTION

A generic definition of embrittlement is the "Reduction in the normal ductility of a metal due to a physical or chemical change". Most common examples are blue brittleness, hydrogen embrittlement and temper brittleness. While such phenomena refer to changes occurring within the metal structure, this definition can be extended to embrittlement resulting from changes generated by the interaction between the metal and its environment. These types of embrittlement are: hydrogen embrittlement, stress-corrosion cracking and liquid metal embrittlement.

Environmental embrittlement of Ductile Iron is usually not a concern for designers. However, more attention has been paid to this matter when an incident occurred in North America in 1990's. On a construction project ADI anchors were used to restrain cables that put a structure in compression. The fasteners that secured the cables in the anchors imparted minor amounts of plastic deformation within the ADI due to surface roughness. After compression loading, the cables were then totally encased in a ceramic grout material. Thousands of anchors were successfully installed in this manner. The installer found it difficult to press the grout into the container surrounding the cables so the grout was reformulated to reduce its viscosity. When this new, more fluid grout was employed, a small percentage of the ADI anchors experienced a catastrophic failure. This type of failure, which was rapidly corrected, nevertheless drained attention from the material community on the phenomenon, and research was conducted to verify what grades of Ductile Iron are sensitive to the phenomenon.

This paper reviews the data found in the literature on environmentally assisted embrittlement of Ductile Irons. Recent data on ADI obtained by Hayrynen and Boeri are included. A discussion on the mechanisms that may cause such environmental embrittlement is presented.

ENVIRONMENTALLY ASSISTED EMBRITTLEMENT MECHANISMS

Hydrogen Embrittlement

Embrittlement may occur in many metals in presence of a very small amount of hydrogen. Hydrogen may be introduced during melting and entrapped during solidification, picked-up during solid state processing or introduced during corrosion. Hydrogen is present in the metal as monoatomic hydrogen due to the dissociation of molecular hydrogen by chemisorption at the surface or as a result of oxidation reaction. Hydrogen causes delayed fracture at a stress level significantly lower than the strength of the metal. The fracture process may be cleavage, intergranular or transgranular and no single fracture mode is characteristic of hydrogen embrittlement.

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There is no univocal mechanism for hydrogen embrittlement; the description of the hydrogen – metal interaction mechanisms can be found elsewhere [1, 2].

Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) is the failure of an alloy from the combined effects of a corrosive environment and a static tensile stress [2, 3]. The chemical environment causing SCC does not produce chemical corrosion of the alloy and the species causing SCC need not be present in large concentration. The formation and rupture of a passive layer at the crack tip is an important mechanism. Moreover, it is widely believed that electrochemical dissolution plays a major role in the crack initiation and propagation. There is a possibility of the adsorption of damaging ions that weaken the atomic bonding at the crack tip. If hydrogen is generated as a result of corrosion species, it is then able to enter the metal, diffuse to the crack tip and cause crack propagation.

Liquid Metal Embrittlement (LME)

Liquid metal embrittlement [2] occurs when a solid metal surface is wetted by a lower melting point metal and results from the direct interaction of the liquid metal atoms with the highly strained atoms at a crack tip. Adsorption of atoms from liquid metal greatly reduces the surface energy, decreasing the fracture stress. The prerequisite for the occurrence of LME are: i) a good intimate contact between the solid and liquid surfaces; ii) an applied or residual stress; iii) some measure of plastic flow and some obstacle to dislocation motion at the solid-liquid interface. Other promoting factors are reported in [2]. LME is unlikely to occur in Ductile Iron which is not usually exposed to liquid metal. However, some liquids may behave like liquid metal under certain conditions.

ENVIRONMENTALLY ASSISTED EMBRITTLEMENT OF DUCTILE IRONS

The interest for understanding the environmental embrittlement of Ductile Irons resulted in many R&D programs. Table 1 lists the Ductile Iron grades investigated for environmentally assisted embrittlement by various authors. Also included are unpublished data recently obtained by Hayrynen and Boeri [9].

Table 1. Ductile Iron Grades Investigated for Environmentally Assisted Embrittlement

Grades	Ref. 4	Ref. 5	Ref. 6	Ref. 7	Ref. 8	Ref. 9
Ferritic	X	X	X		X	
F + 10% P	X				?	
Pearlitic	X	X	X		X	
Q & T	X	X			X	
ADI 1	X	X	X	X	X	X
ADI 2			X	X		
ADI 3			X	X		X
ADI 4					X	
ADI 750					X	X

When comparing the stress-strain behavior of normal and embrittled materials, the property mainly affected by embrittlement is the ductility. Fracture toughness behaves similarly to ductility and was also used to quantify the phenomenon. Note that the authors utilized different experimental parameters and/or investigated the effect of different variables. This analysis tried to take these differences into consideration.

