NPS ARCHIVE
1969
FERRADA, N.

ALUMINUM AS A SHIPBUILDING MATERIAL

LT. (C.N.) NELSON FERRADA

COURSE XIII-A
MAY, 1969

GRADUATE SCHOOL
MONTEREY, CALIF. 93940

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

ALUMINUM AS A SHIPBUILDING MATERIAL

by

LT. (C.N.) NELSON A. FERRADA AROCA

S.B., Escuela de Ingenieria Naval
(1964)

SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE IN NAVAL
ARCHITECTURE AND MARINE ENGINEERING
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 1969

NPS ARCHIVE
1969
FERRADA, N

~~Thesis~~
~~F267~~

LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIF. 93940

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

ABSTRACT

ALUMINUM AS A SHIPBUILDING MATERIAL

by

NELSON A. FERRADA AROCA

Submitted to the Department of Naval Architecture and Marine Engineering on 21 May, 1969 in partial fulfillment of the requirement for the degree of Master of Science.

The objective of this work is to summarize information, both theoretical and practical, about the aluminum as a shipbuilding material. The presentations cover: history of the use of aluminum in shipbuilding, mechanical and physical properties, corrosion, buckling and strength characteristics, construction facilities and the review of current regulations. A summary is given on fire safety standards. The problems arising in the welding of aluminum are emphasized in view of their great significance.

Distortion problems are discussed as applications and extensions of the methods found in the current literature concerning analogous problems in steel usage. This work is closed with an analysis of the potential, the possibilities of actual implementation, and eventual problems of the use of aluminum to be found in the Chilean Shipbuilding Industry.

Thesis Supervisor: Dr. Koichi Masubuchi

Title: Associate Professor of Naval Architecture

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Professor K. Masubuchi, Thesis Supervisor, for his useful suggestions in development of this thesis.

TABLE OF CONTENTS

Page

Abstract 2

Acknowledgements 3

Table of Contents 4

List of Tables 6

List of Figures 8

1. Introduction 10

2. Aluminum Production 12

3. Historic Review 15

4. Corrosion

4.1 Corrosion Characteristics of Aluminum 20

4.2 Dissimilar Metals 28

5. Elasticity and Buckling 33

6. Other Characteristics of Aluminum

6.1 Allowable Design Stresses 47

6.2 Strength at Low Temperatures 50

6.3 Fatigue Properties 51

6.4 Cutting Aluminum 53

6.5 Construction Facilities 54

6.6 Regulations 55

6.7 Protection of Aluminum 59

6.8 Economics of Aluminum 60

Page

7. Welding

7.1 Welding Generalities 67

7.2 Brief History and the Present State of Art of Welding Aluminum 70

7.3 Physical Properties 79

7.4 Problems in Aluminum Welding 79

7.5 Further Analysis of Distortion Problems 101

8. Conclusions and Recommendations 123

List of References 128

LIST OF TABLES

		Page
1a	Corrosion Resistance of Unprotected Aluminum Alloys in Seawater	21
1b	Corrosion Resistance to Tide Range Seawater Immersion	22
2	Results of Buckling Loads of Aluminum (5086-H32) Columns	39
3	Results of Buckling Loads of Aluminum (5456-H311) Columns	41
4	Comparison of Yield Strength for Butt Welded Columns	43
5	Allowable Design Stresses for Aluminum Alloys	48
6	Approximate Tanker Costs of Steel and Aluminum	61
7	Relative Economics of Aluminum and Steel-Hulled Ocean Ore Carriers	64
8	Nominal Compositions of some Aluminum Filler Alloys	73
9a	Strengths of As-Welded Joints Reported During Certain Years	76
9b	Strengths of Heat-Treated Welds Reported During Certain Years	77

Page

10 Analytical Results of Buckling Conditions of Aluminum vs. Steel 117

LIST OF FIGURES

		Page
1	Major Advantages of Aluminum	19
2	Aluminum Deckhouse Joint Detail	30
3	Typical Stress-Strain Diagrams for Hull Materials	49
4	Relation Between New Development and Improved Ship Design	58
5	Contamination Concentration Levels at Which Significant Changes Occur in Weld Quality	83
6	Volume of Water Available to Weldment from Saturated Air Contamination	84
7	Calculated Volume of Hydrocarbon Available to Weldment from Hydrocarbon Contamination	86
8	Strength Versus Pore Area, 2219-T87	89
9	Typical Distribution of Residual Stresses in Butt Weld	94
10	Fundamental Dimensional Changes that Occur in Weldments	96
11	Distortions Induced by Longitudinal Shrinkage	97

Page

12 Distribution of Yield Strength and Longitudinal Residual Stresses in Welded 5456-H321 Plate 99

13 Schematic Representation of Temperatures and Stresses During Welding 100

14 Residual Stress in a Long Welded Strip 105

15 Relationship Between Wavelength and Residual Stress in a Long Welded Strip 114

16 Curve of L_1/a for Aluminum vs. Steel 118

17 Curve of L_1/a for Aluminum vs. Steel 119

18 Curve of L_1/a for Aluminum vs. Steel 120

1. INTRODUCTION

During the last 20 years, much progress has been made in and a great deal has been learned about aluminum as applied to ship structures. It is the objective of this work to summarize information both theoretical and practical about aluminum as a shipbuilding material. There are many available handbooks and publications that contain excellent technical data, but they cover a wide spectrum of the use of aluminum. The Naval Architect is only interested in a narrow part of it, therefore, their usefulness is reduced. The survey has been made in order to have a better understanding of the material, its problems, characteristics and its use, keeping in mind its application in the development of the Chilean shipyards.

Chilean shipyards date back to the early 1900's, but their purpose was only to provide for repairs and spare parts to the Chilean Navy. The old state suffered an abrupt change in the late 1950's when the Naval shipyard's objective changed to form part of the Government plan to industrialize the country which now provides not only repairs and docking periods to the Navy, but also a program of ships' construction for the Navy, Merchant Marine and the needs

of a country with 4200 kms. of coast line.

The first attempts in shipbuilding have been confined to changes in superstructures and limited building of small crafts.

The author believes that aluminum can play an important role in future designs and major structural changes due to a Mission change of existing Naval ships. Although cost is recognized as a very important item, the presentation is centered on technical problems and technical feasibility aspects.

The presentation is organized as follows:

1) methods of aluminum production;
2) an historic review of the use of aluminum in ship construction;
3) corrosion characteristics;
4) buckling and elasticity;
5) other characteristics, such as allowable design stresses and fatigue properties;
6) analysis of the welding problem, which is considered a key aspect in obtaining maximum advantages of aluminum as a part of a ship's structure.

2. ALUMINUM PRODUCTION

A cheap production process of aluminum became possible in 1886 when C.M. Hall discovered a practical method for obtaining aluminum by dissolving aluminum oxide in molten cryolite and passing an electric current through the solution.

We essentially find two processes in the production of aluminum: The Bayer Process for producing aluminum oxide from the principal ore of aluminum Bauxite and the Hall Process for reducing aluminum oxide to aluminum.

The Bayer Process involves a series of technical treatments in which the ore is first crushed, then ground wet in a caustic soda solution which subsequently dissolves the aluminum hydroxides. After filtering, the aluminum is precipitated out of the solution as hydrated alumina which is separated from liquor and then changed to aluminum oxide by calcining at 1900°F.

Power is converted by a battery of mercury arc rectifiers to 600 V.D.C. for the cells. A cell consists of a rectangular steel shell insulated with fire-brick and lined with a carbon mix with iron bars embedded for electrical connections. The lining acts as the cathode.

It also acts as the container for the molten electrolyte and aluminum. The Sodeberg continuous anode, set down vertically into the two, consists of a casing of sheet aluminum filled with a hot mixture of petroleum, coke, and pitch. As the electrode is consumed and lowered into the cell, volatile matter escapes and the remainder is baked hard. The electrode is four feet wide and ten feet long.

In operation, a cell contains a bottom layer of molten aluminum several inches deep, an upper layer of fused electrolyte, and dissolved aluminum oxide six to twelve inches deep. Electrolysis reduces the oxide content from six to eight percent to a value where gas tends to form on the electrodes stopping the action. But before this occurs, an operator stirs an additional oxide in and restores maximum activity.

Further processes obtain alloy and cast ingots weighing from 2,000 to 9,000 pounds. Finally, hot and cold rolling reduces the material to sheet thickness, followed by heat treatments, tempering, etc. Details on those operations are out of the scope of this work.

It is important to mention here that there are additional costs of plates longer and wider than specified

as "base". For pricing purposes, a length range of 72 inches to 240 inches is used. "Base" prices are established in width and thickness ranges within the length range. Beyond 240 inches, an additional charge of approximately one to three cents is assessed. The most economical widths are 24 inches to 60 inches. Plate widths of 132 inches will cost approximately ten cents per pound more than "base".

