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Hot Ductility Behavior and Hot Cracking Susceptibility of Type 303 Austenitic Stainless Steel(1)

—Hot Ductility Behavior—

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303 오스테나이트계 스테인레스강의 고온연성거동과 고온균열감수성(I)

—고온연성거동—

이 영 호 · 이 창 희 · 칼. 디. 룬딘

Key Words : Hot Ductility(고온연성), Austenitic Stainless Steel(오-스테나이트계 스테인레스강). Gleeble Evaluation(글리블-평가), Rolling Direction(압연방향), Liquid Film(액막), Intergranular Fracture(입계파괴)

초 록

오-스테나이트계 스테인레스강에 대한 용접은 용접재료의 개발과 더불어 각종 산업계에 널리 이용되고 있으며 최근 Type 303 오-스테나이트계 스테인레스강 등은 free machining재로서 널리 응용되고 있다. 그러나 이 303계는 피삭성, 절삭성, 칩형성개선을 위한 특수원소(Se, S 등)의 첨가때문에 용접성에 문제점을 제기하고 있다. 본 연구에서는 Type 303을 중심으로 AISI 304- 316NG 및 347NG계의 오-스테나이트계 스테인테스강의 고온연성거동과 고온균열감수성(용접성)에 관한 연구에 대한 검토중 고온연성거동에 관하여 조사하였다. 고온연성평가는 Gleeble Simulator에 의하여 재료와 방향성에 따라 검토하였으며 그 결과 모든 재료는 압연방향을 종방으로 시험하였을 때는 거의 유사한 고온 연성을 나타내었으나 횡방향으로 시험하였을 때는 종방향에 비하여 연성저하를 나타내었다. 이와 같은 고온연성은 후속연구에서 검토될 고온균열 감수성과 밀접한 관련성에 의하여 용접성을 평가할 수 있다.

1. Introduction

It is widely accepted that the free machining type austenitic stainless steels are "unweldable" due to the nature of elemental species added to enhance machinability, enabling faster cutting rates and better chip formation. Selenium and sulfur are the principal additions, however, the use of selenium has been discontinued due to its toxicity. Therefore, the sulfur bearing materials are the only remaining grades of free machining austenitics.

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The weldability of free machining austenitic stainless steels from various lots/heats has been known to be significantly different, albeit within the AISI 303 composition limits. Some producers claim that chemistry controlled 303 materials can be readily welded by any of the fusion processes even without the addition of a filler metal. AISI 303 specification requires a sulfur of 0.15% min. and most lots exceed this value(a common level being 0.3%). The solubility of sulfur in austenite is less than 0.01% at ambient temperatures, thus the sulfur exists largely as metallic sulfides (chip breakers). Upon melting or exposure to high temperatures(as in welding). the sulfur has been assumed to be redistributed, tending to segregate to grain boundaries in the solid state or to solidification sub-boundaries in the fusion zone, promoting liquid films and enhancing hot cracking tendencies. Very little literature exists on the weldadility of the 303 grade of free machining type austenitic stainless steels. Existing data further show that weldability varies on a heat to heat or producer to producer basis.

This study has evaluated the hot ductility behavior of several lots of 303 materials before weldability evaluation. The Gleeble hot ductility test which has been recently developed in the Welding Research Gorup at The University of Tennessee, was used to evaluate and form a basis of comparison between the 303 materials and 304, 316NG(nuclear grade) and 347NG grades of austenitic stainless steels.

2. Experimental Procedures

2.1 Materials

The materials evaluated in this research comprise 4 heats of AISI303 free machining type austenitic stainless steels. The compositions of the steels, together with the estimated ferrite potentials from the Delong diagram and measured ferrite content (Magnegage) in the fusion zone are given in Table 1. As Table 1 shows, three heats of 303 were received as round bars with different diameters. One heat(1G5703) was a square bar. Heats B652133 and C656133 came from one master heat but were processed differently; B652133: continuously cast to near net shape, C656133: ingot forged to not shape. Heat 656471(4 1/2″ diameter) was used to investigate effects of working direction(longitudinal and transverse to the rolling direction) on the hot ductility.

The hot ductility test results for the 303 materials were compared with those of recently evaluated 304, 316NG and 34NG materials at The University of Tennessee(1). The compositions of the AISI 304, 347 and the nuclear grades of 347 are also given in Table 1.