ASTM-A536 Ductile Iron Grades

Ferritic Ductile Iron

Figure 1 presents the results of the investigation carried out by Druschitz et al [8] on 65-45-12 ferritic Ductile Iron tested at low strain rate (1% per minute) at room temperature, in contact with various liquid environments; no embrittlement was detected. Other studies [4, 5, 6] reported similar results. It has been clearly shown by Komatsu et al [5] that the occurrence of residual pearlite (~ 10%) does not affect the behavior of ferritic irons.

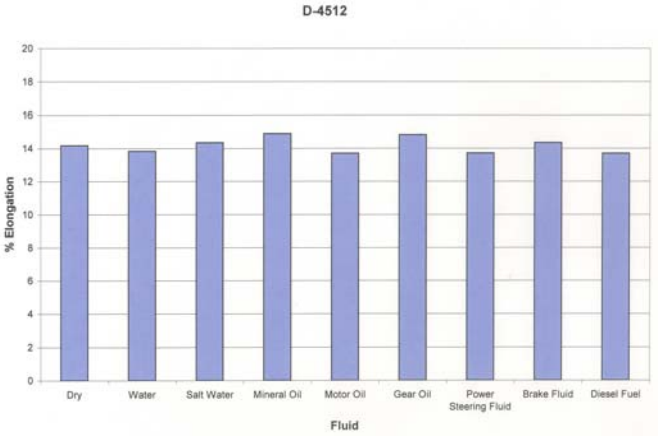

Figure 1. Effect of Liquid Environments on the Elongation of Ferritic Ductile Iron [8]

Pearlitic Ductile Iron

The data on the embrittlement of pearlitic Ductile Irons in contact with water is presented in Table 2. It is seen that embrittlement of pearlitic iron is reported by Shibutani [5] and Martinez [6], but not by Druschitz [8]. It is worth noting that Komatsu [4] also observed the embrittlement phenomenon when measuring fracture toughness.

Table 2. Effect of Water Environment on the Elongation of Pearlitic Ductile Irons

Reference	5	6	8
Dry Condition	~ 3%	~ 5%	7.5
Wet Condition	~ 1%	~ 2%	6.8

A review of the process routes used to produce the pearlitic Ductile Irons revealed that Druschitz [8] tempered the specimens at 565^{o}C for 2 hours while the others [5, 6] tested them as normalized. Tempering is carried out to reduce iron hardness [10]. Druschitz reports 7.5% elongation after tempering, a value significantly higher than the one obtained (3 to 5%) for normalized/non tempered or as-cast pearlitic castings [11, 12]. The description of the microstructure by Druschitz (fine pearlite) does not allow one to conclude on the microstructural changes that may have taken place during tempering. However, while the rapid decomposition of pearlite to ferrite and graphite is unlikely at 565^{o}C [13], pearlite spheroidization, which is the precursor step to pearlite decomposition, may occur and result in isolated carbide particles in a continuous ferrite matrix [13]. Although not verified on Druschitz's specimens, this may explain the different embrittlement behavior reported.

Quenched and Tempered (Q&T) Ductile Iron

Figures 6a) and b) present the results obtained by Druschitz [8] and Komatsu [4] on Q&T Ductile Iron. While Druschitz did not report the embrittlement of Q&T Ductile Iron, whatever the fluid used, severe embrittlement (measured by fracture toughness) was observed by Komatsu. The heat treatments used in the two studies were, however, different as shown in Table 3. According to published data on steel [2, 3] the treatment used by Druschitz should result in a fully tempered martensite structure in which carbides are spheroidized in a ferritic matrix while the one used by Komatsu probably partially retained the original plate-like lamellar structure.

a) **b)**

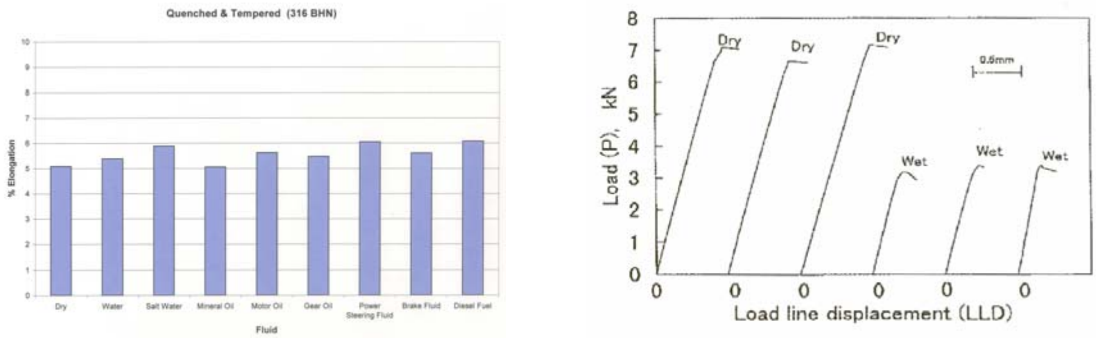

Figure 2. Effect of Liquid Environments on the Properties of Quenched and Tempered Ductile Iron
a) Elongation [8] - b) Fracture Toughness [4]