A less expensive method of producing aluminum is investigated (33,49). If that is possible, probably the industrial use of aluminum can have a large increase. Bauxite fields, discovered in Chile, now are not commercial (43), therefore, aluminum is imported to cover its actual demand.

3. HISTORIC REVIEW

The history of aluminum boats can be traced back to the early 1890's. Several aluminum hulls were built, including sailing yachts, torpedo and gun boats. We see the first application in U.S. Naval vessels, in the torpedo boats Dahlgren and T.A.M. Craven built in 1899 by Bath Iron Works. Plates, angles, and rivets of aluminum were used in these vessels in the galley, hatch covers, and observation towers (13).

Prior to this, in Europe we find another Naval vessel, La Foundre, a 60 foot aluminum torpedo boat, built by Yarrow and Company for the French Government. The total weight of the boat was ten tons and it used aluminum 50 percent thicker than that used if it were made of steel. A weight saving of two to five tons was obtained. The reason for this choice was the desire of weight saving, since this boat was supposed to be lifted and lowered by the tackle available in another vessel, and the purpose of gaining speed (three and one-half knots was reported over vessels of the same class and dimensions).

All the alloys used at that time had a lack of resistance to salt water corrosion, adequate strength and high cost (5). Only in 1926 did aluminum start to be used more for warship

application in the United States due to the urgent need for weight savings. We find then, two battle cruisers, Lexington CV-2 and Saratoga CV-3, converted to aircraft carriers. At that time, there were Disarmament Treaty limitations on displacement. In order that these two ships did not exceed the limitations, a study was carried out in the use of aluminum to increase weight savings. At that time, aluminum was used for ventilating systems, pilaster bulkheads, flightdeck palisades, airports, etc.

During that time, ships like cruisers Salt Lake City, Houston, Portland and Phoenix had extensive aluminum applications with weight saving in mind. Use of aluminum was mainly in superstructures and deckhouses. A copper alloyed aluminum, Duralumin No. 17S, was used. Soon it was found out that this alloy was not good in a salt water medium. Later, another alloy (aluminum-magnesium-silicon-chromium) was used extensively in destroyers, cruisers, and aircraft carriers. Its applications were in superstructures, catapults, masts, elevators, etc. Those alloys were with low strength, therefore, to improve this situation, the 60 series of heat-treated alloys used in deckhouses, masts, elevators, and many other applications appeared. The aluminum structures were fastened by steel and stainless steel rivets, due to the lack of aluminum alloy for

riveting that gives reliable results (13,26).

One of the first vessels designed and built from a true aluminum alloy was the Diana II (55 feet) launched in 1931 in England. It was a twin-screw motor cruiser. Riveted construction was used in deckhouses and hulls.

The Morag Mhor, built in England in 1953, was part of the first all welded hulls. She is a twin-screw auxiliary motor yacht, 72 feet in overall length and displaces 45 tons. In 1965, the U.S. Navy shipbuilding program included 53 ships and 170 service and landing craft, barges, and assault boats with aluminum use ranging from 33,500 to 2,265,000 pounds per vessel. The U.S.S. Independence, for example, has over 2,250,000 pounds of aluminum in its construction with a weight saving of approximately two million pounds over its steel counterpart. This reduction was used mostly in its top side. We find the aluminum applied to parts of bridges, stack enclosure hatches, windows, ladders, walks, platforms, gratings, heating coils, fitting piping, ducts, life boats, etc. In today's destroyers, aluminum is used widely in superstructure to keep its weight low and to maintain stability.

In the submarines field, we find, for example, 40,000 to 50,000 pounds of aluminum used structurally in each George Washington nuclear powered submarine. Aluminum

has been used also in PT's, hydrofoil craft, mine sweepers, military amphibious craft, Naval weapons (Tartar, Ternier, Talos), torpedo shells, barges, tankers (Aluminia), transportation and storage of liquid gases, etc.

Aluminum has been chosen for all these applications keeping in mind height, strength, light weight, and corrosion resistance, however, a penalty of considerable increase of cost was paid (50,42,44).

Aluminum has been also used in Civil Engineering, forming part of structural members in buildings, windows, doors, etc. It has been used widely in Aircraft Industry in which the overall aircraft structure is assembled with rivets. We find, also aluminum playing an important role in the fabrication of space vehicle structures, such as fuel and oxidizer tanks in Saturn V (17).

Chilean usage of aluminum has been limited to minor structural components of buildings, lifeboats, yachts, domestic objects, electric conductors, furniture, etc.

WEIGHT STRENGTH IN PERCENT Aluminum vs. Steel

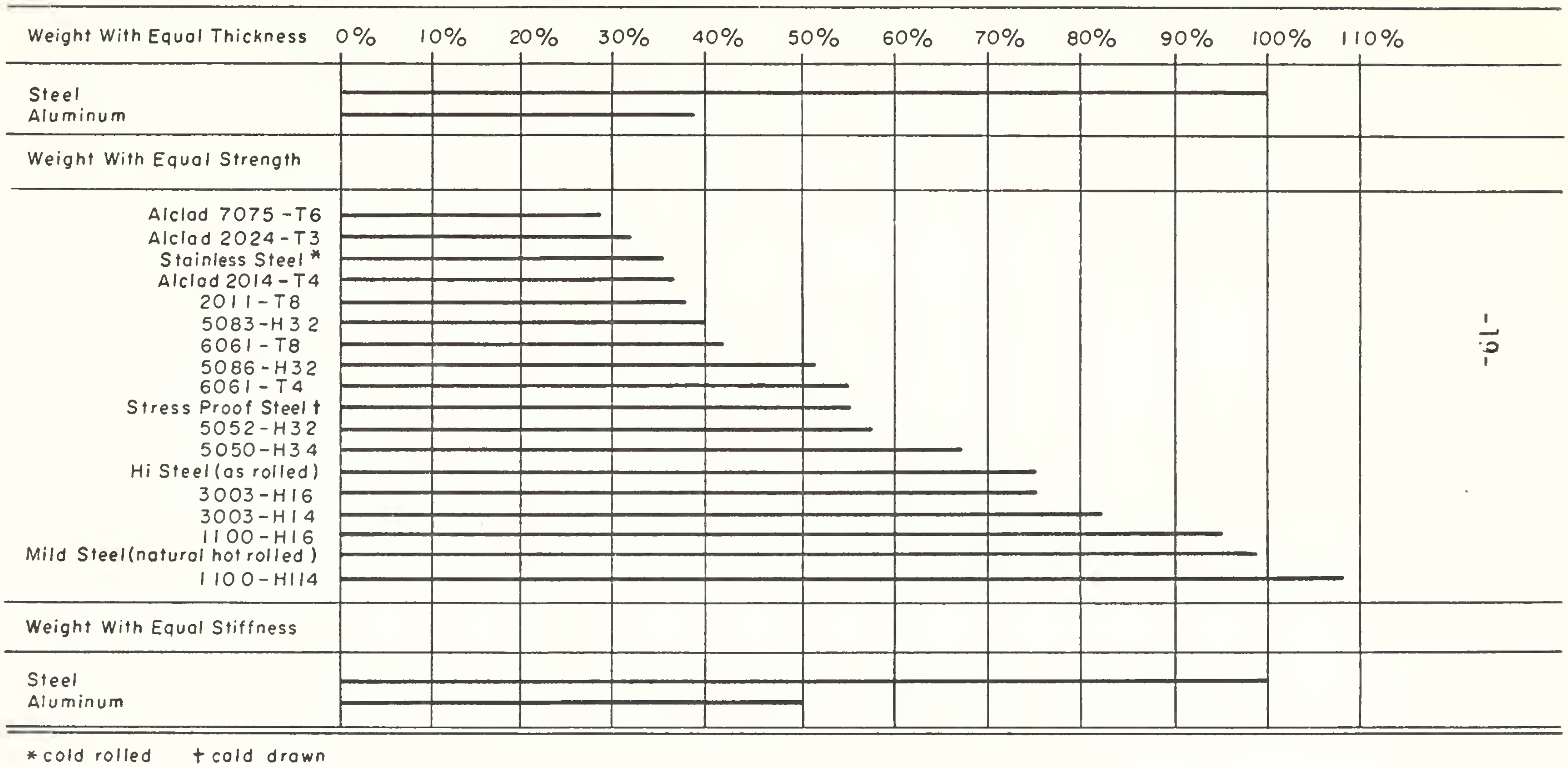


FIG. I MAYOR ADVANTAGES OF ALUMINUM

4. CORROSION

4.1 Corrosion Characteristics of Aluminum

For marine applications, it is very important to have a good resistance to corrosion as well as immunity from stress corrosion. We know that corrosion is defined as the destruction of a metal by chemical or electro-chemical reaction with its environment. Resistance to corrosion is determined experimentally by the change in mechanical properties and by measuring the depths of individual pits on test panels after prolonged periods of exposure (44). Such tests are available as published sources in handbooks and reliable publications by the National Bureau of Standard, SNAME and others, and have shown that most aluminum alloys in seawater will undergo localized pitting to an average depth of two or three mills in one to two years. With larger exposures, corrosion continues but the rate of increase in depth diminishes with time. This has been named as the "self-stopping" nature of corrosion on aluminum, and is considered to be due to the formation of protective corrosion products over the small pits. Tables la. and lb. show the same experimental results of corrosion resistance of 5083, 5086, and other aluminum alloys (Aluminum in Naval Craft, W. Leveau, Naval Engineers Journal, April 1965).