2.2 Hot Ductility Tests

Hot ductility tests were conducted using a Gleeble (Photo. 1), which is essentially a high speed,

Table 1. Materials Studied

Type	Heat	C	Mn	P	S	si	Cr	Ni	Mo	N	N_b	GS[a]	Cr_{eq}	Ni_{eq}	$\frac{Cr_{eq}}{Ni_{eq}}$	FN[b]	Shape
316NG	D441103	0.011	1.70	0.020	0.001	0.51	17.25	12.85	2.47	0.094	—	3.2	20.5	16.9	1.23	0	Pipe
316NG	D440104	0.010	1.75	0.019	0.001	0.52	17.25	12.90	2.56	0.101	—	3.3	20.6	17.1	1.20	0	Pipe
304	56072	0.065	1.54	0.030	0.025	0.51	18.39	8.60	0.21	—	—	4.2	19.4	11.3	1.72	2.4	Pipe
304	638731	0.058	1.62	0.020	0.029	0.68	20.32	9.16	0.24	—	—	4.3	21.6	11.7	1.85	4.0	Pipe
347	876195	0.045	1.60	0.032	0.007	0.54	17.80	9.71	—	—	0.67	9.0	19.0	11.9	1.60	3.0	Plate
TP 347 NG	173268	0.025	1.74	0.033	0.006	0.34	18.25	10.77	—	0.022	0.37	5.0	19.0	13.1	1.46	4.0	Pipe
303	0A1090	0.022	1.75	0.023	0.035	0.39	17.32	9.69	0.40	0.036	—	—	18.3	12.3	1.49	2.0	$\frac{1}{4}$″ ϕ Bar
303	1G5713	0.092	1.78	0.029	0.310	0.52	17.49	8.90	0.38	—	—	—	18.7	12.6	1.48	2.0	Square 1″ × 1″ Bar
303	B652133	0.038	1.44	0.029	0.310	0.72	17.64	9.34	0.24	0.044	—	—	19.0	12.5	1.52	2.0	1″ ϕ Bar
303	C656133 656471	0.038	1.44	0.029	0.340	0.69	17.74	6.35	0.34	0.044	—	—	19.1	12.5	1.53	3.0	4$\frac{1}{2}$″ ϕ Bar

a. ASIT grain size. b. Measured ferrite potential with Magne-Gage. c. Split from one Master Heat.

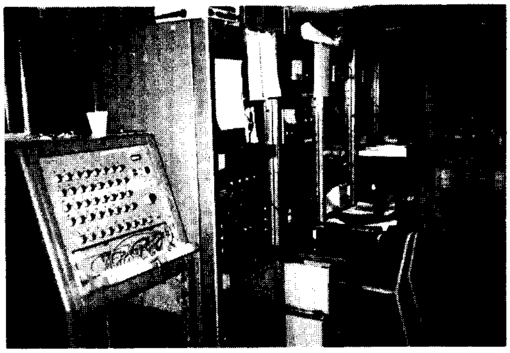

Photo. 1 Gleeble Apparatus for Hot Ductility Test.

hot tensile tester, instrumented so that the heating and cooling of the test specimen can be accurately programmed to reproduce the rapid temperature changes that occur during welding.

The Gleeble consists of a high speed, time-temperature resistance heating control device coupled with a high-temperature tensile testing apparatus, The essential features of the Gleeble employed in this investigation are shown in Fig. 1. As shown in the figure, the test specimen was clamped between the two water-cooled alloy wedge alloy wedge grips. The grips were contained in plates, one fixed and one movable, which in turn were connected to the secondary power transformer. The specimen was heated by its own resistance to the passage of an electric current supplied by the power transformer, or was cooled by the longitudinal extraction of heat to the water cooled jaws.

The dilatometer is an attachment to the Gleeble apparatus which measures specimen dilation(contraction or expansion) during rapid heating and cooling. As shown in Figure 2, the dilatometer consisted of quartz contact rods connected to a precision rectilinear transducer by a solid-hinge mechanical linkage. The change in volume accompanying an on-cooling phase change was transferred through to the rectilinear potentiometer which was in turn connected to a precision bridge circuit. The output of the bridge was connected to a multiple channel recording oscillograph.

The peak temperature employed in the hot ductility tests may be any temperature below the bulk melting temperature of the material being studied. Therefore the technique can provide the tensile properties of any microstructure which may occur within the weld heat affected zone.

The tests employed a cylindrical specimen 0.25

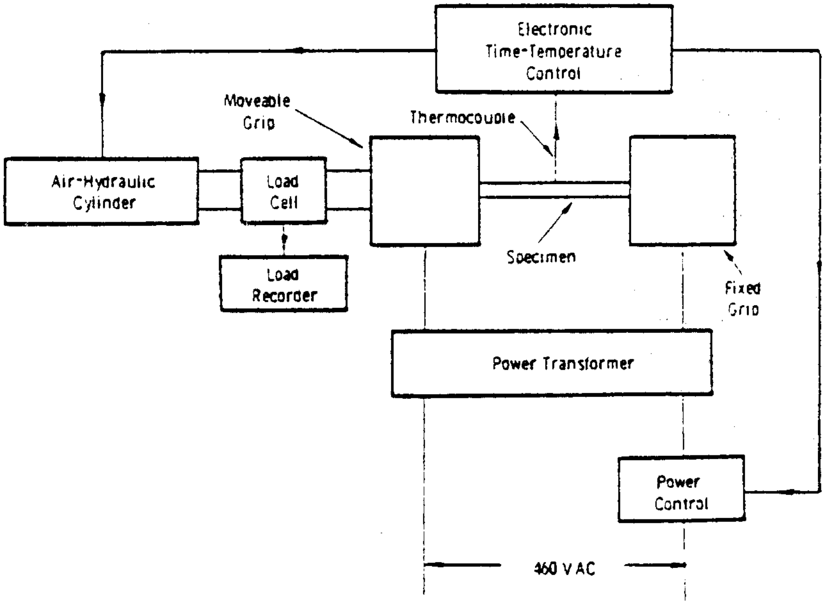

Fig. 1. Schematic diagram of the Gleeble apparatus.