Table 3. Tempering Treatments Used for Q&T Specimens

Reference	Temperature	Time
Komatsu *[4]*	400°C	1 hour
Druschitz *[8]*	620°C	2 hours

Austempered Ductile Irons

ASTM A897/897M Grades

All ASTM A897/897M ADI grades (1 to 4) were embrittled when tested in liquids. As examples, data reported by Martinez [6], Druschitz [8] and Hayrynen [9] are presented in Figure 3 and Table 4. Table 6 compares the various relative reductions in elongation measured.

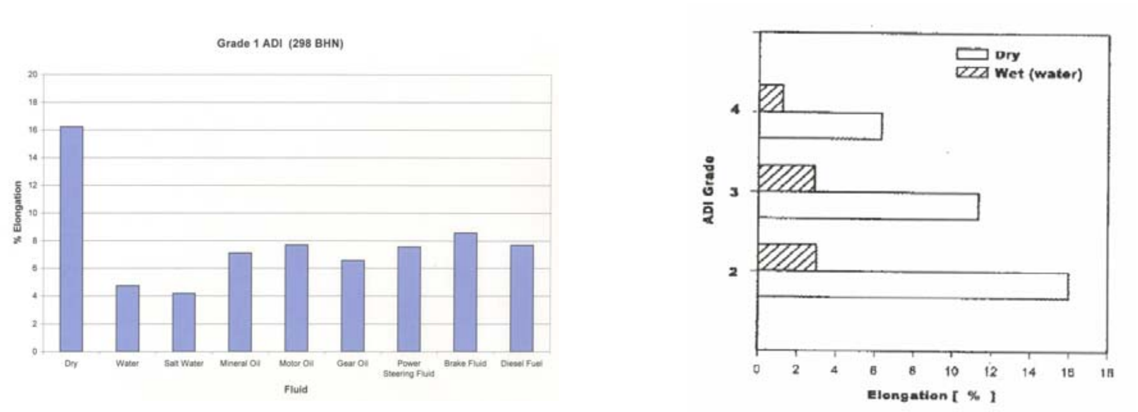

Figure 3. Effect of Liquid Environments on the Elongation of a) ASTM A897/897M Grade 1 (Druschitz [8]) and b) ASTM A897/897M Grades 2, 3 and 4 (Martinez [6])

Table 4. Effect of Water Environment on UTS and Elongation of ASTM 897M Grades 1 and 3 [9]

Grade	Property	Dry	Wet
1	UTS (MPa)	1012	575
	Elong. (%)	11.2	3.4
3	UTS (MPa)	1274	1015
	Elong. (%)	8.3	4.0

Table 5. Relative Reduction of Elongation for ASTM A897/897M ADI Materials when in Contact with Water

Grade	References					
	4	5	6	7	8	9
1	80 %	75 %	-	75 %	72 %	70 %
2	-	82 %	80 %	73 %	-	-
3	-		72 %	83 %	-	52 %
4	-		70 %	-	-	-

It is seen in Table 5 that the reduction of ductility is about 70 to 80 % for all grades, the only data differing being reported by Hayrynen for grade 3. However, the initial value was 8% compared to 11% for Martinez. The rupture nevertheless occurred at 4% in both studies. Indeed in most cases all grades fractured at 3-4% elongation.

SAE-J-2477-750 Grade

This grade of ADI was investigated by Druschitz et al [8] and Hayrynen and Boeri [9]. Druschitz investigated materials with different hardnesses; for comparison purpose with Hayrynen's data, the data on the more ductile material (247 BHN) is presented in Figure 4, while Hayrynen's results are listed in Table 6.