TABLE la.

a) Corrosion Resistance of Unprotected Aluminum Alloys in Seawater

Alloy and Temperature	Exposure Period (years)	Maximum Measured Pit, Depths Mils	Percent Change in T.S.
3003-H14	8	7.0	-1
Alclad 3004-H18	8	2.5	0
5050-H34	8	12.0	-3
5052-H34	8	10.5	-2
5052-H36	6	23.0	-2
5086-H34	6	34.0	0
6061-T4	8	14.0	-8

TABLE 1b.

b) CORROSION RESISTANCE TO TIDE RANGE SEAWATER IMMERSION, SEVEN YEARS

Alloy and Temperature	Location Inside Samples	Percent Change in Strength	
		Tensil Strength	Yield Strength
5083	Totally immersed	-2	0
	Water line	-3	-2
	Splash zone	-6	-2
5083-H34	Totally immersed	0	0
	Water line	0	0
	Splash zone	-3	0
5086-0	Totally immersed	-2	0
	Water line	-2	0
	Splash zone	-3	0
5086-H34	Totally immersed	0	0
	Water line	0	0
	Splash zone	-1	0

We see that non-welded 5086 and 5083 sheets show negligable loss in strength. Pitting was infrequent. In the partial immersion test, non-welded 0.125 inch 5086 and 5083 sheets also show negligable loss in strength regardless of whether the exposure was water line, splash zone or total immersion.

We also find the galvanic corrosion which is an accelerated attack on metals which occurs as the result of the flow of electric current induced by contact between dissimilar metals in a conducting solution (51). This action is much like that of a wet battery. Galvanic corrosion of aluminum is more severe when aluminum is coupled to copper or copper-bearing alloys, bronze, brass and monel than when coupled to steel, lead or nickel. Also, galvanic corrosion of aluminum is more severe in a bimetallic couple immersed in sea water than in a couple merely exposed to marine atmosphere or immersed in fresh water.

Generally, bimetallic couples are undesirable. Through appropriate design, however, galvanic corrosion of aluminum can be prevented or minimized. Galvanic corrosion in bimetallic connections is most commonly controlled by separating the interfaces with gaskets, washers, sleeves and bushings of insulating materials such as neopreme,

pressite and others (37). These materials prevent the flow of galvanic current. Another means of preventing galvanic corrosion is by avoiding direct contact of dissimilar metals by painting the facing surfaces. Numerous metallic structures, whether operating under conditions of continuous or intermittent contact with liquid media or in atmosphere exposures, are often subjected to conjoint action by the liquid media and mechanical stresses. We can differentiate five distinct characteristic cases of corrosion deterioration of metals that can be distinguished by the distinct action of the mechanical factor (41,45):

1) General corrosion of a stressed metal;
2) Corrosion fatigue;
3) Stress Corrosion Cracking
4) Cavitation corrosion;
5) Corrosion by erosion.

4.1(a) General Corrosion

We can consider as proven that even in relatively uniformly distributed corrosion deterioration, the presence of constant stresses in the metal whether internal or external will increase the velocity of the corrosion process. It is a known fact that the most stressed parts of the hull and plating of a seagoing vessel of low alloy steel suffer

the most from the action of sea water.

N.D. Tomashov and V.A. Titov, (Zavodscaya Laboratoriya, 1 (1949), 48) showed that a steel wire cable, 1.0 mm in diameter, under conditions of maximum load in a corrosive media corroded 25 percent faster than a wire under no load.

4.1(b) Stress Corrosion Cracking

This type of destruction is caused by the conjoint action of the corrosive medium and the externally applied or locked up or gradually increasing tensile mechanical stresses. For this reason, a corrosion crack, known as intergranular cracking, can not only spread along the grain boundaries, but also can cut across the individual crystals, generally known as transcrystalline cracking. Wrought high strength aluminum alloys containing copper or zinc as the principal alloying element and aluminum-magnesium alloys containing more than five percent magnesium may be susceptible to stress corrosion cracking (48). Aluminum alloys that can be strengthened only by cold work are generally considered to be immune to stress corrosion cracking. Extruded alloys show directional sensitivity to stress corrosion cracking (40). They are most susceptible to cracking when stressed in the short transverse direction and are much more resistant to

cracking when stressed in the direction of extrusion (39,41). Stress corrosion cracking is an electrochemical process, at least in part. It is intercrystalline. It may follow paths adjacent to the grain boundaries in aluminum-copper alloys that are impoverished in copper and, hence, anodic to both the grain interior and boundary. It may result, in the aluminum-zinc alloys, from attack on an anodic grain boundary precipitate, considered to be the Mg.Zn phase or $Mg.Zn_2$. There is a question as to what is the anodic phase in the aluminum high magnisium alloys (39,40).

Casting alloys containing nine percent to eleven percent magnesium were reported to be susceptible to stress corrosion cracking in laboratory tests.

In addition to the usual procedures for preventing stress corrosion cracking (e.g. removing residual tensile stresses) of metals, there are several which are specifically applicable to aluminum alloys. Forgings and extrusions should be machined as nearly as practicable to final dimensions prior to heat treatment; stressing of extrusions in their short transverse direction should be avoided; cathodic protection in the form of clad or alclad layers on the surface of height strength sheet material may be used to protect it from general corrosion

and stress corrosion cracking (42).

4.1(c) Corrosion Fatigue

This is caused by simultaneous action of the corrosion medium and by alternating or pulsating tensile stresses. This form of destruction is also characterized by intercrystalline and transcrystalline cracks, the development of which occurs primarily during the period of application of tensile stresses. Deterioration of metals due to corrosion fatigue is commonly encountered in ship propeller shafts, auto springs, sea and mine cables and so on.

4.1(d) Corrosion Cavitation

This type of destruction usually occurs because of an energetic mechanical action directly by the corrosion medium itself. An example is the action of a rapid stream of sea water producing repeated local impact (due to the collapse of vapor cavities) with resultant pulsating stresses on various regions and surfaces.

4.1(e) Corrosion Erosion

This type of destruction inflicted on surfaces of solid bodies is caused by the mechanical abrasive action of other solid bodies in the presence of a corrosive medium or by direct abrasive action of the corrosive medium itself. Aluminum alloys are No. 2 after Cu-Ni in application, where corrosion erosion is the factor

that controls the design.

Although aluminum has been used successfully in sea water for many years, the greatest growth in marine applications has occurred since World War II with the development of aluminum-magnesium alloys. These have excellent corrosion resistance, are weldable and have good mechanical properties. Al-Mg-Si alloys are used for superstructure, interior bulkheads and deck gear. Sand castings of Al-Si and Al-Mg are used in valve bodies and heavy fittings. Alclad 3003 is the most satisfactory aluminum material for all fresh water and salt water piping and for heat exchanger applications. We can rank aluminum alloys as far as corrosion resistance is concerned, saying that alloys in the 3XXX, 4XXX, 5XXX and 6XXX series have good to very good corrosion resistance. Alloys in the 2XXX and 7XXX series require some kind of protection for adequate corrosion resistance (51,39).

