ชื่อ-นามสกุล...รหัสนักศึกษา..

ภาควิชาวิศวกรรมเหมืองแร่และวัสดุ
คณะวิศวกรรมศาสตร์
มหาวิทยาลัยสงขลานครินทร์

การสอบไล่ประจำภาคการศึกษาที่ 1 ปีการศึกษา 2550

วันที่ 8 ตุลาคม 2550 เวลา 09.00-12.00 น.

วิชา 237-407 Failure Mechanics and Analysis ห้อง A200

<u>คำชี้แจงสำหรับนักศึกษา</u>

1. ข้อสอบมีทั้งหมด 2 ข้อหลัก (14 ข้อย่อย) ให้ทำทุกข้อ
2. ตอบคำถามในสมุดคำตอบ เขียนหมายเลขข้อให้ชัดเจน
3. สามารถนำเอกสารทุกชนิดเข้าห้องสอบได้
4. คะแนนสอบคิดเป็น 30 % ของคะแนนรวมทั้งหมด

<u>คำชี้แจงสำหรับกรรมการจัดทำข้อสอบ และผู้คุมสอบ</u>

1. ให้แจกสมุดคำตอบคนละ 2 เล่ม

อ . ณรงค์ฤทธิ์ โททรัพย์

แบบทดสอบการวิเคราะห์การชำรุดอย่างเป็นระบบ ปีการศึกษา 2550

I. ข้อกำหนดในการสอบ

1. สามารถนำเอกสารทุกชนิดเข้าห้องสอบได้
2. จากรายงานผลการวิเคราะห์การชำรุด 2 ฉบับ

Case Study I **Failure of steel castings welded to heavy truck axles**

Case Study II **Gear Tooth Fatigue Pit**

ให้นักศึกษา ใช้ความรู้ ด้าน Fracture Mechanics, Systematic Failure Analysis, Heat Treatment, Welding Metallurgy , Materials Engineering และความรู้อื่น ๆ ด้านวิศวกรรม ศาสตร์ อธิบายผลการวิเคราะห์ เพื่อใช้ในการตอบ ข้อสอบ

3. เวลา 3 ชั่วโมง ข้อสอบ มีทั้งหมด 2 ข้อหลัก(14 ข้อย่อย)

II. วัตถุประสงค์ในการสอบ

เพื่อให้นักศึกษาสามารถวิเคราะห์ปัญหาเป็นระบบ นำทฤษฎี มาเชื่อมโยงกับการปฏิบัติ และประยุกต์ใช้ในการอธิบายปรากฏการณ์ที่เกิดขึ้นกับชิ้นงานจริง

คำสำคัญ

IIW = International Institute of Welding สถาบันเชื่อมสากล

AWS = American Welding Society สมาคมเชื่อมแห่งอเมริกา

ASTM = American Society for Testing and Materials สมาคมทดสอบวัสดุของอเมริกา

HAZ = Heat affected Zone

CE = Carbon Equivalent

DIN = Deutsches Institut für Normung มาตรฐานเยอรมัน

EN = European Standards มาตรฐานยุโรป

ผู้ออกข้อสอบ : ณรงค์ฤทธิ์ โทธรัตน์

ให้นักศึกษาตอบคำถามดังต่อไปนี้

I. Case Study I "Failure of steel castings welded to heavy truck axles"

1. ในกระบวนการเชื่อมเหล็กกล้า(Steel) ปัจจัยสำคัญในการกำหนดการทำ Preheat & Post heat เพื่อป้องกันการแตกร้าวจาก Hydrogen assist cracking (5 คะแนน)

2. ให้นักศึกษา วิจารณ์ Carbon Equivalent(CE) ที่ได้จาก IIW และ จาก AWS (5 คะแนน)

3. ผู้ผลิต Bracket เลือกใช้เหล็กกล้าหล่อ(Cast Steel) ตามมาตรฐาน ASTM A 148 (A 148/A 148M-03) แต่ไม่เหมาะสม เมื่อนำไปใช้ในการผลิตที่มีกระบวนการเชื่อม อย่างไร (5 คะแนน)

4. โครงสร้าง Martensite เป็นโครงสร้าง ที่ต้องการในกระบวนการชุบแข็ง(Heat treatment) แต่ในกระบวนการเชื่อม(Welding Process) ไม่พึงประสงค์ให้เกิด Martensite บริเวณ HAZ เพราะเหตุใด (5 คะแนน)

5. .ให้นักศึกษาเขียน Flow chart การชำรุดของ Case Study I และอธิบายกลไกการชำรุดในเชิง Fracture Mechanics ตั้งแต่ กลไกการกำเนิดรอยแตกจนกระทั่งชำรุด (20 คะแนน)

6. ให้นักศึกษาวิจารณ์ ความไม่เหมาะสมของกระบวนการเชื่อม ที่ผู้ผลิตใช้ในกระบวนการผลิต Bracket (5 คะแนน)

7. ถ้านักศึกษา ถูกมอบหมายให้แก้ไขและป้องกันการชำรุดของ Case Study I นักศึกษาจะมีวิธีการบริหารปัญหานี้อย่างไร (10 คะแนน)

8. จะป้องกันการเกิด Hydrogen assist Cracking (Hydrogen Induce Cracking, Cold cracking) ได้อย่างไรบ้าง (5 คะแนน)

II. Case Study II "Gear Tooth Fatigue Pit"

9. ทำไมต้องดำเนินการชุบแข็งผิวเฟืองดังกล่าว (5 คะแนน)

10. ทำไมวัสดุ 17CrNiMo ต้องชุบแข็งด้วย Carburizing เพราะเหตุใด ถ้าเปลี่ยนไปใช้กระบวนการ Induction ได้ผลแตกต่างกันอย่างไร จงประมาณค่าความแข็ง ที่ได้จากกระบวนการชุบแข็งทั้ง สองวิธี(10 คะแนน)

11. .ให้นักศึกษาเขียน Flow chart การชำรุดของ Case Study II และอธิบายกลไกการชำรุดในเชิง Fracture Mechanics ตั้งแต่ กลไกการกำเนิดรอยแตกจนกระทั่งชำรุด (10 คะแนน)

12. กรณีขาดสารหล่อลื่น เฟืองจะชำรุดด้วยกลไกการอย่างไร อธิบายอย่างละเอียด (5 คะแนน)

13. Gear ที่เกิด Pitting หรือสึกหรอ บริเวณผิวเฟือง สามารถใช้กระบวนการซ่อมผิว แบบ Hard coating ด้วย Thermal Spray ได้หรือไม่ เพราะเหตุใด (5 คะแนน)

14. ปัญหาสำคัญของ Case Study II นี้มาจากอะไร ถ้านักศึกษาเป็นผู้ผลิตเฟือง จะปรับปรุงกระบวนการอย่างไรบ้าง(5 คะแนน)

ผู้ออกข้อสอบ : ณรงค์ฤทธิ์ โทธรัตน์

เอกสารประกอบการสอบ

1. **Failure of steel castings welded to heavy truck axles**
2. **Gear Tooth Fatigue Pit**
3. **ASTM A 148**
4. **DIN EN 10084 (06/1998) 1.6587 17CrNiMo6**
5. **AWS D.1.1-2006 Structural Welding Code**
6. **ข้อความสำคัญจากงานวิจัย ตีพิมพ์ใน AWS Welding Journal**

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Engineering Failure Analysis 11 (2004) 115–125

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Failure of steel castings welded to heavy truck axles

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Received 7 March 2003; accepted 10 March 2003

Abstract

Minor changes in steel chemistry can have a significant affect on weld quality. Weld procedures performed in a manufacturing environment are usually developed based on the steel composition required in a material specification. This is done to consistently produce acceptable weld properties without developing a high hardness heat-affected zone (HAZ) in the adjacent base metal. Fatigue cracks were visually detected in cast steel suspension brackets after operators reported noticing looseness in the rear suspension system. These trucks were associated with a particular vocation that resulted in significant loads transferred through the torque rods that position the rear axles. It was discovered that the carbon equivalent (chemistry) in the steel castings had increased slightly over a period of time which ultimately resulted in a higher than expected hardness in the HAZ. Underbead cracks had formed in the HAZ of the casting that subsequently propagated by fatigue that could have resulted in detachment of the castings from the axle housing.
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Keywords: Welds; Chemical analysis; Heat-affected zone; Intergranular fracture; Fatigue

1. Introduction

Rear axles on heavy trucks are positioned and aligned laterally by torque rods while unique suspension components and/or track rods maintain the fore–aft axle spacing. These torque and track rods as well as other suspension members are usually attached with rubber lined bushings to the axle housing through brackets welded onto the housing. The complete assembly allows limited movement of the axles during turning maneuvers and auto realignment after the turn is completed. Loads are transferred through these brackets and undetected flaws that exist in the attachment welds or brackets may initiate cracks that can propagate by fatigue. A generic style axle housing with welded brackets is shown in Fig. 1 to facilitate visualization of this particular problem.

Rear axles usually have several welded-on brackets and not all of the cast steel brackets necessarily come from the same foundry. In this particular instance, at least two different foundries supplied brackets that were welded onto opposite sides of the axle housing. If the cracked bracket had not been noticed in a timely manner, it was possible that the remaining brackets could have been overstressed allowing the axle

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doi:10.1016/S1350-6307(03)00042-6

to detach from the chassis. This would have been catastrophic with all of the ramifications associated with loss of vehicle control, cargo and whether the incident occurred in a populated area or remote site.

2. Failure observations

The cracked brackets were noticed during routine inspections of the trucks involved with this problem. The axles were subsequently replaced and the brackets removed from the axle housings. Two typical failed brackets are shown in Figs. 2 and 3. Close inspection revealed that the dominant fracture occurred in the bracket casting and not in the weld metal or axle housing. The crack had initiated very close to the weld and subsequently propagated by fatigue in the HAZ of the casting as shown in Figs. 4 and 5. Some of the weld metal appears in the photograph.

The region of crack initiation exhibited a significant degree of intergranular cracking as seen in Fig. 6 when the fracture surface was examined using a scanning electron microscope (SEM). As the crack continues to propagate through the casting, the surface topography changes to transgranular fatigue crack propagation as shown by the fracture appearance in Fig. 7.

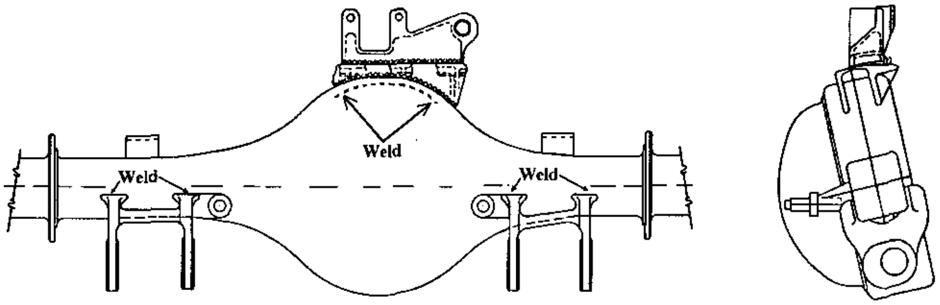

Fig. 1. Generic axle housing with welded brackets.

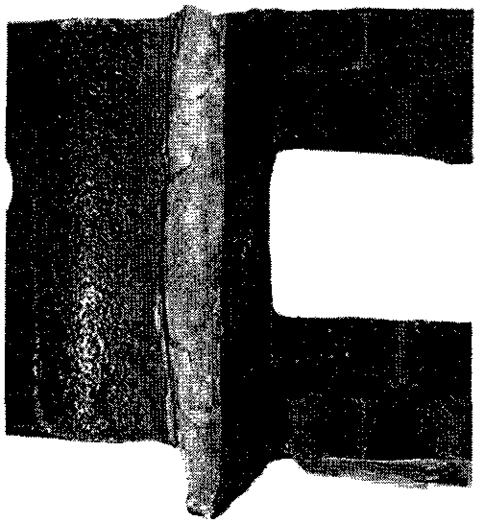

Fig. 2. Failed axle bracket.