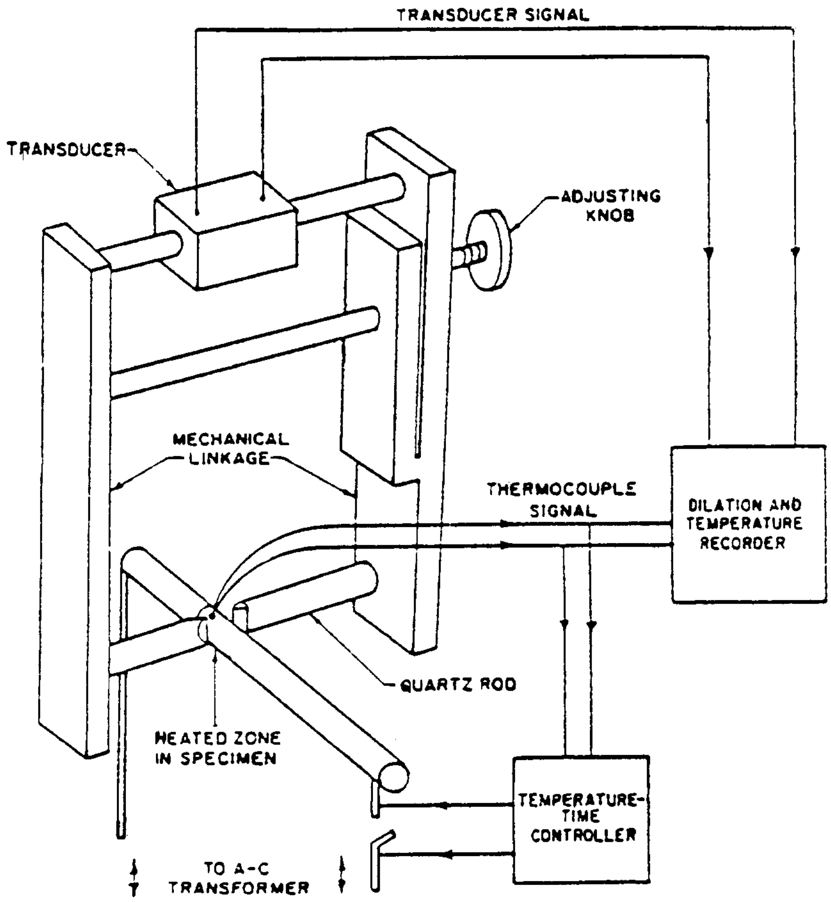

Fig. 2. Schematic representation of the Gleeble dilatometer.

inch in diameter and 4 inches long aligned(Figure 3) in the rolling direction(all heats) and transverse direction(heat 656471). The specimen was clamped between two water cooled jaws separated 0. 8 inches from each other which in addition to serving as grips for tensile testing, also provide a means for introducing a current through the specimen and ensure a rapid rate of cooling when the current flow is interrupted. The heating current is controlled electronically throughout the desired thermal by means of a signal obtained from a fine wire thermocouple percussion welded to the center of the specimen gauge length. During testing, the instantaneous temperature of specimen is compared with a reference temperature and the flow of current is increased, decreased, or interrupted as required.

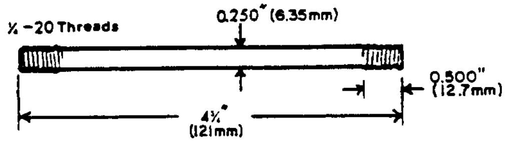

Fig. 3. Hot ductility test specimen.

The thermal cycle utilized corresponds to that in 1-1/2 inch thick stainless steel welded with an energy input of 70KJ/inch. The cross head speed was 2. 5 inches/sec. The on-cooling tests were conducted from the zero ductility temperature (ZDT) which was determined from the on-heating tests. The principle data of interest in the test evaluation are the percentage reductions in area upon tensile fracture. These reduction in area data are plotted versus test temperature for comparative evaluations.

In order to obtain clean unoxidized fracture surfaces, some selected hot ductility tests were conducted with argon shielding in an atmosphere chamber incorporated into the Gleeble. Alternate chamber evacuation and backfilling with arogon provided a chamber atmosphere which resulted in clean fracture surfaces with no detectable oxidation. These samples were utilized to clearly reveal the fracture morphology and delineate the evidence of liquid films present during fracture.