4.2 Dissimilar Metals

Although aluminum alloys, in general, are resistant to corrosion in a marine environment, galvanic corrosion can result when combined with other metals in the presence of an electrolyte. Aluminum is subject to some attack when combined with most shipbuilding metals, unless the joint is effectively protected. Galvanic corrosion can

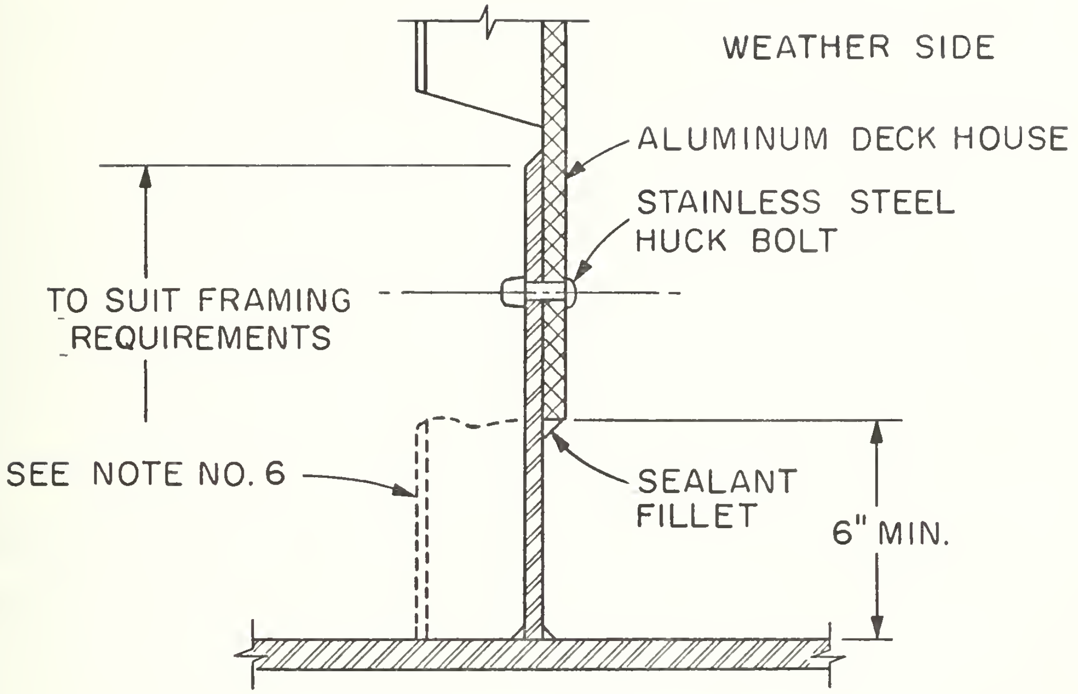
occur in aluminum deckhouses at the junction of the steel boundary bars and on aluminum hulls in the vicinity of fittings, struts, shafts, propellers and rudders. For galvanic action to occur, there must be both metal to metal contact and electrolyte (41). If the metals can be separated by a non absorbent meterial such as a neoprene sheet or if the electrolyte can be excluded, then electrolysis will not take place. The degree of attention is proportional to the location of the joint and the metal combination. Under water connections, joints exposed to salt spray, wet interior spaces, and dry interior spaces should be given design attention in the order listed.

From the available literature, we can summarize some basic rules that can help minimize the problem in the most common joint actually used in shipbuilding, which is the connection between steel boundary bars and aluminum deckhouses (33,42):

a) Keep the aluminum on the weather side of the boundary bar so that it acts as a flashing.

b) The lower edge of the aluminum section should be a minimum of 6 inches from the deck. This prevents water from pooling below the joint and seeping up into it.

c) The sealant and/or tape should be uniformly applied so that areas of the joint are sealed.



NOTES:

(1) PRIME BOTH SURFACES WITH ZINC CHROMATE
(2) APPLY BUTYL RUBBER ON SURFACES - LET DRY
(3) APPLY SECOND COAT BUTYL RUBBER BEFORE MAKE UP
(4) SET HUCK BOLTS, EXCESS SEALANT SHOULD FILL HOLE
(5) FORM FILLET FROM EXCESS SEALANT
(6) WHERE DESIGN REQUIRES, STEEL FRAMING CAN LAP ALUMINUM FRAMING. FAYING SURFACES SHOULD BE TREATED AS 1 AND 3

FIG. 2 ALUMINUM DECKHOUSE JOINT DETAIL

d) A sealant fillet should be applied to the joint on the weather side and preferable on both sides of the joint.

e) When the fasteners are set, some caulking material should be available in the hole in order to completely fill it up after the fastener is in position.

Underwater connections are treated differently. Propeller shafts, struts, rudders and propellers are generally constructed of a material which will affect the aluminum hull (44). Lets assume a bronze propeller and a stainless steel shaft are being used on a boat. The first chance at isolation is at the strut bearing. Use of a cutless rubber bearing will break electrical flow at this point. If the size of the shaft or other requirements preclude the use of a cutless rubber bearing, then the bearing casings must be isolated from the strut.

The shaft penetrates the hull at the stuffing box. The packing breaks metal to metal contact unless it contains graphite or some other electrical conductor. If necessary, the entire assembly can be isolated from the aluminum hull with a thin neopreme gasket. An isolation flange should be used at the coupling to the gear box. The rudder arrangement is similar. It can be connected to the

post by normal methods. Piping systems can contain a great deal of dissimilar metals. Salt water lines and engine cooling systems need to be isolated at the hull penetration. Dissimilar metal lines should be connected to the hull with insulated pipe hangars.

The author's comment at this point is to call the attention to the fact that even isolation is not a difficult thing to do, however, it requires extensive additional labor and supervision. Also, we must keep in mind that modifications, repairs, new equipment and so forth can cause a breakdown in the isolation system.

5. ELASTICITY AND BUCKLING

The modulus of elasticity of aluminum is about one-third of that of steel which, depending on the application, may or may not be advantageous. Compared with state steel structures, aluminum is disadvantageous because of its lower stiffness characteristics. This can be overcome by increasing the moment of inertia of the section by a factor of three so that the EI product remains unchanged. For plates of sheets under normal loading, the aluminum thickness must be increased by 44 percent, and still we get a weight saving of about 50 percent. If we now consider impact loading, we see that the lower modulus is an advantage since the aluminum structure will absorb three times as much energy in reaching the same stress level as will a steel one of the same dimensions. (26).

The modulus of elasticity of metals also has an effect on the buckling strength of compression members. In columns which buckle elastically under load, the critical load is determined by the Euler formula:

$$P = \frac{\pi^2 EI}{(KL)^2} ,$$

(54). For the aluminum column that is to carry the same load as a comparable steel column, we found that the moment

of inertia (I) must be increased by a factor of three, so that the product EI remains unchanged. Again we can achieve a weight saving of about 50 percent. For short compression blocks or intermediate columns, the critical buckling strength is dependent on the yield strength and shape of the stress strain curve just beyond the proportional limit. In such cases, the higher strength aluminum alloys may carry the same load as the steel counterpart with equal cross-section, resulting in further weight savings. Another advantage of aluminum over steel is found in buckling of plates where, for the same stiffness of aluminum and steel in a plate of the same dimensions (except thickness where aluminum is three times thicker than steel), the aluminum has a critical load for buckling bigger than for steel. If we look at the Bryan formula for critical stresses in panels of plating under compression,

$$\sigma_{CR} = \frac{K_c \pi^2 E}{12(1-\nu^2)} (t/b)^2$$

we find that for aluminum:

$$\sigma_{CR\ \text{aluminum}} = 3\sigma_{CR\ \text{steel}}$$

Buckling, in general, will treat several headings, such as columns, beams and girders, flat plates, etc. Of course,

we should distinguish the different types of bucklings as sidewise bending, twisting or wrinkling, but aluminum is an homogeneous isotropic material which reacts to various load conditions in a manner similar to that of steel and other metals (47). Therefore, it is my opinion that standard theories apply in the computation of stresses and deflections. Design is usually based on the yield strength of the different alloys rather than on ultimate strength, assuming that permanent deformation will result in sufficient distortion of the structure to cause it to be inoperative.

All of these considerations are valid for aluminum as an alloy, with aluminum having the outstanding advantages of high strength, light weight and the facility of fabrication of the welding process. However, a combination of these advantages produces a serious welding problem.

The problem is the development of a heat affected zone near the weld, which reduces the original strength of the high strength aluminous alloys to that approaching the lowest strength, the annealed temper of the specific alloy. Basically, aluminum is soft and low in strength. Also, metal combinations with the appropriate alloying elements together with subsequent heat treatments or strain hardenings produce various classes of high strength aluminum alloys (36).

Dissipation of the welding heat through the base metal reduces the high strength of such alloys in the region of the weld. Such heat affected zones develop non uniform material properties over a band width of an undetermined extent (16,17,25). Therefore, a welded aluminum structure would be weaker than expected on the basis of the original uniformly hardened high strength material, unless this weakening effect were taken into account by the designer. However, a quantitative determination of the weakening or degrading effect is difficult to determine (46), has not yet been universally established and is not generally available for design purposes. The unavailability of specific information regarding the actual strength of the degraded material is particularly critical in the design of one fundamental structural component, the column. Column design, as it was mentioned earlier, is based upon and particularly sensitive to the yield strength of the material. The yield strength of aluminum alloys is most readily altered by application of heat. This yield strength of aluminum alloys may be reduced drastically in the heat affected zone. Therefore, where welding is required at a point of structural significance, the design assumes the existance of material of the weakest condition regardless of the initial high strength of the original hard temper of the alloy. Such

designs will be inefficient and will negate the advantages of structural aluminum.