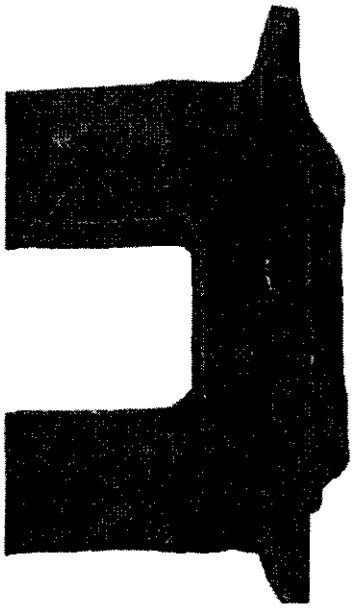

Fig. 3. Failed axle bracket.

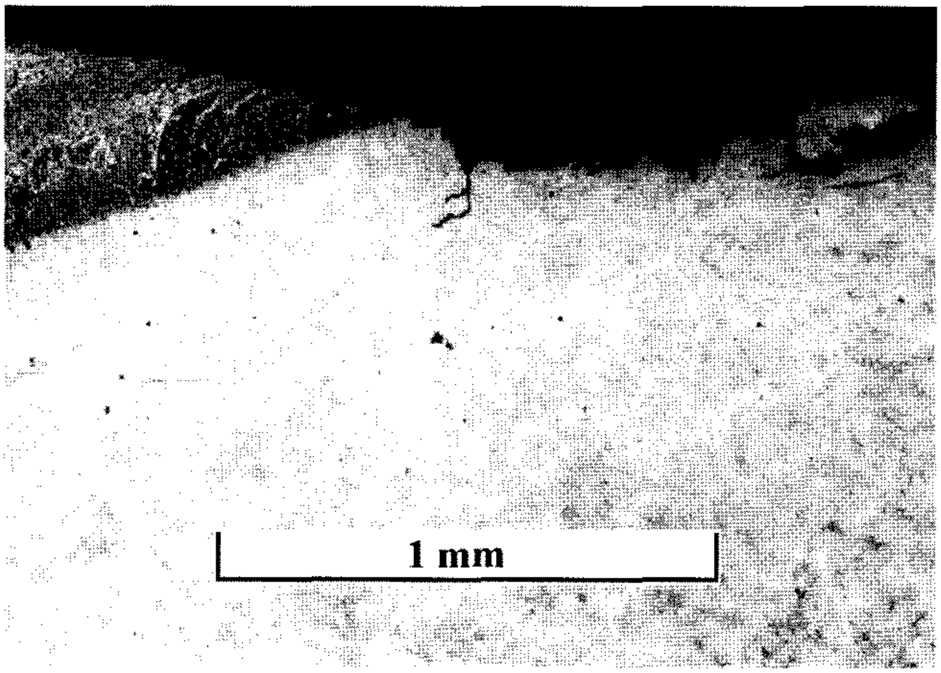

Fig. 4. Crack propagating in the HAZ of the casting.

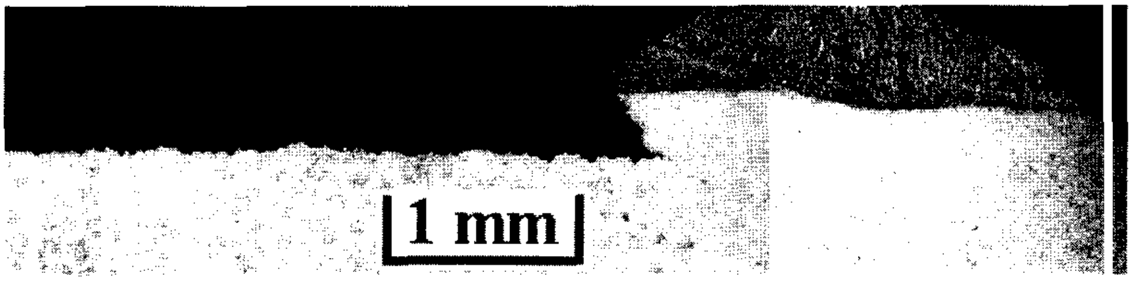

Fig. 5. Crack propagating in the HAZ of the casting.

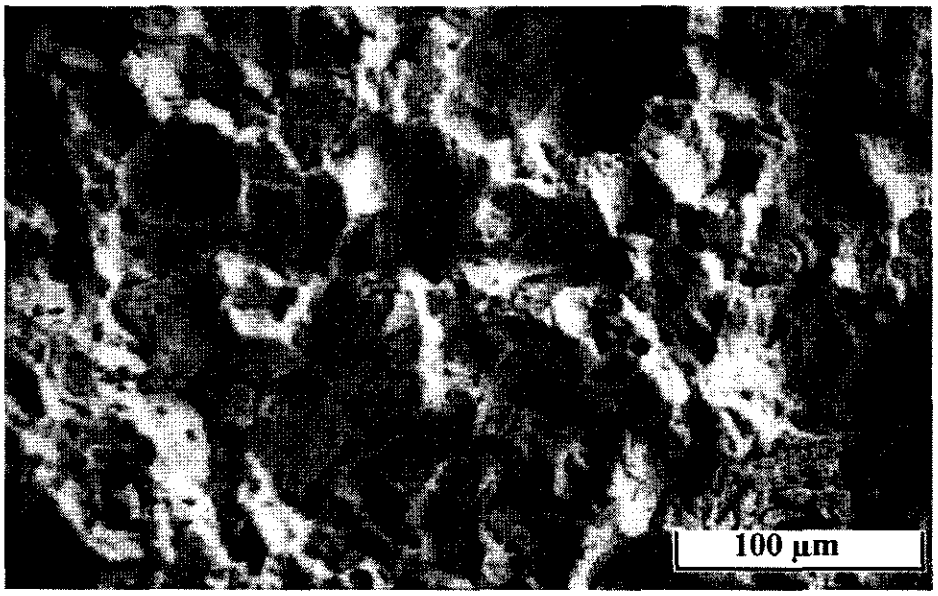

Fig. 6. Intergranular cracking in HAZ.

3. Failure mechanism

The observance of intergranular fracture in the SEM examination immediately suggested some form of embrittlement. It is well known that underbead or cold cracking may occur in welds when the welding parameters and steel chemistry are such as to promote a high hardness HAZ. The fracture mechanism is typically intergranular due to hydrogen and the hydrogen is either introduced from the welding consumables during welding or is present in the base metal from prior processes. The hardness of the HAZ is normally controlled during welding by preheating the work piece prior to welding and sometimes by applying a post weld heat treatment. Metallographic specimens were prepared from the bracket castings so that the polished specimen surface contained a portion of the fracture edge, the HAZ and adjacent base metal casting. The microstructure of the HAZ, base metal casting and the transition zone between the two regions are shown in Figs. 8–10. The HAZ exhibits a martensitic structure compared to the pearlitic/ferritic structure of the casting. If the martensitic HAZ has high hardness, then clearly the conditions are present for underbead or cold cracking to occur.

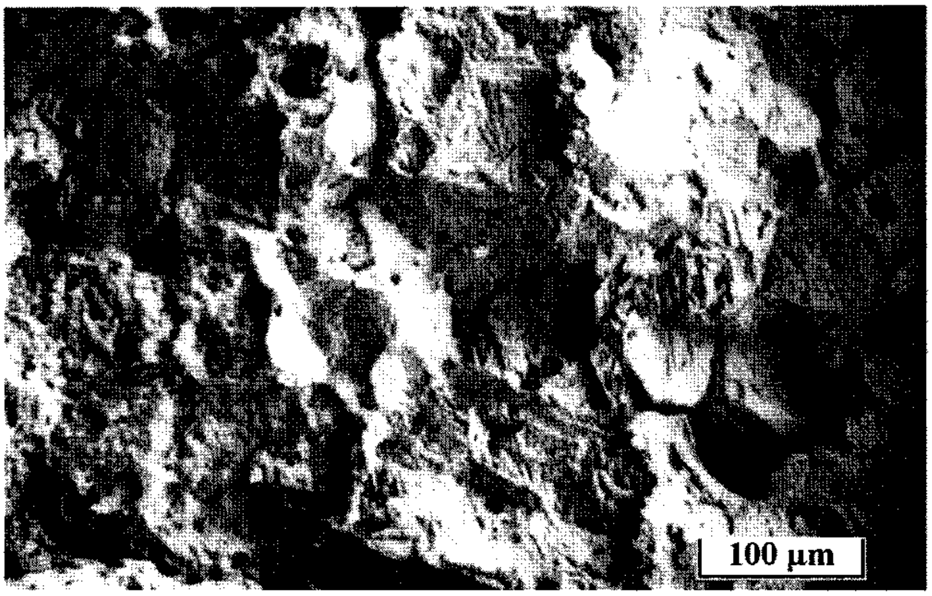

Fig. 7. Fatigue crack propagation in HAZ.

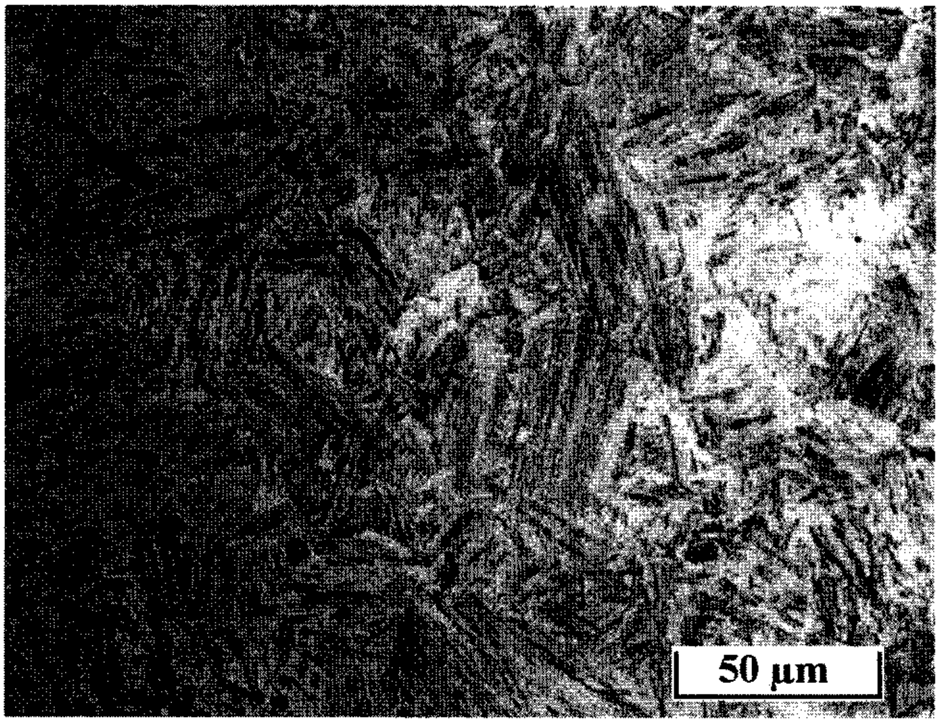

Fig. 8. Martensitic microstructure of the HAZ.