2.3 Metallographic Examination

For metallographic examination, the mounted samples were polished to 1μ and electrolytically etched in chrome-acetic solution; 25*g* chromic acid, 133 *ml* acetic acid and 7*ml*H_20. Optical light microscopy, SEM were utilized.

Fractography was conducted on the hot ductility samples tested in the argon atmosphere.

3. Results and discussion

In this study, the criteria generalized by Nippes et al. (2), were used to define differences in the hot ductility behavior of the various lots. The basic criterion is based on the ductility recovery on-cooling from the ZDT when compared to the on-heating ductility. The classifications using this criterion are shown in Figure 4. The on-heating behavior is divided into two categories. Class H1 behavior occurs when the hot ductility increases with increasing temperature and then there is a rapid loss of ductility over a narrow temperature range. Class H2 behavior is described by a continuous decrease in ductilty over a wide range of temperatures as the temperature approaches the ZDT. The on-cooling behavior is characterized as class C1 when the on-cooling ductility is equivalent to the on-heating ductility. Class C2 behavior is characterized by an on-cooling ductility the same as on-heating above 2000-2200°F. but is significantly lower for temperatures below this temperature range(ductility dip). Class C3 behavior is characterized by an on-cooling ductility which is significantly less than the on-heating ductility at all testing temperatures. According to Nippes et al. (2), materials which exhibit either class C2 or

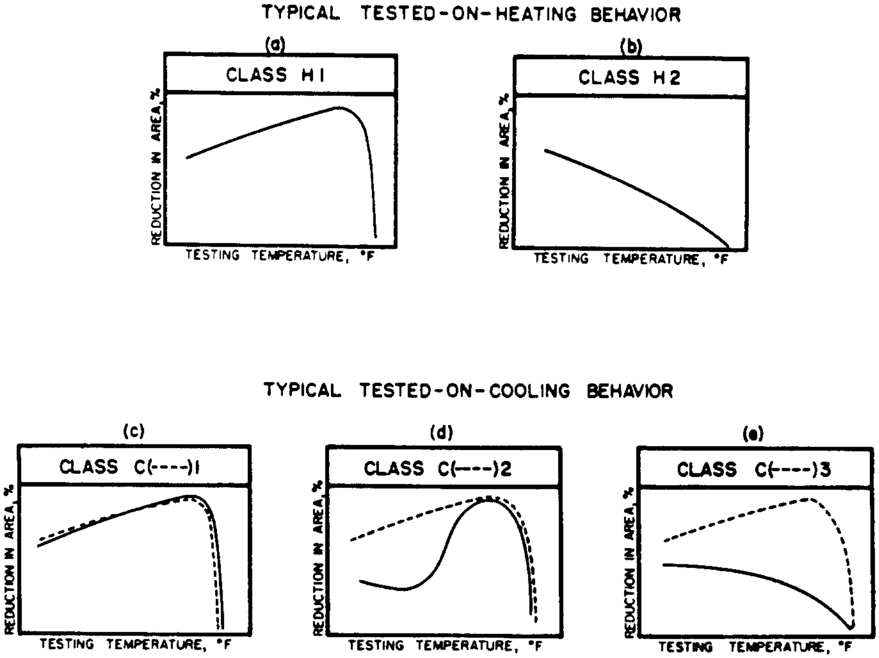

Fig. 4. Schematic representation of the classification of the on-heating and on-cooling hot ductility behavior (after Nippes et al. 2).

class C3 behaviors are susceptible to HAZ cracking either during welding or subsequent service. 5-8

The hot ductility behavior of 4 heats of AISI 303 is shown in Figure 5 to 8. Figures 7a and 7b are results for a material in the continuously cast condition(B652133) and in the ingot forged condition (C65133), respectively. These were split from one master heat (i.e. B652133 and C656133 have the

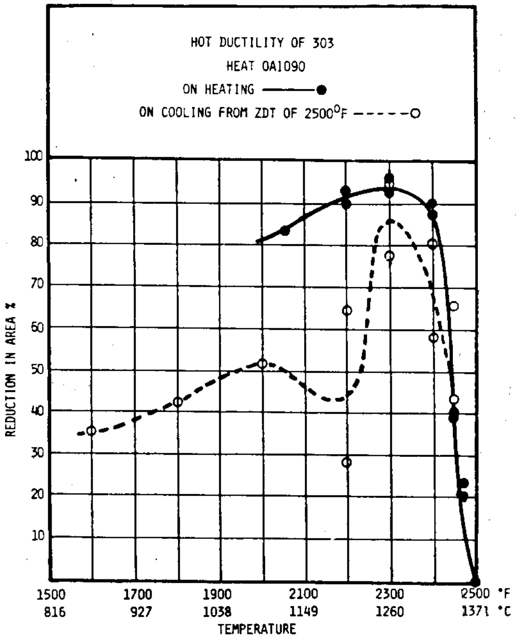

Fig. 5. Hot ductility test results for 0A1090(303).