In order to satisfy the need for specific design data and to get around the problem of testing the welded zone material, a program was planned at the U.S. Naval Applied Science Laboratory to determine actual structural performance. The planned approach was to compare the structural behavior of welded columns with unwelded ones of the same alloy and of identical dimensions. A tubular cross-section was used for reason of theory and convenience. Identically dimensioned, unwelded, butt welded and longitudinally welded columns were prepared for comparative performance. As a result of the tests, the maximum stresses were calculated for each specimen from the ultimate columns load of failure. The average values for the column stresses are listed in the tables 2 and 3 (11). Each average value is representative of the specimens for a particular combination of joint type and slenderness ratio. The lowest individual stresses in each category are also shown in the tables. As anticipated, the tables show that the unwelded columns developed the highest failure stresses. In addition, this data corresponds most closely with theoretical values in the range of slenderness, l/r, ratios where the Euler Column Theory would be considered applicable, the upper end of the range.

Therefore, the unwelded data was used as a basis for comparing the relative capacity of corresponding welded columns. The structural performance of the welded columns, as represented by the tabulated data, indicates that currently recurrenced design procedures (Bureau of Ships Instructions 9110.46 Ser. 443-71 February 19, 1960) were too conservative for some aluminum alloys, such as 6061-T-6 and 5086-H32, whose strength was observed to be significantly higher than called for by recommended practice. The main conclusion was that the assumption of total annealing of the heat affected welding zone is not universally applicable to all aluminum alloys. Although, some alloys, such as strain hardened 5436-H311, do behave in comformity with current design concepts regarding the degraded welding zone, others, such as strain hardened 5086-H32 and heat treated 6061-T-6, develop significantly higher strengths than are predicted by the assumption made in current practice. Efficient design requires that the degree of degradation of the heat affected zone be determined for specific aluminum alloys in order to be applied to structural design.

TABLE 2

Result from Testing 5086-H32 Aluminum Tubular Columns with One-half Inch Walls for Buckling Loads

Joint Welded	L/R	Diameter (Inches)	Maximum Load P(lbs.)	Nominal Stress P/A (psi)	Average Stress (psi)	Average Percent
None	20	6	280,000	32,100	--	--
			270,500	31,000	31,000	100
Butt	20	6	270,000	30,900	--	--
			269,000	30,700	--	--
			264,000	30,200	30,600	97
Long	20	6	284,500	30,800	--	--
			270,000	29,400	30,100	95
None	40	6	232,000	26,600	--	--
			231,500	26,500	26,600	100
Butt	40	6	227,500	26,100	--	--
			223,500	25,500	--	--
			218,500	25,200	25,600	96
Long	40	6	243,500	26,100	--	--
			236,000	25,200	25,700	97

Joint Welded	L/R	Diameter (Inches)	Maximum Load P(lbs.)	Nominal Stress P/A (psi)	Average Stress (psi)	Average Percent
None	60	4	123,000	22,200	22,200	100
Butt	60	4	116,000	21,000	--	--
			114,000	20,500	--	--
			107,000	19,300	20,300	91
Long	60	4	119,000	20,100	--	--
			118,600	19,900	20,000	90
None	80	4	78,200	14,100	14,100	100
Butt	80	4	74,600	13,500	--	--
			73,200	13,300	--	--
			71,800	13,000	13,300	94
Long	80	4	83,200	13,900	--	--
			76,800	12,900	13,400	95

TABLE 3

Results from Testing 5456-H311 Aluminum Tubular Columns with One-half Inch Walls for Buckling Loads

Joint Welded	L/R	Diameter (Inches)	Maximum Load P(lbs.)	Nominal Stress P/A (psi)	Average Stress (psi)	Average Percent
None	20	6	215,400	25,000		
			222,600	26,200	25,900	100
Butt	20	6	208,400	24,600		
			214,000	25,200		
			222,600	26,200	25,300	98
Long	20	6	222,800	25,300		
			219,400	25,200	25,300	98
None	40	6	178,800	21,300		
			180,200	21,200	21,300	100
Butt	40	6	166,600	19,600		
			158,300	18,900		
			164,300	19,300	19,300	91
Long	40	6	184,200	21,100		
			158,400	18,700	19,900	93

Joint Welded	L/R	Diameter (Inches)	Maximum Load P(lbs.)	Nominal Stress P/A (psi)	Average Stress (psi)	Average Percent
None	60	4	103,600	19,000		
			94,900	17,400	18,200	100
Butt	60	4	97,400	17,700		
			98,600	18,000		
			96,400	17,600	17,800	98
Long	60	4	92,200	15,800		
			106,700	18,200		
			95,600	16,300	16,800	92
None	80	4	81,400	15,100		
			78,900	14,600	14,900	100
Butt	80	4	67,000	12,400		
			64,000	11,700		
			71,000	13,000	12,400	83
Long	80	4	66,800	11,500		
			69,000	11,800	11,700	79

TABLE 4

Comparison of Yield Strength and Design

Curve Designations for Butt Welded Columns

Aluminum Alloy	Temper		Yield Strength		Column, Curve Designation	
	No.	Condition	Value (psi)	Difference (psi)	From Buships	From Data (experiments)
5456	H-311	Hard	25,000			
	0	Annealed	19,000	6,000	AL-19	AL-19
5086	H-32	Hard	28,000			
	0	Annealed	14,000	14,000	AL-14	AL-22
6061	6T6	Hard	35,000			
	0	Annealed	16,000	19,000	AL-16	AL-21

The disagreement or inconsistent curve relations noted in the last two columns of Table 4 may be explained by the difference in yield strength values between the annealed and hard tempers for the respective alloys (27). The difference in yield strength between the annealed and hard tempers for the 5456 alloy is relatively small (6,000 psi) compared to the respective values of 14,000 psi, and 19,000 psi for the 5086 and 6061 alloys. The relative magnitudes suggest the following explanation based upon heat input to the welded joint. The heat input at the butt weld of the 5456-H311 columns caused the degraded zone materials to approach the fully annealed condition. This is the significance of the agreement of the two Al-19 curves. The curve agreement shows column performance in accordance with current practice design assumptions. That is, the column behaved as if the original strength of the 5456-H311 base metal had been reduced from 25,000 psi to 19,000 psi by the heat of welding. Now, it seems evident that the total heat input for a welded joint of specific dimensions would be approximately constant for any aluminum alloy. If this amount of heat was great enough to cause a strength reduction of 6,000 psi, but smaller than the amount needed to cause a 14,000 or 19,000 psi reduction, it would result in the observed agreement of the Al-19 curves for the 5456 alloy.

It would result in the disagreement shown by the Al-14 versus Al-22 for the 5086 alloy, and by the Al-16 versus Al-21 for the 6061 alloy.

These conclusions raise another question related to the guide for design procedures (Bureau of Ships Instructions 9110.46 Ser. 443-71, February 19, 1960) which recommends, "If the member is butt welded at the ends, it should be considered pin ended.". That is, instead of the higher capacity of a restrained column, the actual load that an end welded column may support should be only one-fourth the theoretical value:

$$P_c = \frac{4\pi^2 EI}{L^2}$$

because of the uncertain effect of the heat degraded material at the column end of the overall column strength. Obviously, any less restrictive guide would improve design efficiency. The results discussed before of the mid-length butt welded column experiments suggest the possibility of a more optimistic measure of the degree of end-restraint which could provide the basis for more effective design.

Some experiments were carried out by the U.S. Naval Applied Science Laboratory indicating that simply supported mid-length butt welded columns would carry loads equal to

0.6 the load supported by a similar unwelded column (27).

It was also assumed that the effect of welding the base of the fixed, free-ended column would be similar to the effect of a mid-length butt welded joint on the structural performance of a pin-ended column. That is, the ultimate load for the fixed, free-ended column would be:

$$0.6 \cdot \frac{\pi^2 EI}{L^2}$$

and for the fixed-ended column:

$$0.6 \cdot \frac{4\pi^2 EI}{L^2}$$

This is assumed because the free-ended column can be considered as a two fixed,free-ended column of length $\frac{L}{2}$.

However, the factor 0.6 was found only for the 6061-T6 alloy; additional data is required for any specific aluminum alloy.

We see that aluminum columns will, in fact, save weight, but the heat affected zone must be taken into consideration for design work. We also see that more study has to be done to increase our knowledge in heat effects produced by welding.

6. OTHER CHARACTERISTICS OF ALUMINUM

6.1 Allowable Design Stresses

Aluminum alloys do not have a clearly defined yield point. The typical stress strain curve is a continuously rising curve and does not exhibit a flat spot or sharp break at the yield strength. As is the case with other materials that yield gradually rather than abruptly, it has been necessary to adopt an arbitrary criterion of yield strength. The criterion used is the stress at which the material exhibits a permanent set of 0.2 percent, established by the American Society for Testing Material (Fig.3).

Table 5 has been taken from The Buships Instruction 9110.46, February 19, 1960.