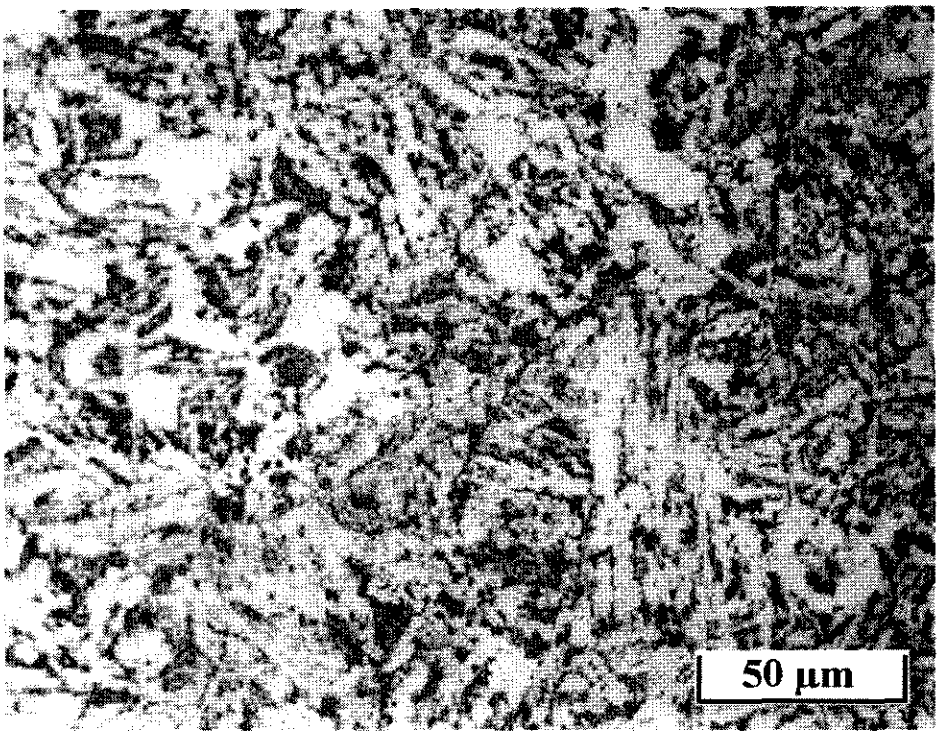

Fig. 9. The pearlitic/ferritic microstructure of the base metal casting.

A microhardness survey was conducted using a Knoop hardness indenter to characterize the HAZ, transition zone, and the core hardness of the casting. The hardness survey is shown in Fig. 11 and confirms the suspicion that the hardness of the HAZ is sufficient to promote underbead cracking when a small amount of hydrogen is present.

4. Root cause of failure

The cause of cracking in the cast steel brackets is the result of several factors acting concurrently and which are described as follows: (1) a high hardness in the HAZ from phase transformation resulting from the heat input and welding temperature, (2) tensile residual stress induced from phase transformation and mechanical constraint during cooling, and (3) sufficient hydrogen in the metal, either from the welding consumables or present in the casting itself.

5. Discussion of root cause

The welding process at the manufacturing facility had been developed for these materials and utilized for many years to produce thousands of axle welds. The historical record has been consistently good. The temperature of the castings and axle housings are typically above a minimum temperature of 16 °C prior to welding. They are moved from a storage site to an inside factory location at least 12 h in advance of welding. Normal practice is to bring the next day's assembly materials into the factory the night before to

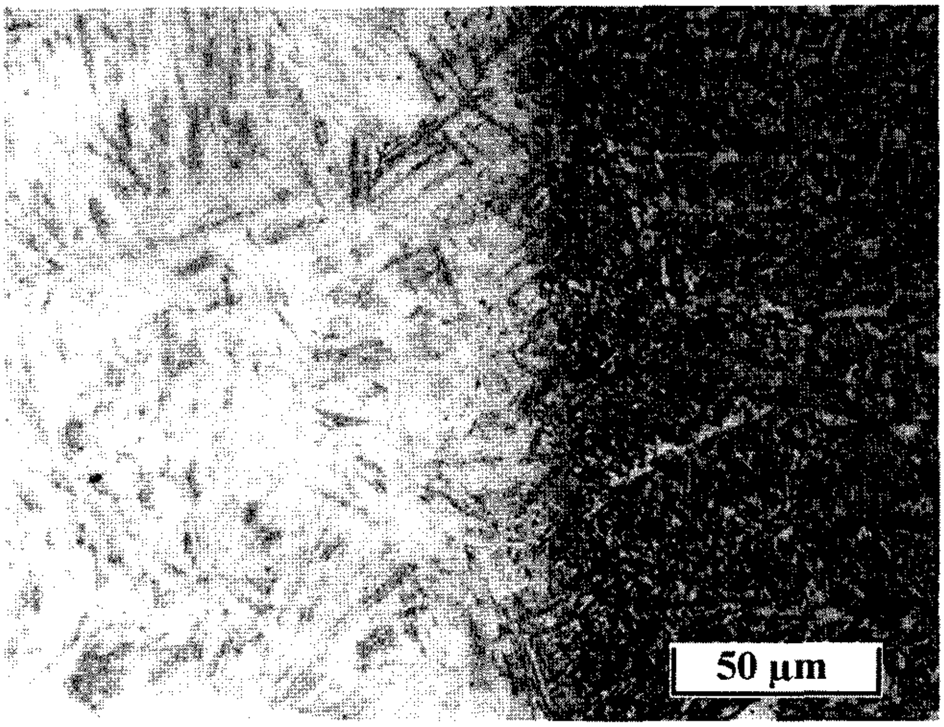

Fig. 10. The transition microstructure between the HAZ and base metal casting.

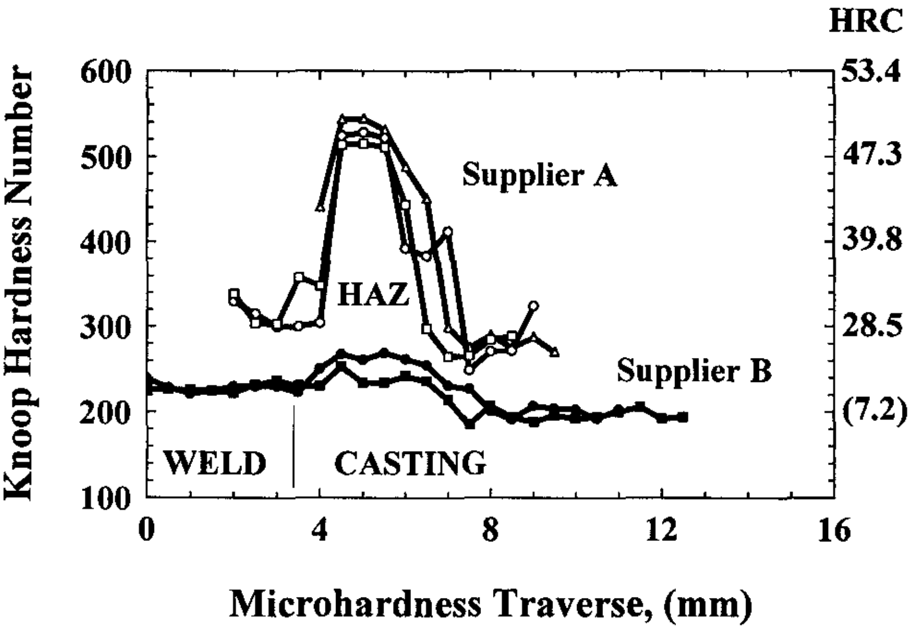

Fig. 11. Microhardness survey of the HAZ, transition zone, and casting.

allow temperature stabilization in the parts before welding. A preheat operation prior to welding had not been necessary since the plant temperature was generally maintained above 16 °C. The welding parameters were developed based on a material specification that limited the carbon content to 0.3%, the carbon equivalent (CE) to 0.6, and the maximum hardness of the HAZ to 350 HV (RC 35.5). The CE formula referenced in the specification is associated with the International Institute of Welding (IIW) which does not include the element silicon. The IIW formula for CE in weight percent is:

$$\mathrm{CE} = \mathrm{C}\% + \mathrm{Mn}\%/6 + (\mathrm{Cr}\% + \mathrm{Mo}\% + \mathrm{V}\%)/5 + (\mathrm{Ni}\% + \mathrm{Cu}\%)/15 \leqslant 0.6\% \tag{1}$$

It can be seen from Fig. 11 that the maximum HAZ hardness of the failed castings was in excess of HRC 47. Two of the axle housings with broken castings also contained cast steel brackets supplied by a different foundry. These steel castings were in compliance with the material specification, welded during the same working shift with the same personnel and with the same weld parameters as the castings that cracked. The microhardness traverses across the HAZ for these two castings produced by casting Supplier B are also included in Fig. 11. It is evident that the carbon equivalent for the cracked castings was either at the very high range of the specification, or exceeded the material specification.

Additional insight into this problem was gained by examining the time sequence history of consecutive casting heats from Supplier A. Fig. 12 shows the variation in chemical elements in the steel affecting hardenability, including Si, that are used to calculate the carbon equivalent. There are a few heats showing elevated concentrations of chromium, nickel or silicon but in general the variation appears fairly typical of cast steel according to the ASTM A148, grade 80-50 specification. When the carbon equivalent is calculated for these heat lot chemistries and plotted sequentially, there is a gradual trend with time to higher values. Fig. 13 shows this trend over a 15-month period.

The importance of maintaining a low value for carbon equivalent when either preheat or postheat treatments are not employed during the welding process is to control the hardness level in the HAZ and

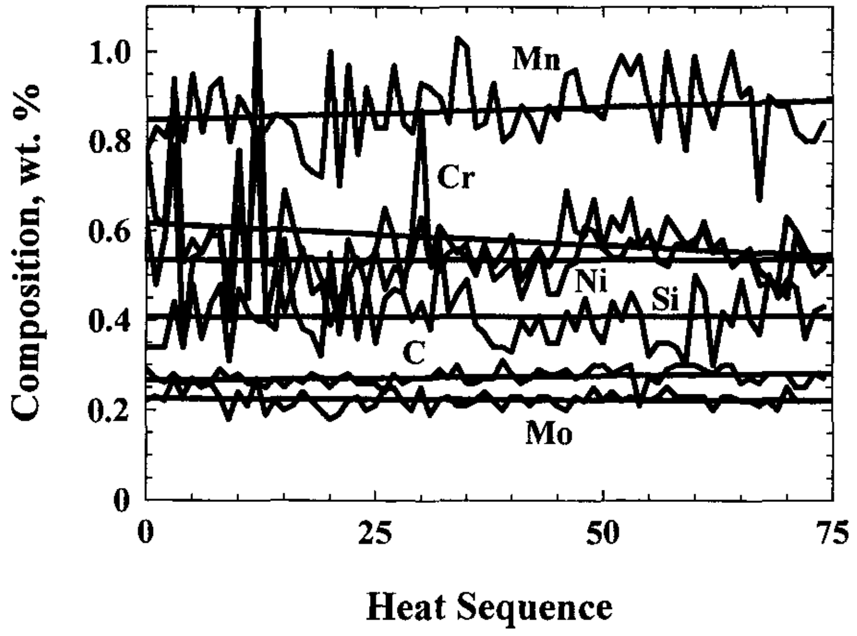

Fig. 12. Steel chemistry variation in consecutive heats of castings.

prevent hydrogen assisted cold cracking. Brian Graville developed a diagram showing the sensitivity to cold cracking based on the carbon content and the carbon equivalent of steels which represents a methodology to aid in developing appropriate weld parameters [1–3]. The diagram is divided into three zones which are described as follows: Zone I "Cracking is unlikely, but may occur with high hydrogen or high restraint." Zone II "For steels with high carbon, a minimum energy to control hardness and preheat to control hydrogen may be required." Zone III "The hydrogen control method shall be used" meaning preheat and possibly postheat thermal treatments. His diagram has been adopted by the American Welding Society (AWS) and is included in the the AWS Structural Welding Code for Steel and can be described as "an alternative method for determining welding conditions to avoid cold cracking" [4]. The formula for carbon equivalent used by Graville includes the element Si and is shown in Eq. (2).

$$\mathrm{CE} = \mathrm{C}\% + (\mathrm{Mn}\% + \mathrm{Si})/6 + (\mathrm{Cr}\% + \mathrm{Mo}\% + \mathrm{V}\%)/5 + (\mathrm{Ni}\% + \mathrm{Cu}\%)/15 \tag{2}$$

There are many formulas in use for CE but this is the formula adopted by AWS for structural steel The steel foundry industry acknowledges that Si is more difficult to control because of refractory linings in the melt shop and the potential for the steel melt to pick up Si from that source. Hardenability of the HAZ is primarily due to alloy content but grain size also has an influence. Since the grain size is smaller in wrought steels compared to foundry products, the grain size effect tends to increase hardenability in castings.