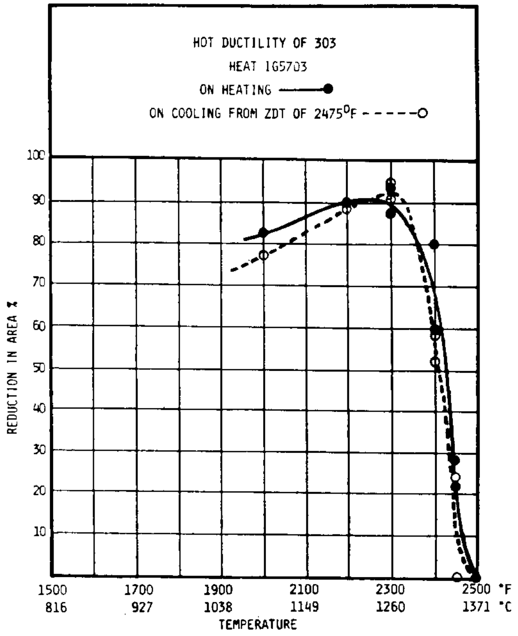

Fig. 6. Hot ductility test results for 1G5713(303).

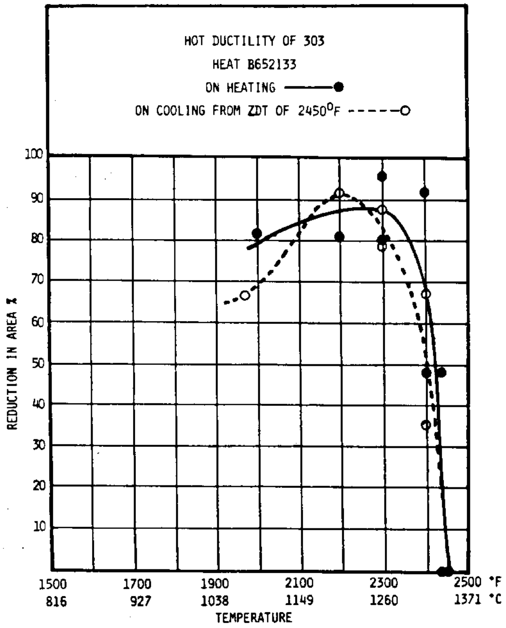

Fig. 7a. Hot ductility test results for continuous cast B652133 (303).

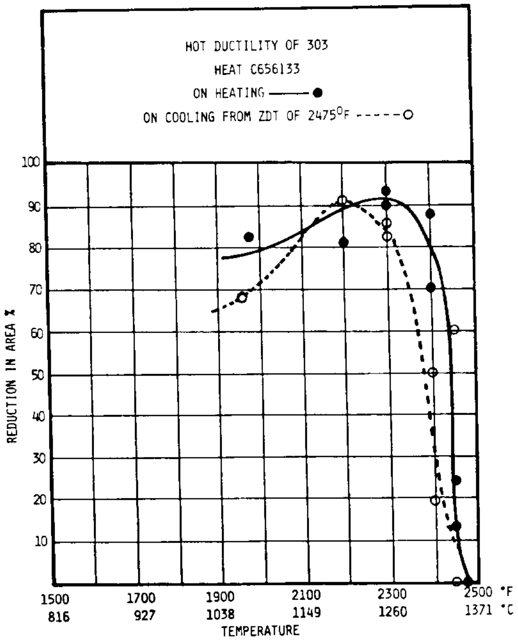

Fig. 7b. Hot ductility test results for ingot forged C656133(303).

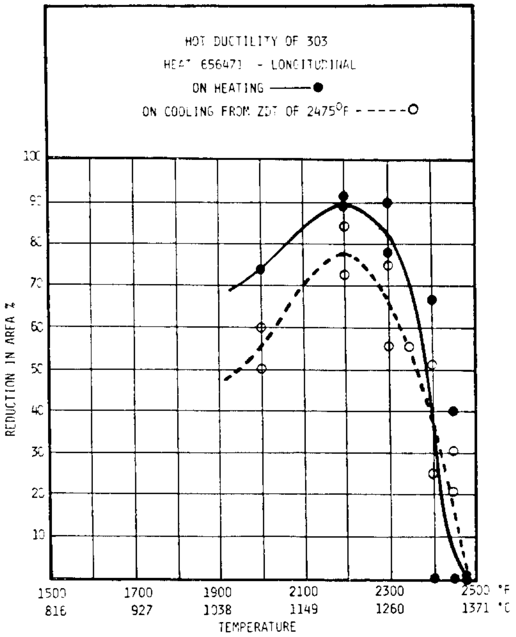

Fig. 8a. Hot ductility test results for 656471(303) longitudinal orientation.