TABLE 5

Allowable Design Stresses for Aluminum Alloys

Alloy	Tension and Bending (K.S.I.)	Assumed Yield Strength (K.S.I.)
5086-H-32	18	22
5086-H-112	14	16
5086-0	13	14
5456-H-321	21	26
5456-H-311	17	21
5454-H-34	16	16
5454-H-311	12	13
6061-T-6	*	*

* This alloy only used for riveted structures.

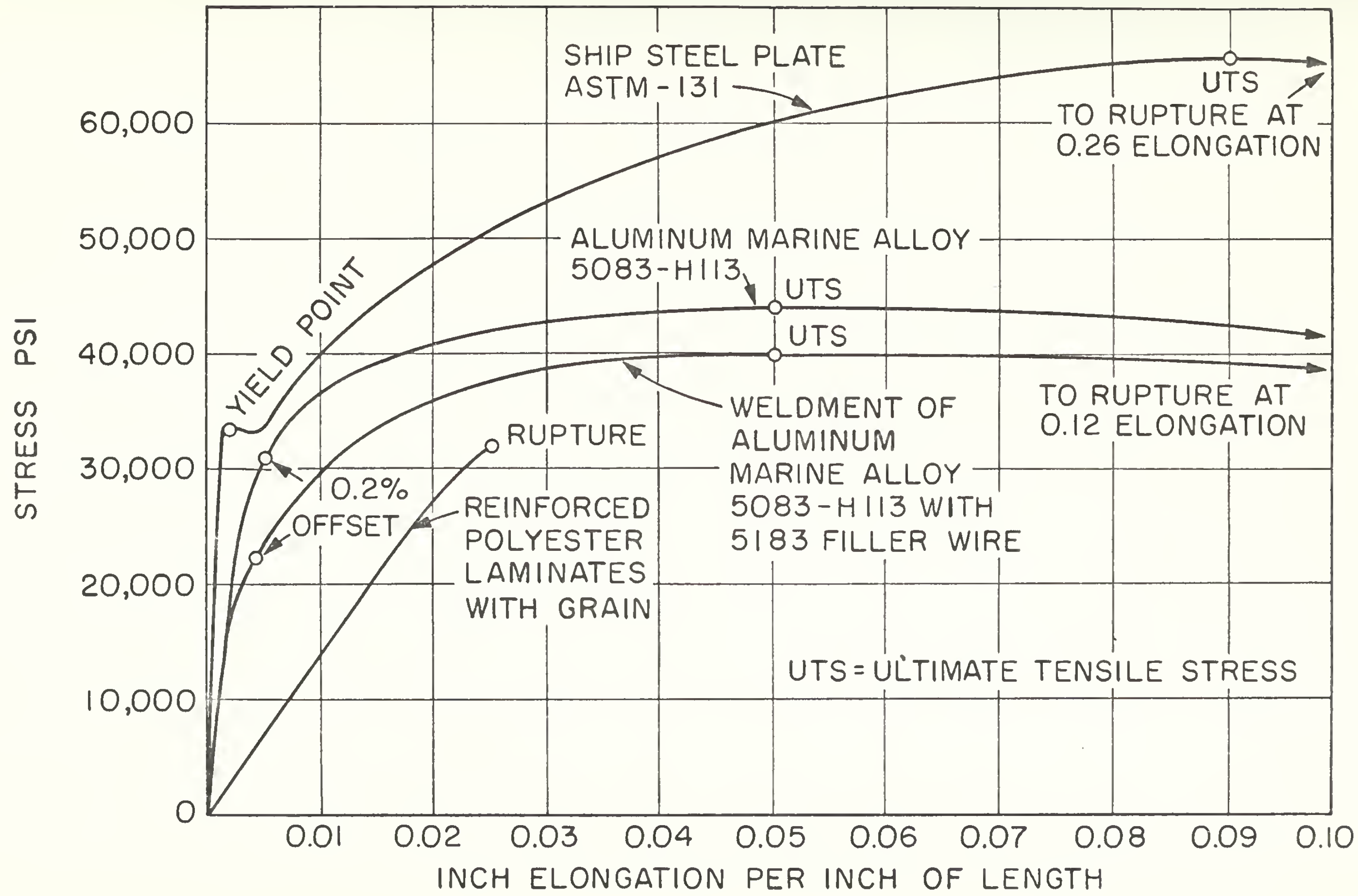


FIG. 3 TYPICAL STRESS - STRAIN DIAGRAMS FOR HULL MATERIALS

These alloys are the most commonly used in ship structures. Aluminum has a mass of 0.1 pounds per cubic inch as compared with about 0.28 for steel. This low density may be combined with high yield and ultimate strengths by suitable alloying. Consequently, many structural parts can be designed and fabricated with a weight of 40 or 50 percent that of a comparable steel unit. This property makes aluminum attractive to the improvement of mobility, or increasing of pay loads.

6.2 Strength at Low Temperatures

It is a known fact that aluminum has an increased strength and has a small change in ductility at very low temperatures as referred to the same properties in ambient conditions. This makes magnesium and manganese aluminum alloys inexpensive and suitable in the storage and transportation of liquified gases, called cryogenic applications (50). In this field, as in the field of high temperatures, application care should be taken to choose the proper alloy and analyse each case by itself in order to make a proper design that will take into account the changes in strength and ductility that occurs in the material as the temperature varies. Modulus elasticity is affected by temperature, as indicated on the following page (2,3).

Effect of Temperature on Modulus of Elasticity

Temperature (°F.)	Modulus of Elasticity (Percent of Room Temperature Value)
-320	112
-110	105
- 20	102
+ 75	100
+212	98
+300	95
+400	90
+500	80

6.3 Fatigue Properties

This data is available in published books and manuals (Alcoa Structural Handbook), but is referred to as fatigue specimens of wrought alloys with smooth machined surfaces. These fatigue strengths cannot be applied directly in design without suitable allowance for stress raisers, such as holes, welds and re-entrant

corners. When a fatigue failure occurs in a structure, it is always traceable to some stress raisers such as a notch, hole, or sharp re-entrant corner (12). Fatigue strength curves are also available for some alloys in the riveted conditions, but very little work has been done in the welded conditions (28). It is worth mentioning experiments undertaken by Reynolds Metals Company and Metallurgical Research Division in fatigue specimens of production quality 5083-H-113. These conclusions were:

a) The geometric notch effect, caused by the weld bead, is the prime factor influencing fatigue life of transverse built-weld specimens. Removal of the weld bead gives a significant increase in the fatigue properties.

b) Transverse double-V built-welds, or welding from both sides of a plate, cause a more severe notch and, hence, give lower fatigue properties. It can be expected that the notch effects of the double-V weld will be diminished with an increase in plate thickness.

c) Differences in automatic and semi-automatic welds can be primarily attributed to weld

bead configuration. The irregularities normally associated with hand welds have a greater influence in reducing fatigue properties. Of secondary importance are the metallurgical changes due to different welding techniques.

d) Weld quality is a prime factor in determining the fatigue properties of longitudinal built-welds specimens. As the gage is increased the effects of porosity, oxide inclusion, and lack of penetration to the backup plates are diminished and the metallurgical effects become more prominent.

In the author's opinion, present knowledge of fatigue is not sufficiently advanced to permit a precise design for a specified life. In the marine applications field, it is mandatory to have more available data on aluminum in a condition for use (welded, riveted or bolted). Another important factor to mention is for ship structures and hulls there is a low cycle fatigue, an area where little work has been done.

6.4 Cutting Aluminum

From the many processes in the fabrication of aluminum alloy structures there is a problem of special interest, that of cutting aluminum. The cutting methods for ferrous material using oxygen are not suitable for use on aluminum

alloys (16). Normal procedures for cutting aluminum are sawing, shearing, gas tungsten arc cutting and gas metal arc cutting, all of which have undesirable effects on the cut surface that require additional preparation. With the gas turgsten arc method there is a tendency to cracking, which increases with plate thickness and cutting speed (2,3). Thicker plates impose a greater restraint on the solidifying metal at the kerf wall and may cause shinkrage cracks. Higher cutting speeds produce a steeper thermal gradient at the face of the cut and, therefore, generate greater thermal stress. The heat affected zone next to an arc cut surface may display reduced corrosion resistance in the case of high-strength, heat treatable alloys. In the metal arc cutting process, the cut edges are sharp, but drag lines on the face of a cut may be pronounced. The bottom of the kerf tends to be slightly wider than the top.

Plasma arc cutting is one of the fastest methods of cutting aluminum and is well adopted to production work.