When the CE for the suspect foundry heats are plotted on a Graville diagram (using the formula which includes Si), they are all located in Zone 3 as shown in Fig. 14. Careful attention to welding procedures would be required to prevent cold cracking with these heats of castings. An historical perspective can be gained if similar information from other cast steel suppliers is used for comparison. The CE of weldable axle bracket castings from other suppliers is also included in this diagram. It is apparent that the castings

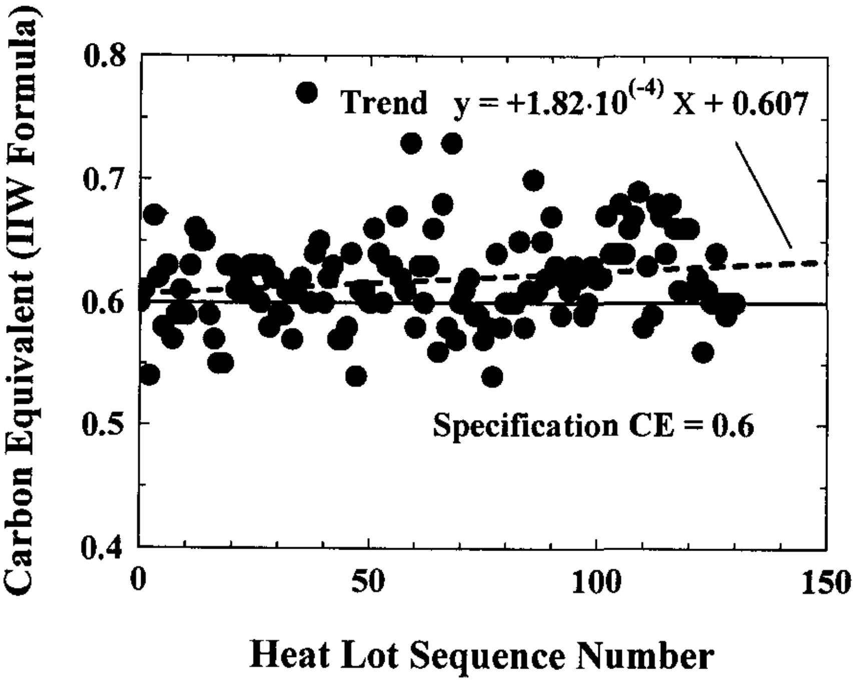

Fig. 13. Increasing trend in the CE with time.

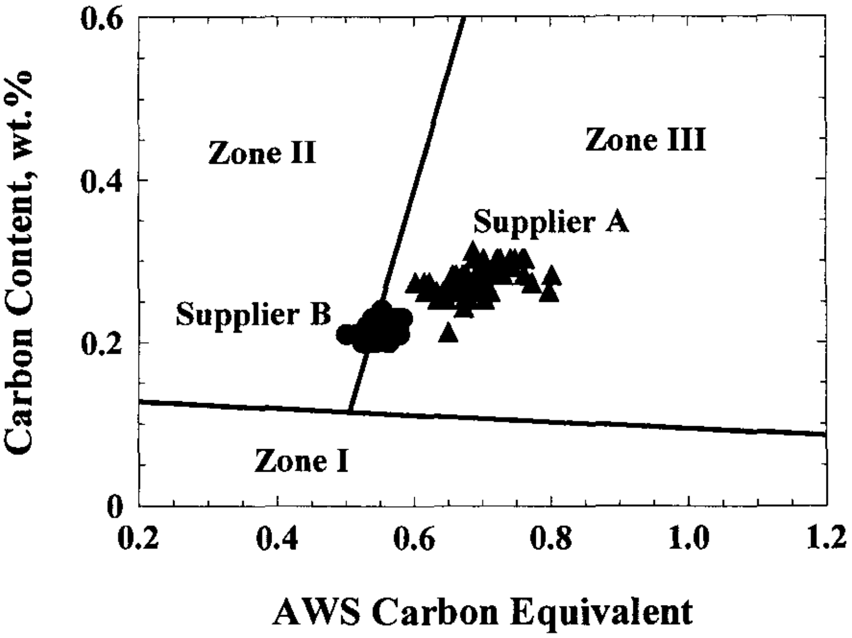

Fig. 14. Sensitivity to cold cracking for various heats of cast steel.

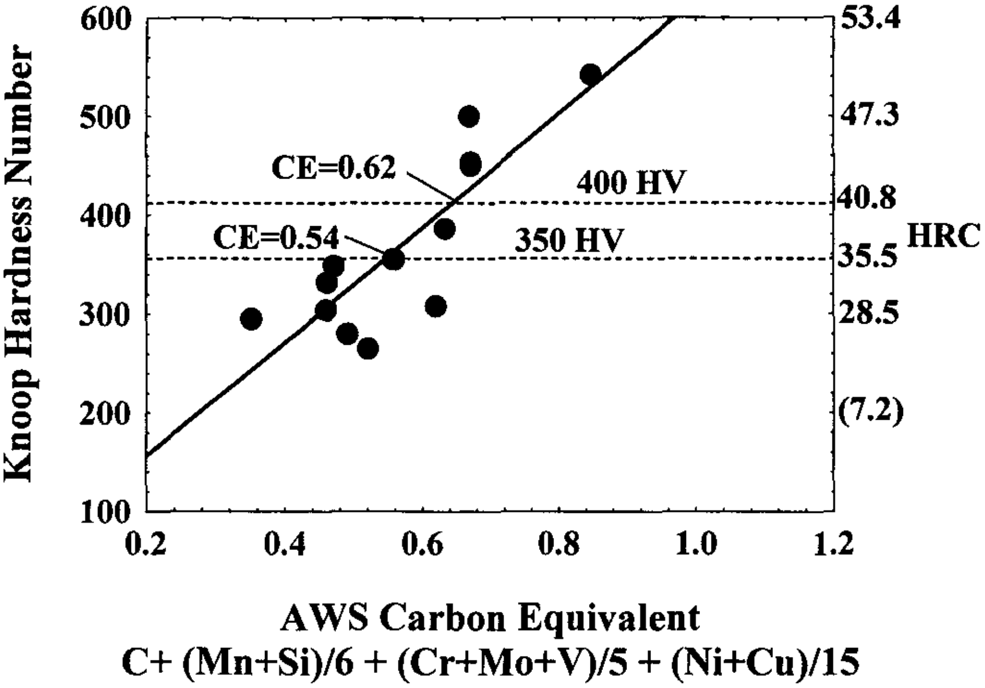

Fig. 15. Relationship of CE to HAZ hardness in welded steel castings.

from supplier A have additional alloy content that results in welds susceptible to cold cracking using the specified welding procedures. Although the steel castings were of excellent strength and quality and would be considered premium castings, the welding procedure developed and used for axle brackets was not optimised for the alloy castings with higher CE. The variation in HAZ hardness maximum that might be expected using the traditional welding procedure is shown in Fig. 15 for several welded axle bracktes This data has been collected over a period of time for various reasons and reflects the expected variation in hardness with CE.

The structural integrity of suspension components for heavy trucks depends on quality systems that are in place at the supplier's facilities as well as at the assembly plants where welding procedures must be strictly adhered to for product consistency and reliability. This particular lot of castings could have been favorably utilized by adjusting the welding process if the steel chemistry had been known to the welding shop prior to assembly. However, manufacturing efficiency would probably have been compromised This investigation ultimately resulted in a revision to the specification for steel castings. Alternatively, the welding procedure could have been revised to include a higher preheat temperature even though the established welding process does not create high hardness HAZ's with castings having the CE in the required range. The CE requirement in the specification was therefore revised to a maximum value of 0.61% or average CE + $3\sigma = 0.61\%$. A requirement of steel foundries is to know the statistical range of the CE for each grade of steel produced when the castings may be welded to other components. This information should be availabe to their customers to insure the final product is fit for the intended application.

6. Conclusions

1. The cracked axle seat brackets were cast from low alloy steel that exceeded the specification for carbon equivalent.
2. The HAZ hardness of the cracked castings was in the range susceptible to hydrogen assisted cold cracking.
3. The established welding procedure was appropriate for the steel chemistry specified and historically, would not result in a high hardness HAZ.

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[3] Somers BR. Introduction to the selection of carbon and low-alloy steels. In: Welding, brazing, and soldering, vol. 6. ASM handbook. ASM; 1993.
[4] Guideline on alernative methods for determining preheat. 1990 structural welding code—steel, appendix XI. 12th ed. AWS 1990.


3
3

Designation: A 148/A 148M – 03

Standard Specification for Steel Castings, High Strength, for Structural Purposes[1]

This standard is issued under the fixed designation A 148/A 148M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope *

1.1 This specification covers carbon steel, alloy steel, and martensitic stainless steel castings that are to be subjected to higher mechanical stresses than those covered in Specification A 27/A 27M.

1.2 Several grades of steel castings are covered, having the chemical composition and mechanical properties prescribed in Table 1 and Table 2.

1.3 The values stated in inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the specification.

2. Referenced Documents

2.1 *ASTM Standards:*

A 27/A 27M Specification for Steel Castings, Carbon, for General Application[2]

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products[3]

A 781/A 781M Specification for Castings, Steel and Alloy, Common Requirements for General Industrial Use[2]

E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications[4]

3. General Conditions for Delivery

3.1 Material furnished to this specification shall conform to the requirements of Specification A 781/A 781M, including any supplementary requirements that are indicated in the purchase order. Failure to comply with the general requirements of Specification A 781/A 781M constitutes nonconformance with this specification. In case of conflict between the requirements of this specification and Specification A 781/A 781M, this specification shall prevail.

TABLE 1 Chemical Requirements

Grade (UNS No.)	Composition %	
	Sulfur, max	Phosphorus, max
80-40 [550-275] (D50400)	0.06	0.05
80-50 [550-345] (D50500)	0.06	0.05
90-60 [620-415] (D50600)	0.06	0.05
105-85 [725-585] (D50850)	0.06	0.05
115-95 [795-655] (D50950)	0.06	0.05
130-115 [895-795] (D51150)	0.06	0.05
135-125 [930-860] (D51250)	0.06	0.05
150-135 [1035-930] (D51350)	0.06	0.05
160-145 [1105-1000] (D51450)	0.06	0.05
165-150 [1140-1035] (D51500)	0.020	0.020
165-150L [1140-1035L] (D51501)	0.020	0.020
210-180 [1450-1240] (D51800)	0.020	0.020
210-180L [1450-1240L] (D51801)	0.020	0.020
260-210 [1795-1450] (D52100)	0.020	0.020
260-210L [1795-1450L] (D52101)	0.020	0.020

4. Ordering Information

4.1 The inquiry and order should include or indicate the following:

4.1.1 A description of the casting by pattern number or drawing (dimensional tolerances shall be included on the casting drawing),

4.1.2 Grade of steel,

4.1.3 Options in the specification, and

4.1.4 The supplementary requirements desired, including the standards of acceptance.

5. Heat Treatment

5.1 All castings shall be heat treated either by full annealing, normalizing, normalizing and tempering, or quenching and tempering. Unless otherwise specified in the inquiry, contract, or order, the castings may be heat treated by any of these heat treatments or combination of these heat treatments at the option of the manufacturer.