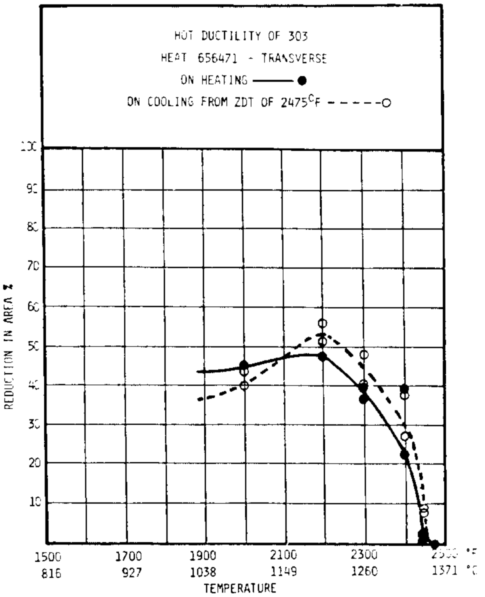

Fig. 8b. Hot ductility test results for 656471(303) transverse orientation.

same chemistiy). Figures 8a and 8b show results fos heat 656471 tested in the longitudinal and transverse orientations respectively. For comparison, the hot ductility behavior of two heats of type AISI 304, 316NG and 347 (AISI 347 and 347NG) alloys, are also given in Figures 9-14. In all figures, the reduction in area is plotted as a function of the testing temperature.

The solid line represents the on-heaing behavior and dashed line is for the on-cooling behavior tested upon cooling from the ZDT which was measured from on-heating tests. The on-heating hot ductility response of all heats of 303 type shows a class H1 behavior. However, the on-cooling behavior shows a heat to heat variation. Heat 0A1090(Figure 5) shows a class C2 on-cooling behavior having a shallow ductility dip around 2200°F on-cooling from the ZDT of 2500°F The other three heats (Fig. 6-8) of 303 reveal a class C1 on-cooling behavior. Figures 7a and 7b reveal that the prior manufacturing conditions(continuously cast and ingot forged conditions) do not have an effect on the hot ductility behavior. The hot ductility behavior of 303 is somewhat orientation sensitive. The longitudinal orientation hot ductility tests result in an H1 on-heating behavior and show almost complete ductility recovery at all testing temperatures, upon cooling from the ZDT of 2475 °F (Figure 8a). The transverse orientation hot ductility test results (Figure 8b) reveal that the ductility, both on-heating and on-cooling is significantly lower than that in the longitudinal orientation. The maximum hot ductility obtained in the transverse orientation both on-heating and on-cooling, is about 50%, which is approximately 60 % of the maximum ductility in the longitudinal orientation(−90%). These data show that the hot ductility of 303 is orientation sensitive and an impaired hot cracking resistance in the base metal HAZ can be expected when strains arise in the transverse orientation.

For comparison, the hot ductility behavior of two heats of AISI 304 are shown in Figures 9 and 10 respectively. Both heats have a class H1 on-heating behavior, that is, as the temperature increases to 2300-2400°F, ductility also increases and at temperatures above 2300-2400°F the ductility falls to about 0%. However, the on-cooling beha-

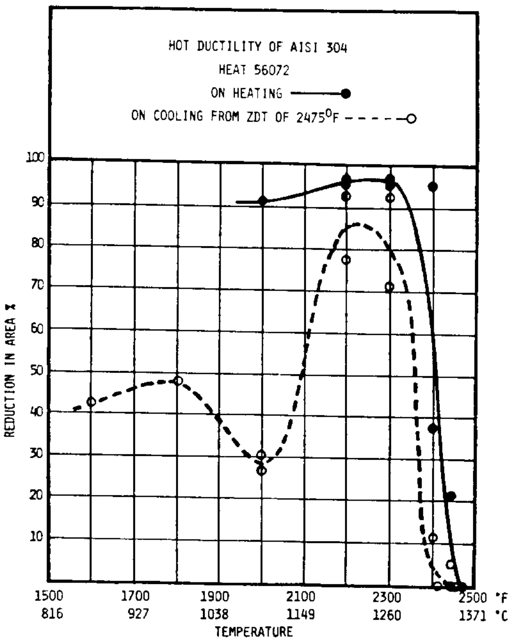

Fig. 9. Hot ductility test results for 56072(304).

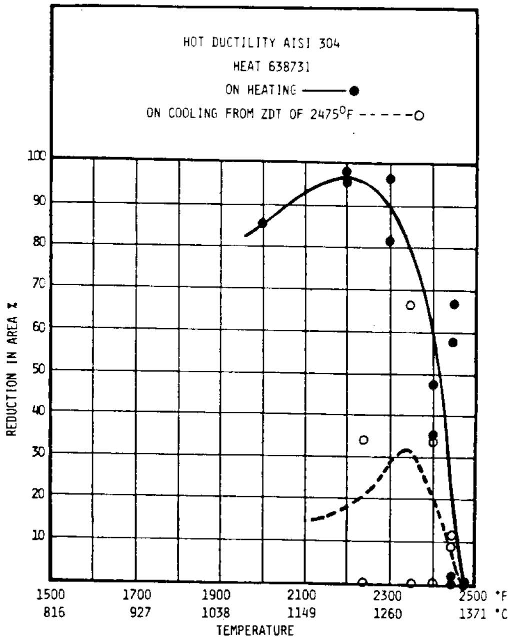

Fig. 10. Hot ductility test results for 638731(304).