In the author's opinion, the aluminum cutting will require skilled workers to produce superior cuts and further cost in edge preparation and supervision

6.5 Construction Facilities

Most U.S. shipyards have little experience with aluminum;

they are mainly familiar with deckhouses and other secondary structures. If persons have in mind to build a complete hull out of aluminum, it seems that a very small percentage of them will be interested in bidding, and these bids will be very high, because these yards generally do not have a steady flow of aluminum work; thus, their average productivity is at the lower end of the learning curve.

The Chilean shipyards can be added to the group. They are without experience in aluminum construction, but they do not face a big problem. Provided experience is developed somewhere, it can be easily passed on to the personnel.

6.6 Regulations

The U.S. Coast Guard and A.B.S. have published regulations governing steel construction. These regulations allow steel designs to be checked against tables of minimum scantlings. In other words, there is a base to measure the success or failure of a particular design. This is not the case in aluminum ship construction. Neither U.S. Coast Guard nor the A.B.S. has a set of published regulations for aluminum construction. There is the tendency of applying steel rules to aluminum ships due to this lack of a standard procedure.

A.B.S.'s present position on hull girder deflection is to allow a 50 percent additional deflection allowance for aluminum construction. To determine the minimum I/y or section modules for an aluminum ship, the following procedure can be used. Establish the steel Rule I/y and I requirements for a vessel at an L/D of 14 for "full ocean", a L/D of 16 for "short coastwise" or a L/D of up to 30 for "river or great lakes". Subtract 10 percent and multiply by two. The aluminum I/y, thus established, has incorporated the 50 percent hull girder deflection increase and a 10 percent corrosion allowance (33).

Shell, bulkhead, and other plating must have a thickness equal to the minimum steel thickness times 80 percent of the ratio of the ultimate tensile of steel to the ultimate tensile of the aluminum alloy plate. Webs and stiffners should have a I/y equal to the minimum steel I/y times 80 percent of the ratio of the ultimate tensile of the steel to the ultimate tensile of the aluminum alloy (42).

When extrusions are used, the ratio of ultimate tensile is higher because extruded properties of any given alloy are generally lower. The author believes that this lack of regulations for aluminum constructions will

continue because most of the steel rules are based on long years of both theoretical and practical experience which is not the case for the aluminum construction which has been limited to ships of low L/D ratios. Also, the inventory is very poor. It comes to my mind that actual rules for deflection of ships structures are actually making the Steel Industry unhappy because it is producing high strength steel alloys that will allow a further reduction in the section modules of ship structures. This cannot be done because of deflection limitations in the rules.

It is my impression that, because of a growing demand for new types of ships and because of the introduction of new materials and fabrication processes, there is an increasing need for a rational, rather than rule-book approach to ship design aluminum. At the same time, there is a need for making inexpensive and rapid calculations involved in ship design. By using computers, a new approach to ship structural design answering both needs may be devised. This new approach will tell us how a ship should be built to have a good performance in its media of operation and will allow us to use all the advantages of a material without being constrained by rules or by making approaches based on steel parents.

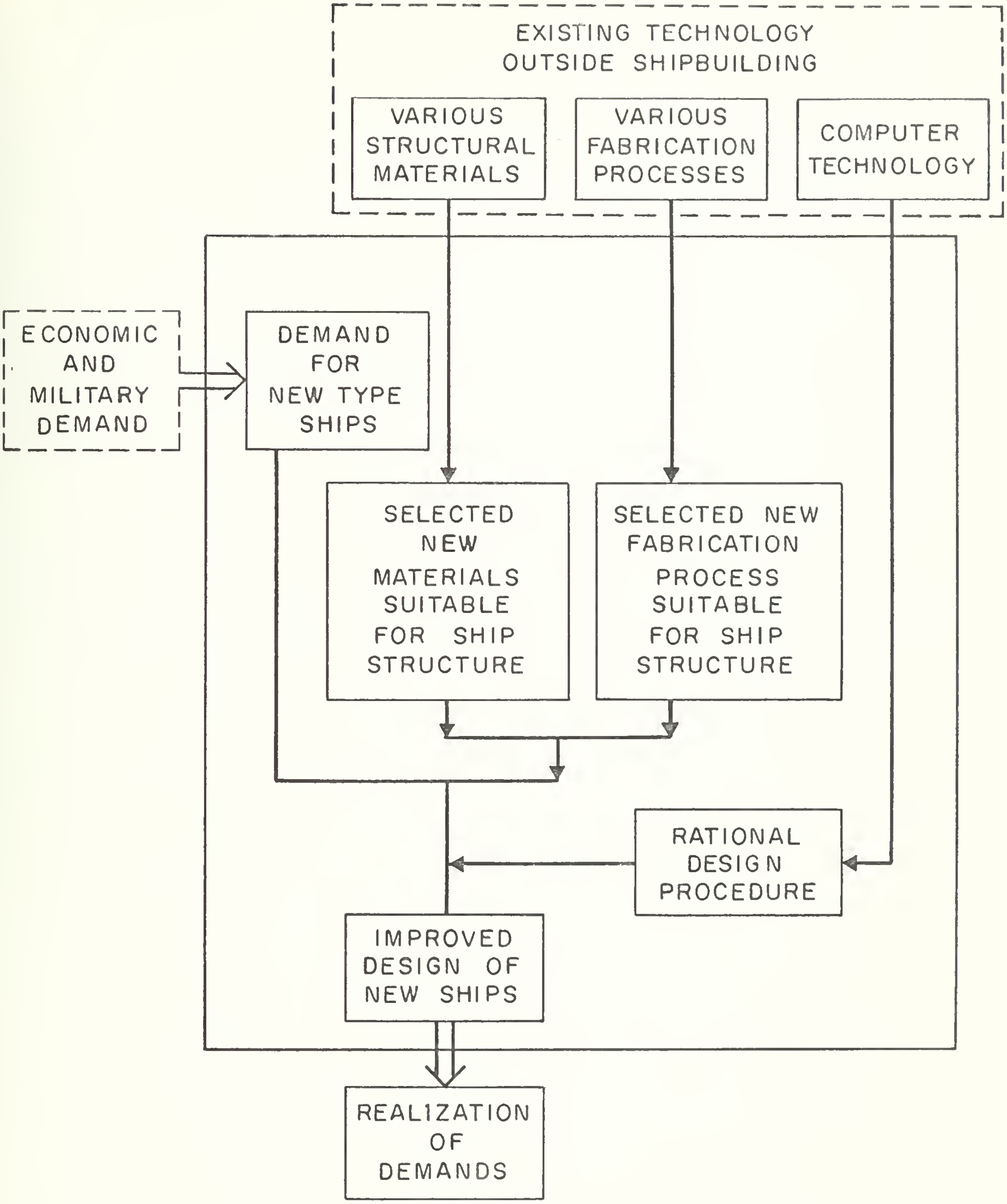


FIG. 4 RELATIONSHIP BETWEEN NEW DEVELOPMENT AND IMPROVED SHIP DESIGN (29)
]

The rules and regulations prepared by ship classification societies, such as the American Bureau of Shipping, are based primarily on experience rather than on theoretical knowledge. If we continue following these rules, the complete aluminum ship will not be a reality attractive to owners, because of economical reasons. Only in isolated cases will we see the complete aluminum ship.

In the case of the Chilean Navy, this new approach can be made, since it has its own rules, provided the economical factor can somehow be overcome.

6.7 Fire Protection of Aluminum

One of the disadvantages of aluminum is its low melting point. This has an important bearing on the use of aluminum in ships because of the fire hazard. McCoomb, A.H. and Ee Be Zenberg ("State Room Fire Test", Trans. S.N.A.M.E., 1950) showed that unprotected aluminum was not adequate to resist the temperatures generated by the type of fire which could orginate in a cabin. Aluminum can melt and this means that fire could spread from one compartment to another and that complete failure of the structure could take place. This is particularly important in the passanger ships where the requirements of the International Convention for the Safety of Life

at Sea have to be met. Broadly speaking, these requirements, so far as the present problem is concerned, require that certain divisions (i.e. bulkheads or parts of decks) must be able to stand up to specified fire conditions for a given length of time. To achieve these conditions with aluminum, it is obviously necessary to insulate the material. This has been done successfully with asbestos board. The detailed results of tests and determination of thickness of board required are to be found in a paper by J. Venus and E.C. Corlett, "Fire Protection on Passenger Ships" (Transactions, R.I.N.A., 1915). It is not in the scope of this work to consider the details of that paper, but aluminum has been accepted as complying with requirements for "A" class divisions if insulated as described in that paper (30).

The problems of insulation raise another source of extra cost and a decrease in the weight saving for aluminum versus steel.