5.2 Heat treatment shall be performed after the castings have been allowed to cool below the transformation range.

6. Temperature Control

6.1 Furnace temperatures for heat-treating shall be regulated by the use of pyrometers.

*A Summary of Changes section appears at the end of this standard.

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[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloysand is the direct responsibility of Subcommittee A01.18on Castings.

Current edition approved April 10, 2003. Published April 2003. Originally approved in 1955. Last previous edition approved in 2002 as A 148/A 148M – 02.

[2] *Annual Book of ASTM Standards*, Vol 01.02.

[3] *Annual Book of ASTM Standards*, Vol 01.03.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

TABLE 2 Tensile Requirements

Grade	Tensile strength min, ksi [MPa]	Yield point min, ksi [MPa]	Elongation in 2 in. or 50 mm, min, %[A]	Reduction of Area, min, %
80-40 [550-275]	80 [550]	40 [275]	18	30
80-50 [550-345]	80 [550]	50 [345]	22	35
90-60 [620-415]	90 [620]	60 [415]	20	40
105-85 [725-585]	105 [725]	85 [585]	17	35
115-95 [795-655]	115 [795]	95 [655]	14	30
130-115 [895-795]	130 [895]	115 [795]	11	25
135-125 [930-860]	135 [930]	125 [860]	9	22
150-135 [1035-930]	150 [1035]	135 [930]	7	18
160-145 [1105-1000]	160 [1105]	145 [1000]	6	12
165-150 [1140-1035]	165 [1140]	150 [1035]	5	20
165-150L [1140-1035L][B]	165 [1140]	150 [1035]	5	20
210-180 [1450-1240]	210 [1450]	180 [1240]	4	15
210-180L [1450-1240L][B]	210 [1450]	180 [1240]	4	15
260-210 [1795-1450]	260 [1795]	210 [1450]	3	6
260-210L [1795-1450L][B]	260 [1795]	210 [1450]	3	6

[A] When ICI test bars are used in tensile testing as provided for in this specification, the gage length to reduced section diameter ratio shall be 4 to 1.

[B] These grades must be charpy impact tested as prescribed in Section 9, and with minimum values as shown in Table 3.

7. Chemical Composition

7.1 The steel shall conform to sulfur and phosphorus requirements as prescribed in Table 1.

7.2 The content of carbon, manganese, silicon, and alloying elements may, by agreement, be prescribed by the purchaser. If not specified, the content may be selected by the manufacturer to obtain the required mechanical properties.

7.3 When the analysis of carbon, manganese, silicon, or any intentionally added alloying element is specifically requested in the contract or order, it shall be made by the manufacturer and reported to the purchaser. The results of these analyses shall not be used as a basis for rejection except by prior agreement.

8. Tensile Requirements

8.1 One tension test shall be made from each heat and shall conform to the tensile requirements specified in Table 2.

8.2 The test coupons and specimens shall conform to requirements specified in Section 11.

8.3 Tension test coupons shall be machined to the form and dimension shown in Fig. 5 of Test Methods and Definitions A 370 and tested in accordance with those test methods.

8.4 To determine conformance with the tension test requirements, an observed value or calculated value shall be rounded off in accordance with Practice E 29 to the nearest 500 psi [5 MPa] for yield point and tensile strength and to the nearest 1 % for elongation and reduction of area.

9. Charpy Impact Requirements

9.1 This section is applicable only to grades 165-150L [1140-1035L], 210-180L [1450-1240L], and 260-210L [1795-1450L].

NOTE 1—Other grades may be ordered to charpy impact test requirements in accordance with Supplementary Requirement S9 of Specification A 781/A 781M.

9.2 The notched bar impact properties of each heat shall be determined by testing one set of three Charpy V-notch impact specimens at −40° ± 2°F [−40° ± 1°C]. The energy value of the three specimens shall not be less than shown in Table 3.

TABLE 3 Impact Requirements

Grade	165-150L [1140-1035L]	210-180L [1450-1240L]	260-210L [1795-1450L]
Impact Requirements Charpy V-notch Energy value, ft·lbf [J], min value for two specimens and minimum average of three specimens	20 [27]	15 [20]	6 [8]
Energy value, ft·lbf [J], min for single specimen	16 [22]	12 [16]	4 [5]

9.3 Test coupons and specimens shall conform to the requirements specified in Section 11.

9.4 Impact test specimens shall be machined to the form and dimensions shown in Test Methods and Definitions A 370, Type A, Charpy V-notch specimen, Fig. 11, and tested in accordance with those test methods.

10. Retests

10.1 If the results of the tensile or charpy tests do not conform to the requirements specified, heat-treated castings may, at the manufacturer's option, be reheat treated. Testing after reheat treatment shall consist of the full number of specimens complying with the specification or order.

11. Test Coupons and Specimens

11.1 Test bars shall be poured from the same heat as the castings represented. Test coupons may be cast integrally with the castings or as separate blocks similar to those shown in Fig. 1 of Specification A 781/A 781M.

11.1.1 In the case of quenched and tempered castings where the ruling section of the casting exceeds three inches, supplementary requirement S 15 of Specification A 781/A 781M shall apply.

11.2 The bar from which the test piece is taken shall be heat treated in production furnaces with the castings or to the same procedure as the castings it represents.

11.2.1 When the bar from which the test piece is taken is not heat treated as part of the same heat treatment load as the casting(s) it qualifies, the austenitizing (or solution, if applicable) temperatures for the bar shall be within 25°F of those for the casting(s). The tempering temperature for the bar shall be no higher than 25°F above that of the casting(s) and no higher than permitted by the heat treatment procedure for the material. The cycle time at each temperature shall not exceed that for the casting(s).

11.3 Test specimens may be cut from heat-treated castings, at the producer's option, instead of from test bars.

11.4 If any specimen shows defective machining, or exhibits flaws, it may be discarded and another substituted from the same heat.

12. Repair by Welding

12.1 Weld repairs shall be inspected to the same quality standards that are used to inspect the castings. When castings are produced with Supplementary Requirement S1 specified, weld repairs shall be inspected by magnetic particle examination to the same standards that are used to inspect the castings. When castings are produced with Supplementary Requirement S2 specified, weld repairs in which the depth of the cavity prepared for repair welding exceeds 20 % of the wall thickness or 1 in. [25 mm], whichever is smaller, or in which the cavity prepared for welding is greater than approximately 10 in.^{2}[65 cm^2], shall be radiographed to the same standards that are used to inspect the castings.

12.2 Welds exceeding 20 % of the wall thickness or 1 in. [25 mm], whichever is smaller, or exceeding approximately 10 in.^{2} [65 cm^2] in area, shall be given a suitable stress relief or heat treatment.

13. Rehearing

13.1 Tested samples representing rejected material shall be held for two weeks from the date of the test report. In case of dissatisfaction with the results of the tests, the manufacturer may make claim for a rehearing within that time.

14. Keywords

14.1 alloy steel; carbon steel; castings; high strength steel; martensitic stainless steel; steel castings; structural castings

SUPPLEMENTARY REQUIREMENTS

The following supplementary requirements shall not apply unless specified in the purchase order. A list of standardized supplementary requirements for use at the option of the purchaser is included in Specification A 781/A 781M. Those which are ordinarily considered suitable for use with this specification are given below together with additional supplementary requirements that are applicable only to this specification. Other supplementary requirements enumerated in Specification A 781/A 781M may be used with this specification upon agreement between the manufacturer and purchaser.

S1. Magnetic Particle Examination.

S2. Radiographic Examination.

S6. Certification.

S8. Marking.

S9. Charpy Impact Test

S9.1 Charpy impact test properties shall be determined on each heat from a set of three Charpy V-notch specimens made from a test coupon in accordance with Test Methods and Definitions A 370 and tested at a test temperature agreed upon between the manufacturer and purchaser. The acceptance requirements shall be either energy absorbed, lateral expansion, or percent shear area, or all three, and shall be that agreed upon by the manufacturer and purchaser. Test specimens shall be prepared as Type A and tested in accordance with Test Methods and Definitions A 370.

S9.2 *Absorbed Energy*—Average energy value of three specimens shall be not less than specified, with not more than one value permitted to fall below the minimum specified and no value permitted below the minimum specified for a single specimen.

S9.3 *Lateral Expansion*—Lateral expansion value shall be agreed upon between the manufacturer and purchaser.

S9.4 *Percent Shear Area*—Percent shear area shall be agreed upon between the manufacturer and purchaser.

S15. Alternate Tension Test Coupons and Specimen Locations for Castings (in lieu of Test Bars Poured from Special Blocks).

SUMMARY OF CHANGES

Committee A01 has identified the location of selected changes to this standard since the last issue (A 148/A 148M – 02) that may impact the use of this standard).

(*1*) Added the UNS Numbers to the grades inTable 1.

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Gear Tooth Fatigue Pit

Industry: Electric power generation

Specimen Description: Turbine gearbox pinion gear

Material: 17CrNiMo6 low alloy steel, case hardened by gas carburizing

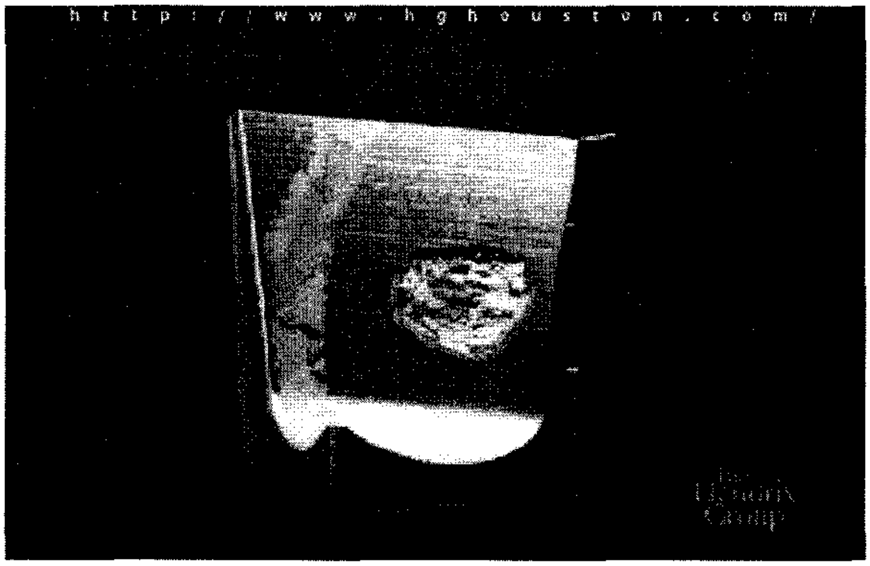
Environment: Lubricating oil

Background: A double-helical pinion gear in a gas turbine gearbox developed pits on the loaded teeth. A laboratory failure analysis was conducted to determine the cause for the gear teeth pitting.