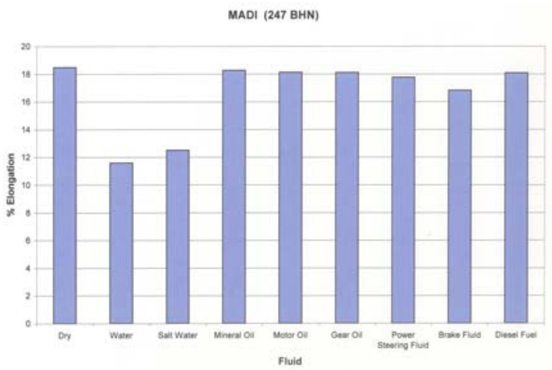

Figure 4. Effect of Fluid Environments on the Elongation of SAE-J-2477-750 ADI [8]

Table 6. Effect of Water Environment on the Tensile Properties of SAE-J-2477-750 ADI [9]

Sample	Property	Dry	Wet
1	UTS (MPa)	768	722
	Elong. (%)	23.2	8.3
2	UTS (MPa)	698	659
	Elong. (%)	22.7	7.9
3	UTS (MPa)	-	722
	Elong. (%)	-	8.3

Both studies report embrittlement when in contact with water. However, as shown in Table 6, the “embrittled” value measured by Druschitz is higher and the relative loss of ductility significantly less than the one reported by Hayrynen. Such a difference is believed to be related to microstructures. These irons being austenitized in the inter-critical zone, the matrix prior to austempering is a mixture of ferrite and austenite, the ferritic phase being not affected by the austempering. According to Druschitz [14], pro-eutectoid ferrite appears as a quasi continuous structure in its specimens, while reported discontinuous in the Hayrynen’s samples. This may explain the different results. Note that Druschitz [8] reported no embrittlement when in contact with liquids other than water base fluids, as for ferritic irons.

Table 6. Comparison of Data Reported on the J-2477-750 ADI Grade

Reference	Druschitz et al [8]	Hayrynen & Boeri [9]
“Dry” Ductility	18.5 %	23.2 %
“Wet” Ductility	11.5 %	8.2 %
Relative Reduction in Ductility	38 %	65 %

DISCUSSION

The review of the data on environmentally induced embrittlement of Ductile Irons shows that all grades, except ferritic irons, are sensitive to the phenomenon. The mechanisms by which it occurs are, however, not clearly identified. The following observations may help to understand the phenomenon.

- The phenomenon is not a grain boundary embrittlement or related to the presence of graphite. Ferritic Ductile Irons, which exhibit a large area of grains boundaries and the highest fraction of graphite, are not sensitive to the phenomenon.
- The phenomenon is independent of the time spent in contact with the liquid and disappears when the liquid is removed, as shown by Komatsu [4] and Martinez [6].
- Increasing strain rate [4, 6, 8] reduces the extent of the phenomenon, which is time sensitive and probably involves time controlled processes (diffusion, chemical reaction, adsorption, …).
- The phenomenon is observed in structures with extended phase interfaces (pearlite, tempered martensite, ausferrite).
- Shibutani [5] reported similar embrittlement when tensile tests are carried out in a hydrogen atmosphere.

- Forming a ferritic layer at the surface of the specimens prevents embrittlement, as does painting [5].

Such observations are not compatible with stress corrosion cracking, and the two following mechanisms for environmentally assisted embrittlement of Ductile Irons have been proposed: hydrogen embrittlement [5] and chemisorption [7, 8], but there is no clear evidence that favours one theory or the other. However, the presence of a high density of phase interfaces appears unavoidable for the phenomenon to occur. These phase boundaries are privileged sites for hydrogen pick-up and diffusion or for adsorption of atoms or molecules, which may cause embrittlement. It is worth noting that chemisorption (Liquid Metal Embrittlement) is favoured by high strain rate, while the opposite was observed for embrittlement of Ductile Irons.

Ferrite, either as a fully ferritic matrix, as a quasi-continuous phase in a composite matrix (spheroidized pearlite, fully tempered martensite) or as a continuous network (J-2477-750 ADI) probably prevents the embrittlement phenomenon by deforming plastically under the applied stress, retarding the initiation of cracks.

CONCLUDING REMARKS

Environmentally induced embrittlement of Ductile Irons is limited to high strength Ductile Iron grades (pearlitic, Q&T and ADI). When these grades are treated in order to get a continuous ferritic matrix (by tempering or intercritical austenitization of ADI), the phenomenon fades.

The review of the data also evidences that three factors have to be present to observe the environmentally assisted embrittlement of high strength Ductile Irons: i) presence of a liquid in contact with the material; ii) applied stress approaching the yield strength of the material; iii) low strain rate.

When designing a part, the “design safety factor” usually ensures that the component will not be loaded near the yield strength of the material. Nevertheless, when working in a liquid environment, additional precautions should be taken to ensure that the three above-mentioned factors are not found at the same time, and, as an additional safety measure, painting of the components should also be considered.

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