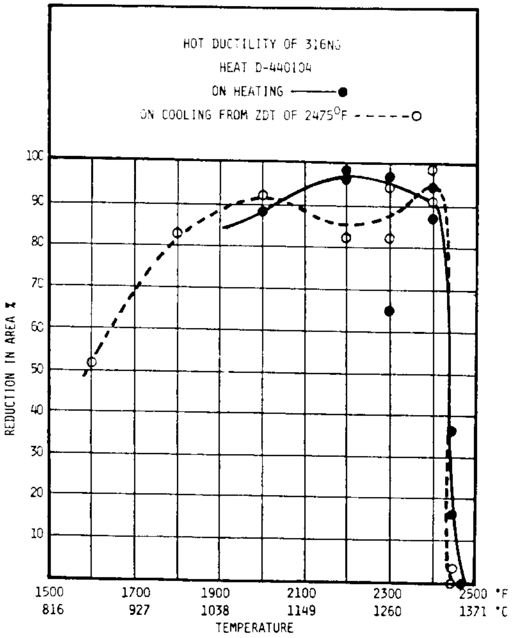

Fig. 11. Hot ductility test results for D440104 (316NG).

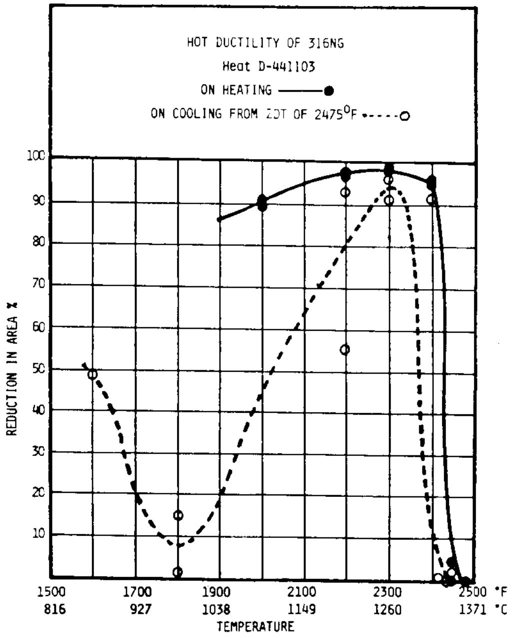

Fig. 12. Hot ductility test results for D441103 (316NG).

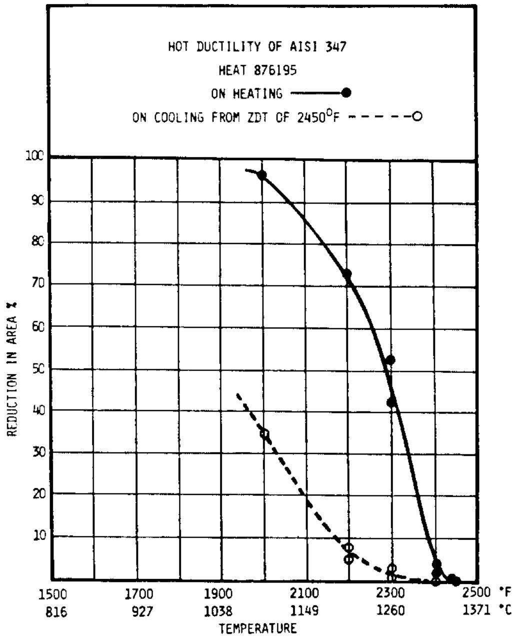

Fig. 13. Hot ductility test results for 876195(AISI 347).

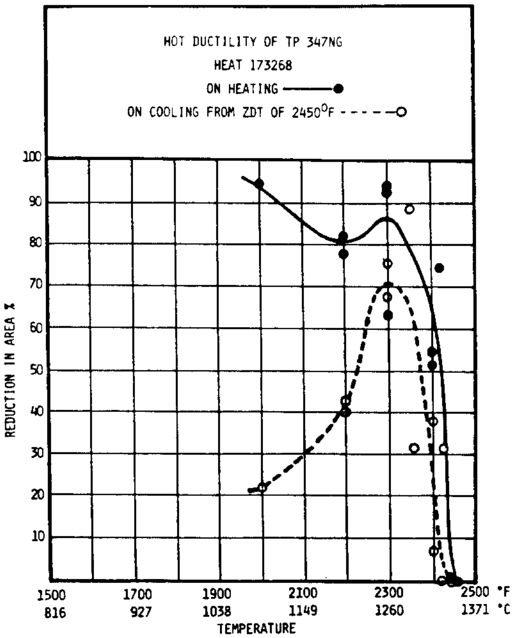

Fig. 14. Hot ductility test results for 173268(TP 347NG).

vior of both heats shows a somewhat different response. Heat 56072(Figure 9) has a class C2 on-cooling behavior, having a ductility dip around 2000°F when tested from the ZDT of 2475°F. However, heat 68731 shows a behavior bordering on class C3, revealing a poor ductility recovery at all testing temperatures.