Time in Service: several years

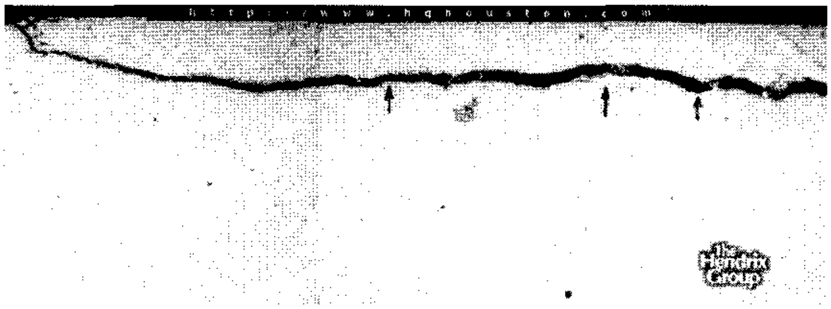
Findings: The pinion gear suffered random, open progressive pitting on the loaded flanks of the teeth. Other areas of the loaded gear teeth exhibited visual images of subsurface fatigue cracks that had not developed into open pits yet. The companion bull gear had not pitted. Microstructural investigation of a representative subsurface pit showed that it propagated parallel to the case hardened surface and contained white etching areas (WEA's). Other subsurface, intergranular cracks were also present that had initiated at inclusions.

Results of the failure analysis showed that the gear tooth pitting was due to surface-contact fatigue cracking. The WEA's have been described as "butterfly wings" and white bands of altered martensite. They reportedly occur in gear teeth that have experienced heavy shear or impact loads.



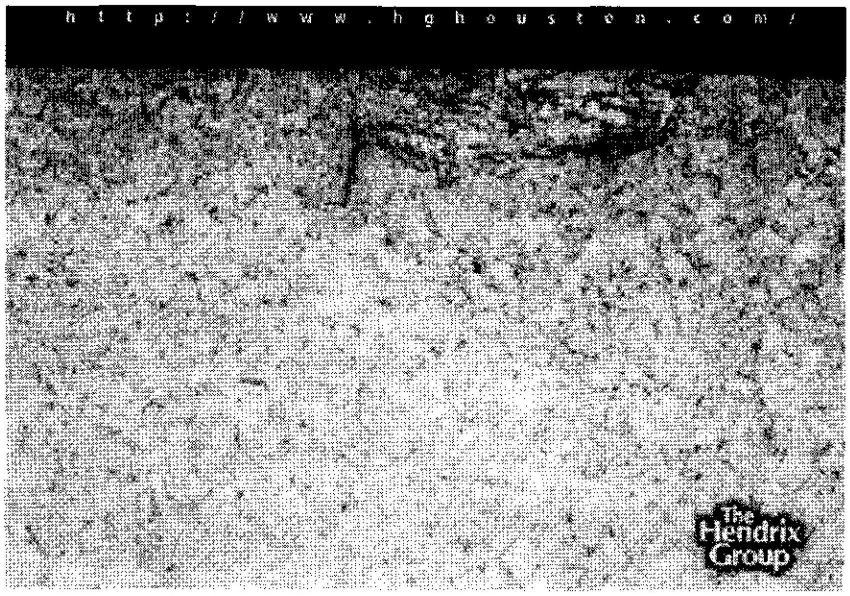
Progressive pit on the loaded surface of a case hardened pinion gear tooth due to surface contact fatigue

Gear Tooth Rolling Contact Fatigue Crack



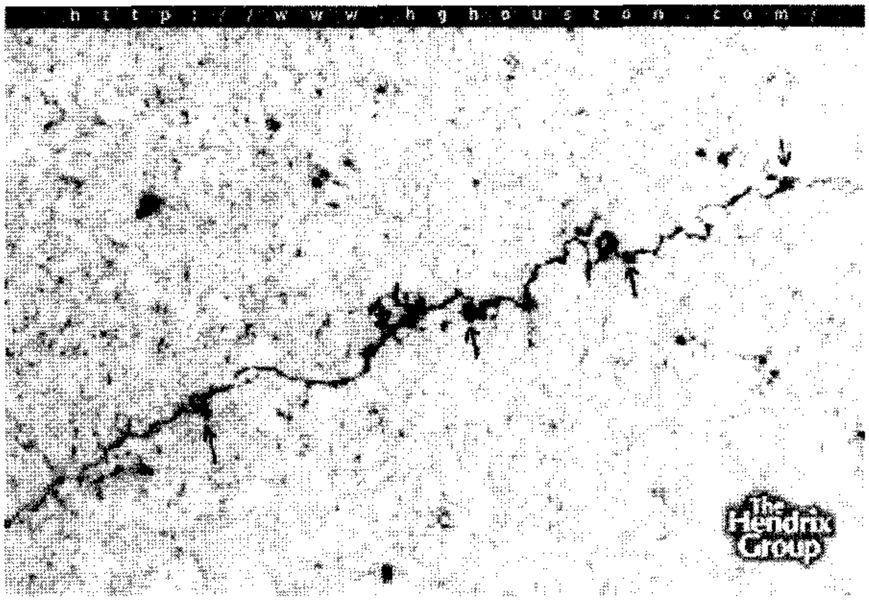
Subsurface rolling contact fatigue crack emanating from inclusions in a case hardened pinion gear tooth.

Gear Tooth White Etching Area



White etching area (WEA) at the surface of a case hardened pinion gear tooth.

Gear Tooth Rolling Contact Fatigue Crack



Subsurface rolling contact fatigue crack emanating from inclusions in a case hardened pinion gear tooth.

Date 25/8/2550

Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

Standards	DIN EN 10084 (06/1998)	Case hardening steels.
	DIN EN ISO 683-17 (04/2000)	Heat-treated steels, alloy steels and free-cutting steels. Ball and roller bearing steels. Ball and roller bearing steels for case hardening

Steelgroup Alloy special structural steels: Structural steels, Cr-Ni-Mo-steels with < 0,4% Mo and < 2,0% Ni

Range of application Case hardening steels:
Plate wheels, driving pinions and highly stressed cog wheels

Chemical composition

Element	min/max	Others	Footnote
C	0.15 - 0.21		
Si	<=0.40		
Mn	0.50 - 0.90		
P	<=0.035		
S	<=0.035		
Cr	1.50 - 1.80		
Mo	0.25 - 0.35		
Ni	1.40 - 1.70		
-			18)

18) DIN EN ISO 683-17 P <= 0,025%; S <= 0,015%; Al <= 0,05%; Cu <= 0,30%; O <= 0,002%

Date 25/8/2550

Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

Mechanical properties

dimension	value	specimen	at temperature	chanical properties	duration
DIN EN 10084 (06/1998) ***Case hardening steels.***					
treated to hardness range					
Hardness [HB]					
	179 - 229 HB				
treated to ferrit-pearlite microstructure and hardness range					
Hardness [HB]					
	159 - 207 HB				
soft annealed					
Hardness [HB]					
	<=229 HB				
quenched					
Jominy test piece (+H)					
~ 1.5 mm	40 - 48 HRC				
~ 3 mm	40 - 48 HRC				
~ 5 mm	39 - 48 HRC				
~ 7 mm	38 - 48 HRC				
~ 9 mm	37 - 47 HRC				
~ 11 mm	36 - 47 HRC				
~ 13 mm	35 - 46 HRC				
~ 15 mm	34 - 46 HRC				
~ 20 mm	32 - 44 HRC				
~ 25 mm	31 - 43 HRC				
~ 30 mm	30 - 42 HRC				
~ 35 mm	29 - 41 HRC				
~ 40 mm	29 - 41 HRC				
Jominy test piece (+HH)					
~ 1.5 mm	43 - 48 HRC				
~ 3 mm	43 - 48 HRC				
~ 5 mm	42 - 48 HRC				
~ 7 mm	41 - 48 HRC				
~ 9 mm	40 - 47 HRC				
~ 11 mm	40 - 47 HRC				
~ 13 mm	39 - 46 HRC				
~ 15 mm	38 - 46 HRC				
~ 20 mm	36 - 44 HRC				
~ 25 mm	35 - 43 HRC				
~ 30 mm	34 - 42 HRC				
~ 35 mm	33 - 41 HRC				
~ 40 mm	33 - 41 HRC				

Date 25/8/2550

Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

quenched

Jominy test piece (+HL)

~ 1.5 mm	40 - 45 HRC
~ 3 mm	40 - 45 HRC
~ 5 mm	39 - 45 HRC
~ 7 mm	38 - 45 HRC
~ 9 mm	37 - 44 HRC
~ 11 mm	36 - 43 HRC
~ 13 mm	35 - 42 HRC
~ 15 mm	34 - 42 HRC
~ 20 mm	32 - 40 HRC
~ 25 mm	31 - 39 HRC
~ 30 mm	30 - 38 HRC
~ 35 mm	29 - 37 HRC
~ 40 mm	29 - 37 HRC

quenched and tempered bei ~ 200 ?C

Tensile strength

<=16 mm	>=1200 N/mm?	1.1)
16 - 40 mm	>=1100 N/mm?	1.1)
40 - 100 mm	>=900 N/mm?	1.1)

treated to capacity for shearing

Hardness [HB]

<=255 HB

1.1) Informative

Date 25/8/2550

Material data sheet

Material Number	1.6587
Country	Germany
Designations	18CrNiMo7-6; 17CrNiMo6

DIN EN ISO 683-17 (04/2000)

Heat-treated steels, alloy steels and free-cutting steels. Ball and roller bearing steels. Ball and roller bearing steels for case hardening

annealed

Hardness [HB]

<=229 HB

treated to hardness range

Hardness [HB]

179 - 229 HB

treated to ferrit-pearlite microstructure and hardness range

Hardness [HB]

159 - 207 HB

quenched

Jominy test piece (+H)

~ 1.5 mm	40 - 48 HRC
~ 3 mm	40 - 48 HRC
~ 5 mm	39 - 48 HRC
~ 7 mm	38 - 48 HRC
~ 9 mm	37 - 47 HRC
~ 11 mm	36 - 47 HRC
~ 13 mm	35 - 46 HRC
~ 15 mm	34 - 46 HRC
~ 20 mm	32 - 44 HRC
~ 25 mm	31 - 43 HRC
~ 30 mm	30 - 42 HRC
~ 35 mm	29 - 41 HRC
~ 40 mm	29 - 41 HRC

annealed to obtain spherical-particled carbides+cold-drawn

Hardness [HB]

<=229 HB 1.1) 1.2)

treated to capacity for cold shearing

Hardness [HB]

<=255 HB

annealed to obtain spherical-particled carbides

Hardness [HB]

<=179 HB 1.2)

1.1) Depending on degre of cold forming

1.2) If cold forming is provided

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Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

Data from Stahlschl?ssel book

Bars

treated to hardness range

Hardness [HB 30]		
<=150 mm	179 - 229 HB 30	1.1)

treated to ferrit-pearlite microstructure and hardness range

Hardness [HB 30]		
<=60 mm	159 - 207 HB 30	1.1)

soft annealed

Hardness [HB 30]		
	<=229 HB 30	1.1)

after case hardening, in core

Yield stress	
<=11 mm	>=835 N/mm?
<=30 mm	>=785 N/mm?
<=63 mm	>=685 N/mm?
Tensile strength	
<=11 mm	1180 - 1420 N/mm?
<=30 mm	1080 - 1320 N/mm?
<=63 mm	980 - 1270 N/mm?
Elongation after fracture (A5)	
<=11 mm	>=7 %
<=30 mm	>=8 %
<=63 mm	>=8 %
Reduction of area	
<=11 mm	>=30 %
<=30 mm	>=35 %
<=63 mm	>=35 %
Impact value (DVM)	
<=11 mm	>=41 J
<=30 mm	>=41 J

1.1) State of delivery

Date 25/8/2550

Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

Heat treatement

DIN EN 10084 (06/1998)
Case hardening steels.

	dimension	value	specimen	at temperature	/ÿ□Heat treatement	duration	
Carburize							
		880 - 980 ?C					3.1)
Harden							
		~ 860 ?C				>=30 minute(s)	3.1)
Core hardening							
		830 - 870 ?C					3.1)
Surface hardening							
		780 - 820 ?C					3.1)
Temper							
		150 - 200 ?C				>=1 hour(s)	3.1)
End quench test							
		~ 860 ?C				>=30 minute(s)	3.1)

3.1) Reference data

Date 25/8/2550

Material data sheet

Material Number 1.6587

Country Germany

Designations 18CrNiMo7-6; 17CrNiMo6

DIN EN ISO 683-17 (04/2000)

Heat-treated steels, alloy steels and free-cutting steels. Ball and roller bearing steels. Ball and roller bearing steels for case hardening

Quenching

855 - 865 ?C

Date 25/8/2550

Material data sheet

Material Number	1.6587
Country	Germany
Designations	18CrNiMo7-6; 17CrNiMo6

Data from Stahlschl?ssel book

Hot working				
	850 - 1150 ?C			
Soft annealing (+A)				
	650 - 700 ?C			
Treated to hardness range (+TH)				
	850 - 950 ?C			
Treated to ferrite-pearlite microstructure and hardness range (+FP)				
	900 - 1000 ?C			
Single hardening				
yes				
Double hardening				
yes				
Carburize				
	880 - 980 ?C	Hot quenching 160-250 ?C		
	880 - 980 ?C	Case hardening box		
	880 - 980 ?C	Salt bath 580-680 ?C		
	880 - 980 ?C	Oil		
	880 - 980 ?C	Air		
	880 - 980 ?C	Water		conditional
Core hardening				
	830 - 870 ?C			
Surface hardening				
	780 - 820 ?C	Water		conditional
	780 - 820 ?C	Hot quenching		
	780 - 820 ?C	Oil		
Temper				
	150 - 200 ?C		>=1 hour(s)	
Intermediate annealing				
	630 - 650 ?C			

AWS D1.1/D1.1M:2006
An American National Standard

Structural Welding Code—Steel

American Welding Society

AWS D1.1/D1.1M:2006
An American National Standard

Approved by the
American National Standards Institute
November 29, 2005

Structural Welding Code —
Steel

20th Edition

Supersedes AWS D1.1/D1.1M:2004

Prepared by the
American Welding Society (AWS) D1 Committee on Structural Welding

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This code covers the welding requirements for any type of welded structure made from the commonly used carbon and low-alloy constructional steels. Sections 1 through 8 constitute a body of rules for the regulation of welding in steel construction. There are ten normative and twelve informative annexes in this code. A Commentary of the code is included with the document.

American Welding Society
550 N.W. LeJeune Road, Miami, FL 33126

Appendix XI

Guideline on Alternative Methods for Determining Preheat

(Mandatory Information)

(This Appendix is a part of ANSI/AWS D1.1- , *Structural Welding Code—Steel,* and includes mandatory requirements for use with this standard)

XI1. Introduction

The purpose of this guide is to provide some optional alternative methods for determining welding conditions (principally preheat) to avoid cold cracking. The methods are based primarily on research on small scale tests carried out over many years in several laboratories world-wide. No method is available for predicting optimum conditions in all cases, but the guide does consider several important factors such as hydrogen level and steel composition not explicitly included in the requirements of Table 4.3. The guide may therefore be of value in indicating whether the requirements of Table 4.3 are overly conservative or in some cases not sufficiently demanding.

The user is referred to the Commentary for more detailed presentation of the background scientific and research information leading to the two methods proposed.

In using this guide as an alternative to Table 4.3, careful consideration must be given to the assumptions made, the values selected, and past experience.

XI2. Methods

Two methods are used as the basis for estimating welding conditions to avoid cold cracking:

(1) Heat-affected zone (HAZ) hardness control
(2) Hydrogen control

XI3. HAZ Hardness Control

XI3.1 The provisions included in this guide for use of this method are restricted to fillet welds.

XI3.2 This method is based on the assumption that cracking will not occur if the hardness of the HAZ is kept below some critical value. This is achieved by controlling the cooling rate below a critical value dependent on the hardenability* of the steel. Equations and graphs are available in the technical literature that relate the weld cooling rate to the thickness of the steel members, type of joint, welding conditions and variables.

XI3.3 The selection of the critical hardness will depend on a number of factors such as steel type, hydrogen level, restraint and service conditions. Laboratory tests with fillet welds show that HAZ cracking does not occur if the HAZ Vickers Hardness No. (Vh) is less than 350 Vh, even with high hydrogen electrodes. With low-hydrogen electrodes, hardnesses of 400 Vh could be tolerated without cracking. Such hardness, however, may not be tolerable in service where there is an increased risk of stress corrosion cracking, brittle fracture initiation, or other risks for the safety or serviceability of the structure.

The critical cooling rate for a given hardness can be approximately related to the carbon equivalent of the steel (see Figure XI-2). Since the relationship is only approximate, the curve shown in Figure XI-2 may be conservative for plain carbon and plain carbon-manganese steels and thus allow the use of the high hardness curve with less risk. Some low alloy steels, particularly those containing columbium (niobium), may be more hardenable than Figure XI-2 indicates, and the use of the lower hardness curve is recommended.

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*Hardenability of steel in welding relates to its propensity towards formation of a hard HAZ and can be characterized by the cooling rate necessary to produce a given level of hardness. Steels with high hardenability can, therefore, produce hard HAZ at slower cooling rates than a steel with lower hardenability.

XI3.4 Although the method can be used to determine a preheat level, its main value is in determining the minimum heat input (and hence minimum weld size) that prevents excessive hardening. It is particularly useful for determining the minimum size of single pass fillet welds that can be deposited without preheat.

XI3.5 The hardness approach does not consider the possibility of weld metal cracking. However, from experience it is found that the heat input determined by this method is usually adequate to prevent weld metal cracking, in most cases, in fillet welds if the electrode is not a high strength filler metal and is generally of a low hydrogen type (e.g., low hydrogen (SMAW) electrode, gas metal arc, flux cored arc, submerged arc).

XI3.6 Because the method depends solely on controlling the HAZ hardness, the hydrogen level and restraint are not explicitly considered.

XI3.7 This method is not applicable to Q & T steels. (See XI5.2(3) for limitations.)

XI4. Hydrogen Control

XI4.1 The hydrogen control method is based on the assumption that cracking will not occur if the average quantity of hydrogen remaining in the joint after it has cooled down to about 120°F (50°C) does not exceed a critical value dependent on the composition of the steel and the restraint. The preheat necessary to allow enough hydrogen to diffuse out of the joint can be estimated using this method.

XI4.2 This method is based mainly on results of restrained partial joint penetration groove weld tests; the weld metal used in the tests matched the parent metal.

There has not been extensive testing of this method on fillet welds; however, by allowing for restraint, the method has been suitably adapted for those welds.

XI4.3 A determination of the restraint level and the original hydrogen level in the weld pool is required for the hydrogen method.

In this guide, restraint is classified as high, medium, and low, and the category must be established from experience.

XI4.4 The hydrogen control method is based on a single low heat input weld bead representing a root pass and assumes that the HAZ hardens. The method is, therefore, particularly useful for high strength, low alloy steels having quite high hardenability where hardness control is not always feasible. Consequently, because it assumes that the HAZ fully hardens, the predicted preheat may be too conservative for carbon steels.

XI5. Selection of Method

XI5.1 The following procedure is suggested as a guide for selection of either the Hardness Control or Hydrogen Control Method.

Determine carbon and carbon equivalent:

$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

to locate the zone position of the steel in Figure XI-1. (See XI6.1.1 for the different ways to obtain chemical analysis.)

XI5.2 The performance characteristics of each zone and the suggested action are as follows:

(1) **Zone I.** Cracking is unlikely, but may occur with high hydrogen or high restraint. Use hydrogen control method to determine preheat for steels in this zone.

(2) **Zone II.** The hardness control method and selected hardness shall be used to determine minimum energy input for single pass fillet welds *without preheat.* If the energy input is not practical, use hydrogen method to determine preheat.

For groove welds, the hydrogen control method shall be used to determine preheat.

For steels with high carbon, a minimum energy to control hardness *and* preheat to control hydrogen may be required for both types of welds; i.e., fillet and groove welds.

(3) **Zone III.** The hydrogen control method shall be used. Where heat input is restricted to preserve the HAZ properties (e.g., some quenched and tempered steels), the hydrogen control method should be used to determine preheat.

XI6. Detailed Guide

XI6.1 Hardness Method

XI6.1.1 The carbon equivalent shall be calculated as follows:

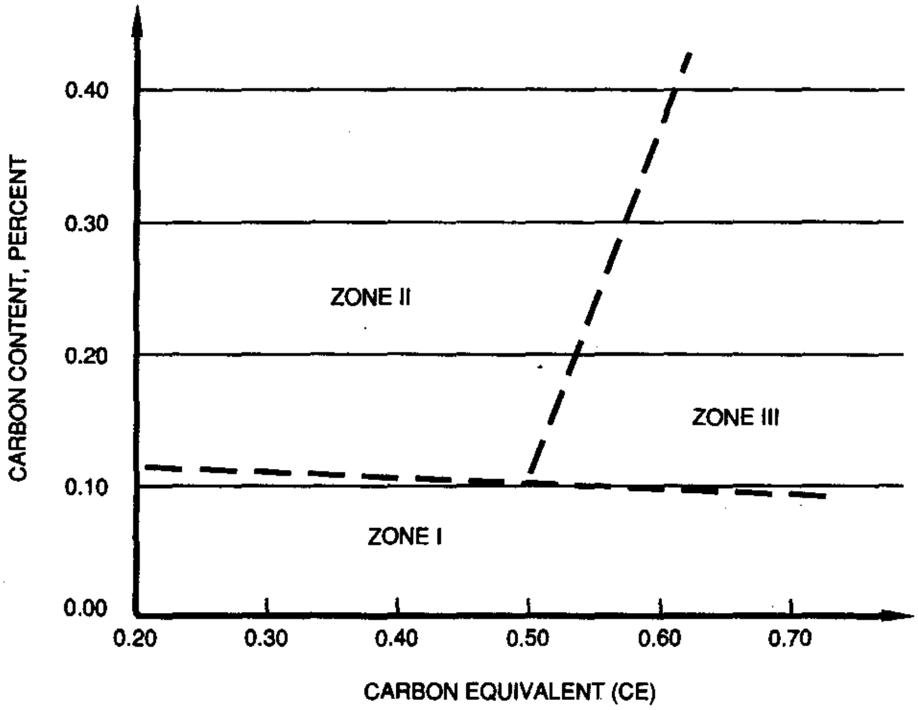
$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

The chemical analysis may be obtained from:

(1) Mill test certificates
(2) Typical production chemistry (from the mill)
(3) Specification chemistry (using maximum values)
(4) User tests (chemical analysis)

XI6.1.2 The critical cooling rate shall be determined for a selected maximum HAZ hardness of either 400 Vh or 350 Vh from Figure XI-2.