Figures 11 and 12 show typical hot ductility behavior of two heats of 316NG material. As in the case of the 303 and 304 materials, the 316 NG materials shows a class H1 on-heating hot ductility response. However, the on-cooling behavior shows heat to heat variations. D441103 reveals a class C2 on-cooling behavior having a ductior having a ductility dip around 1800°F on cooling from the ZDT of 2475°F. Heat Dμ40104 has a class C1 on-cooling behavior.

Figure 13 shows that AISI 347 has a class H2 on-heating behavior; that is, the ductility continuously decreases with increasing temperaturer to the ZDT of 2450°F. The on-cooling behavior exhibits virtually no recovery of ductility upon testing from the ZDT of 2450°F until 2200°F(C3 behavior). However, the modified unclear grade, TP 347NG (Figure 14) exhibits a better hot ductility response, showing a class HI on-heating behavior and class C2 on-cooling behavior. The exact reasons for the different ductility behaviors of AISI 347 and TP 347NG are not known, but it may be related to the lower Nb and C content in the TP 347NG material.

The above comparison shows that the hot ductility behavior of 303 stainless steels is similar to the hot ductility behavior of the other regular and modified grades austenitic stainless steels.

Metallographic examination via optical and scanning electron microscopy was conducted on the fractured hot ductility samples which were tested in an argon atmosphere. The evidence of liquid films at the moment of fracture was easily detectable on the clean fracture surfaces (without any detectable oxidation).

A typeical fracture surface in 303 heat OA190: (2 behavior) tested on-heating to a ZDT of 2500°F is shown in photo. 2(500x). This higher magnification fractograph in photo. 2 shows evidence of a liquid film which existed at the instant of the fracturing. However, the micro-fracture mode is

Photo. 2 Typical fracture surface in heat 0A1090 (303) tested on-heating to a ZDT of 2500°F(SEM5000x).

difficult to discern due to the extensive prior liquid film on the fracture surface. The intergranular nature of the fracture is clearly seen in the longitudinal section of the hot ductility sample shown optically at 300X in photo. 3a. Secondary cracking in regions near to the fracture surface can also be seen. In photo. 3b, the evidence of grain boundary liquation that occurred during the thermal cycle and the subsequent propagation of cracks along the liquated grain boundary are clearly delineated. Thus, the intergranular fracture at the ZDT is related to grain boundary liquation.

4. Conclusions

This paper evaluates hot ductility behavior of free machining type 303 austenitic stainless steel. The materials utilized, for evaluation and comparison, include several lots of type 303, AISI 304, 316NG(Nuclear Grade) and 347NG austenitic stainless steels. The results of this study can be summarized as follows:

1) The on-heating hot ductility response of all heat of 303 type shows a class H1 behavior, However, the on-cooling behavior shows a heat to heat variation.

2) The hot ductility behavior in the longitudinal orientation is variable but all lots tested to date exhibited behavior similar to the standard 304, 316 NG and 347 alloys.

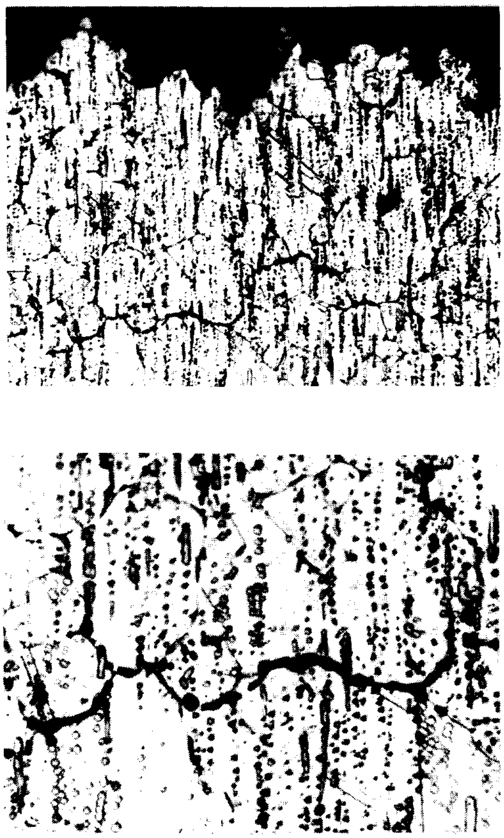

Photo. 3 Typical longitudinal section of heat 0A 1090(393) tested on-heating to a ZDT of 2500°F(OLM).

3) The transverse orientation hot ductility revealed reduced hot ductility as compared to the longitudinal tests on the same lot.

4) Liquid film formation that occurs during the heating portion of the thermal cycle is of prime importance in decrease in ductility.

5) The intergranular fracture at the ZDT is related to grain boundary liquation.

Acknowledgements

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