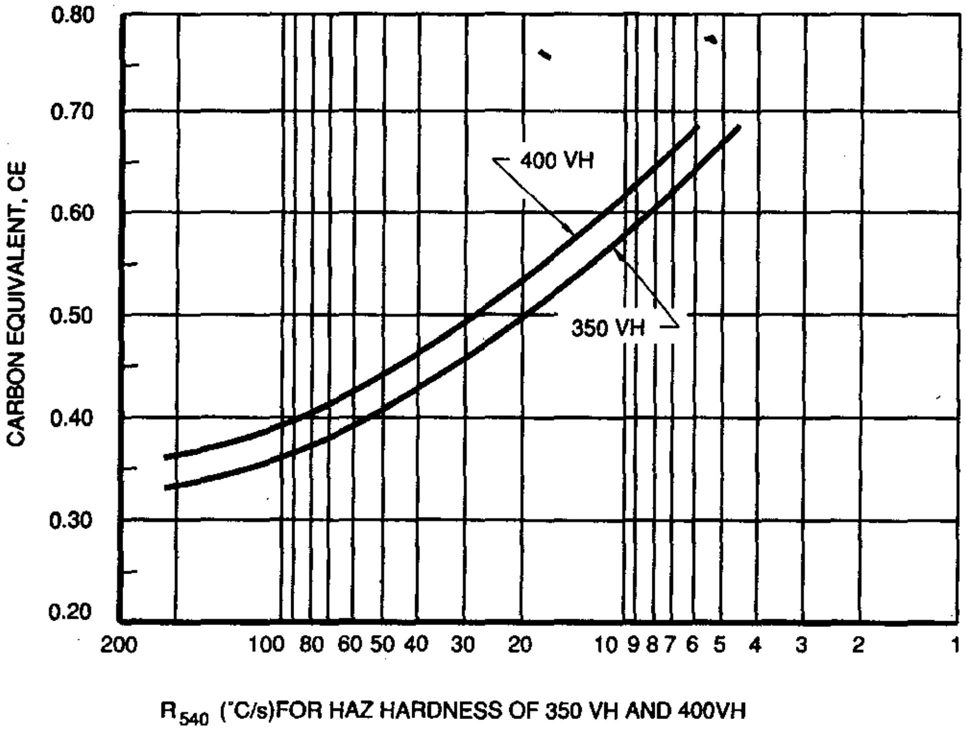
XI6.1.3 Using applicable thicknesses for "flange" and "web" plates, the appropriate diagram shall be selected from Figure XI-3 and the minimum energy input for single pass fillet welds shall be detemined. This energy input applies to submerged arc welds.



Note 1: CE = C+(Mn+Si)/6+(Cr+Mo+V)/5+(Ni+Cu)/15

Note 2: See XI5.2(1), (2), or (3), for applicable zone characteristics.

Figure XI-1 — Zone Classification of Steels (see XI5.1)



Note: CE = C+(Mn+Si)/6+(Cr+Mo+V)/5+(Ni+Cu)/15

Figure XI-2 — Critical Cooling Rate for 350 VH and 400 VH (see XI3.3)

XI6.1.4 For other processes, minimum energy input for single pass fillet welds can be estimated by applying the following multiplication factors to the energy estimated for the submerged arc welding process in XI6.1.3:

Welding Process	Multiplication Factor
SAW	1
SMAW	1.50
GMAW, FCAW	1.25

XI6.1.5 Figure XI-4 may be used to determine fillet sizes as a function of energy input.

XI6.2 Hydrogen Control Method

XI6.2.1 The value of the composition parameter, P_{cm}, shall be calculated as follows:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

The chemical analysis shall be determined as in XI6.1.1.

XI6.2.2 The hydrogen level shall be determined and shall be defined as follows:

(1) **H1 Extra Low Hydrogen.** These consumables give a diffusible hydrogen content of less than 5 ml/100g deposited metal when measured using ISO 3690-1976 (E) or, a moisture content of electrode covering of 0.2% maximum in accordance with AWS A5.1 or A5.5. This may be established by testing each type, brand, or wire/flux combination used after removal from the package or container and exposure for the intended duration, with due consideration of actual storage conditions prior to immediate use. The following may be assumed to meet this requirement:

(a) Low hydrogen electrodes taken from hermetically sealed containers, dried at 700°F-800°F (370°-430°C) for one hour and used within two hours after removal.

(b) GMAW with clean solid wires

(2) **H2 Low Hydrogen.** These consumables give a diffusible hydrogen content of less than 10 ml/100g deposited metal when measured using ISO 3690-1976, or a moisture content of electrode covering of 0.4% maximum in accordance with AWS A5.1. This may be established by a test on each type, brand of consumable, or wire/flux combination used. The following may be assumed to meet this requirement:

(a) Low hydrogen electrodes taken from hermetically sealed containers conditioned in accordance with 4.5.2 of the Code and used within four hours after removal

(b) Submerged arc welding with dry flux

(3) **H3 Hydrogen Not Controlled.** All other consumables not meeting the requirements of H1 or H2.

XI6.2.3 The susceptibility index grouping from Table XI-1 shall be determined.

XI6.2.4 Minimum Preheat Levels and Interpass. Table XI-2 gives the minimum preheat and interpass temperatures that shall be used. Table XI-2 gives three levels of restraint. The restraint level to be used shall be determined in conformance with XI6.2.5.

XI6.2.5 Restraint. The classification of types of welds at various restraint levels should be determined on the basis of experience, engineering judgement, research, or calculation.

Three levels of restraint have been provided:

(1) **Low Restraint.** This level describes common fillet and groove welded joints in which a reasonable freedom of movement of members exists.

(2) **Medium Restraint.** This level describes fillet and groove welded joints in which, because of members being already attached to structural work, a reduced freedom of movement exists.

(3) **High Restraint.** This level describes welds in which there is almost no freedom of movement for members joined (such as repair welds, especially in thick material).

Table XI-1
Susceptibility Index Grouping as Function of Hydrogen Level "H" and Composition Parameter P_{cm} (see XI6.2.3)

Hydrogen Level, H	Susceptibility Index[2] Grouping				
	Carbon Equivalent = P_{cm}^{1}				
	<0.18	<0.23	<0.28	<0.33	<0.38
H1	A	B	C	D	E
H2	B	C	D	E	F
H3	C	D	E	F	G

Notes:

1. $P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$

2. Susceptibility index — $12\ P_{cm} + \log_{10} H$.

3. Susceptibility Index Groupings, A through G, encompass the combined effect of the composition parameter, P_{cm}, and hydrogen level, H, in accordance with the formula shown in Note 2.

The exact numerical quantities are obtained from the Note 2 formula using the stated values of P_{cm} and the following values of H, given in ml/100g of weld metal (see XI6.2.2, a, b, c):

H1 — 5; H2 — 10; H3 — 30.

For greater convenience, Susceptibility Index Groupings have been expressed in the table by means of letters, A through G, to cover the following narrow ranges:

Susceptibility Index Groupings

A = 3.0; B = 3.1-3.5; C = 3.6-4.0;
D = 4.1-4.5; E = 4.6-5.0; F = 5.1-5.5;
G = 5.6-7.0

These groupings are used in Table XI-2 in conjunction with restraint and thickness to determine the minimum preheat and interpass temperature.

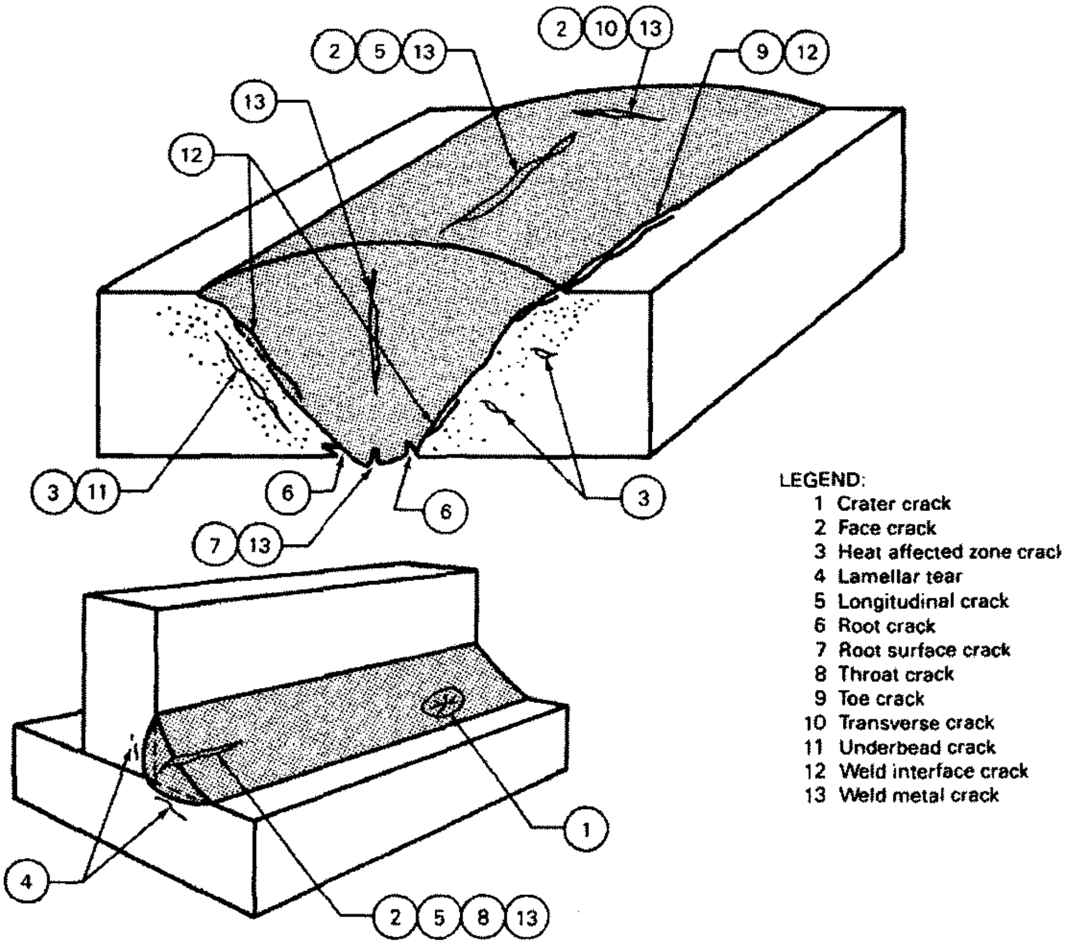


Figure 20 — Various Types of Cracks

ข้อความสำคัญจากงานวิจัย ตีพิมพ์ใน AWS Welding Journal

ในกรณีที่ HAZ มีโครงสร้างจุลภาคเป็น มาเทนไซท์(HV_M) เบนไนท์(HV_B ซึ่งในปี พ.ศ. 2524 (1981) **K. Lorenz และ C. Duren** ได้แสดงในรูปของความสัมพันธ์ของความแข็งสูงสุดที่เกิดที่ HAZ ดังนี้

$$HV_M = 2019\left[\left(1-0.5\log t_{8/5}\right)\cdot C + 0.3\left(CE_B - C\right)\right] + 66\left(1-0.8\log t_{8/5}\right)$$

$t_{8/5}$ = เวลาของการเปลี่ยนอุณหภูมิจาก 800 =>500 องศา C เป็น วินาที

C = carbon %

$$\mathbf{CE_B = C + \frac{Mn}{8} + \frac{Si}{11} + \frac{Ni}{17} + \frac{Cr}{5} + \frac{Cu}{9} + \frac{Mo}{6} + \frac{V}{3}}$$

For 100 % Martensite

$$HV_M = 802C + 305$$

For 100 % Bainite

$$HV_B = 350(C + \frac{Si}{11} + \frac{Mn}{8} + \frac{Cu}{9} + \frac{Cr}{5} + \frac{Ni}{17} + \frac{Mo}{6} + \frac{V}{3}) + 101$$

ในปีเดียวกัน N. Yurioka ได้เสนอการหาค่าความแข็ง ดังนี้

$HV_M = 844C(1-0.3C^2)+294$ Fullly Martensitic(Yurioka)

เพื่อความปลอดภัยในงานเชื่อมค่าความแข็งวิกฤติ ของ HAZ AWS D1.1 –2006 Structural Welding Code Steel

กำหนดให้ Hardness at HAZ < 350 HV with high Hydrogen

< 400 HV with Low Hydrogen

หมายเหตุ มีงานวิจัย กรณีไม่มีการ Preheat เวลาในการลดอุณหภูมิจาก 800 °C => 500 °C ใช้เวลา 6 วินาที