6.8 Economics of Aluminum

In the broad sense, the two outstanding advantages of aluminum that attract the ship owner, operator and builder are its light weight and its corrosion resistance. Properly applied, these properties can improve performance and

TABLE 6

Approximate Tanker Costs of Steel and Aluminum (33)

	130'		219'	
	London Design Tanker		German Tanker "Aluminia"	
	Steel	Alum.	Steel	Alum.
Length (B.P.)	130'	130'	219'2"	219'2"
Beam	25'6"	25'6"	26'8"	26'8"
Depth of Hull	9'	9'	12'1"	12'1"
Barrels cubic cap.			8365	8365
Hull weight (H) L.T.	127.0	54.2	241	91
Machinery weight (M) L.T.	9.7	9.7	67	67
Outfit weight (O) L.T.	23.3	18.7	26	26
Light ship L.T.	160.0	82.6	334	184
Total deadweight L.T.@Listed Draft	505 (1)	582	800 375	950 525
Deadweight gained		77.4		150

	130'		219'	
	London Design Tanker		German Tanker "Aluminia"	
	Steel	Alum.	Steel	Alum.
Hull steel at 7 1/2¢/#	$21,400		$40,500	
Hull alum. at 50¢/#		-60,500		-100,000
Hull labor at 21¢/# steel	60,000	60,000	114,000	114,000
Machinery cost	35,000	35,000	200,000	200,000
Outfit cost @ $2500/T	58,500	46,000	65,000	65,000
Alum. extra items (15% M + O)		14,000	--	40,000
Coating tanks	--	--	--	--
TOTAL COST (U.S.)	$174,900	$216,000	$419,500	$519,000

influence the economic picture. Only from the first of these may it be stated that up to 60 percent of the weight of a steel structure may be saved

Weight saving of this magnitude is extremely important from a design point of view and, were it not for the fact that aluminum is much more expensive than steel, very large applications of the material in ships could be expected. Table 6 shows that the total initial cost of aluminum is about 20 percent greater than steel construction, a fact in agreement with many publications (26,30,33) This means that the annual charges, which are a function of first cost, will be about 10 to 12 percent greater. Therefore, the aluminum ship should have higher earnings by an amount necessary to cover this extra cost.

Those earnings are considered possible because of the extra carrying capacity of aluminum ships, the savings in coating protection, the probable higher velocity, and other secondary factors ($^{5}\ ^{13}_{26}\ ^{6}$). The overall economic evaluation of an aluminum ship is then approximately the same as a steel ship. This is shown in Table 7 prepared by Professor Harry Benford (Discussion, 5)

Although we have concluded that the use of aluminum in ship building does not have a clear economic advantage influence the [illegible] these may it [illegible] weight of a [illegible]

Weight [illegible] from a design [illegible] that aluminum [illegible] large applications [illegible] expected. [illegible] aluminum is [illegible] a fact in [illegible] This means that [illegible] of first [illegible] Therefore, [illegible] by an amount [illegible]

Those [illegible] extra carrying [illegible] costing pro[illegible] other secondary [illegible] evaluation [illegible] the same [illegible] prepared [illegible]

Although [illegible] in ship [illegible]

TABLE 7

Relative Economics of Aluminum and Steel-Hulled Ocean Ore Carriers

Hull	Steel	Aluminum
Weights (in long tons)		
Structural hull............	10,600	4,240
Outfitting.................	1,678	1,678
Machinery..................	882	882
Light ship.................	13,160	6,800
Fuel, fresh water, etc.....	3,730	3,730
Cargo capacity.............	36,220	42,570
Displacement...............	53,100	53,100
Building Costs ($1,000)		
Structural hull matl.......	2,566	6,360
Structural hull labor......	2,400	2,640
Outfitting matl............	3,055	3,055
Outfitting labor...........	1,606	1,767
Machinery matl.............	2,330	2,330
Machinery labor............	438	481
Total material.............	7,951	11,745
Total labor................	4,444	4,888
Total overhead (70%).......	3,111	3,422
Sub-total..................	15,506	20,055
Profit (5%)................	775	1,003
Total for one ship.........	16,281	21,058
Total for each of 5 ships..	13,853	17,917

Hull	Steel	Aluminum
Required Freight Rate		
Annual operating costs....	\$1,574,000	\$1,574,000
Annual costs of capital... recovery (CRF=0.175)....	\$2,424,000	\$3,135,000
Average annual cost.......	\$3,998,000	\$4,709,000
Annual transport capacity, long tons..............	186,400	219,000
RFR......................	\$ 21.45	\$ 21.50

over steel construction, there are cases where weight savings, lower draught, increase deadweight, or reduction in power will make the use of aluminum very attractive to the designer.

7. WELDING

7.1 Welding Generalities

Today, about 40 different processes, used in various applications, are available commercially to join metals. These joining processes can be classified into the five basic categories (1,56):

1) Fusion welding, where the parts to be joined are heated until they weld together. Pressure is not a requisite. Examples are arc welding, gas welding, and electronbeam welding.
2) Electrical resistance welding, which first involves heating by passage of air electric current through the parts to be welded, and, second, the application of pressure. Examples are spot welding, upset welding, and percussion welding.
3) Solid-phase welding, in which pressure is applied but the metals to be joined do not welt, except in very thin layers near the surfaces to be joined. Examples are forge welding, friction welding and pressure welding.
4) Liquid-solid phase joining, in which the parts to be joined are heated to a temperature lower than their melting points and a dissimilar molten metal

is added to form a solid joining upon cooling. Examples are brazing and soldering.

5) Adhesive bonding, in which joints are formed as a result of the molecular attraction exerted between the surface to be bonded and the adhesive. Examples of adhesives are animal and vegetable glues, cements, asphaltenus and various plastic such as epoxty.

The term "welding" is used for those processes included in categories one through three. The development of modern welding processes, including fusion welding processes, started to take place around the late 1800's when the use of electrical energy became available. Welding processes which were originally developed in this period and still are used widely today include metal arc welding, electric resistance welding, and oxyacetylene welding. Electric resistance welding is used widely today for the fabrication of automobile bodies, various aircraft parts, etc. Oxyacetylene welding is also used to join sheet metal, plate and pipe. However, the metal-arc welding is, by far, the most commonly used today for the fabrication of large structures such as ships, pressure vessels, and buildings (1).

The phenomenal growth in the use of arc welding started after Kjellberg, a Swede, introduced covered

electrodes in about 1910. From this time on, numerous types of covered electrodes were developed. Coating, which melts simultaneously with the core rod, performs several functions, including stablizing the arc, producing gases to shield the arc from the surrounding air, reacting with the molten metal and purifing it. It also produces slag to cover the solidified metal and provides slow cooling and possible further reaction between the welding metal and the surrounding atmosphere (35). Even though many welding processes have been developed recently, the shielded metal-arc welding, using a covered electrode, represents a major part of the welding industry today, especially in the welding of ordinary carbon steel which is still the largest part of the welding business in dollars as well as in tonnage.

The 1930's saw another upsurge in new joining processes, due partly to the greater use of welding and an increased application of all joining processes in World War I. Efforts to mechanize metal-arc welding processes in the U.S. led to various automatic arc welding processes including submerged arc welding (49).

During the 1930's, when aluminum alloys were increasingly used for airplane structures, attempts were made to develop a technique for successfully welding

these metals. Light metals, such as aluminum and magnesium, are chemically active and difficult to weld with covered electrodes and oxyacetylene blow-pipes. Weld metals were porous, and chloride and fluoride compounds, which were used as flux, produced toxic fumes and corrosive slags. Two Americans, Hobart and Dever, experimented with an electric arc, operating in an inert gas atmosphere. These experiments led to the development of the inert gas tungsten arc, or TIG process, and in the 1940's, the inert gas metal arc, or MIG process, was introduced. In TIG welding, the tungsten electrode does not melt and a filler wire is used, normally, to provide the weld metal while, in MIG welding, the metal electrode is melted and consumed. Argon and helium are commonly used for the shielding gas (1).

Success in the inert gas welding of stainless steel and ordinary carbon steel was not reached until the 1950's. A key to this success was the addition of a small percentage of oxygen to the inert shielding gas which improved welding characteristics without adversely affecting the weld metal properties. In the late 1950's, it was found that a very common material, CO_2, sometimes with the addition of oxygen, could be used for welding steel. The CO_2 shielded process is the fastest growing

welding technique today (35).

During the last 15 years, many new welding processes have been developed, such as:

1) electroslag welding,
2) electrogas welding,
3) ultrasanic welding,
4) friction welding,
5) electronbeam welding,
6) plasma welding,
7) high-frequency resistance welding, etc.

7.2 Brief History and the Present State of the Art of Welding Aluminum

A review of aluminum welding reveals that along with the tremendous growth of this technology came new aluminum alloys and new welding methods. Behind all of this growth stands the ever increasing strength of aluminum welds. These increases in weldment strength came about as new plate and filler alloys were joined by various welding methods. In tracing these developments, we must deal principally with alloys that were commercially weldable with the techniques available at different stages in the history of the art. Throughout the 60 years of that history there runs the vital thread of filler alloy characteristics.

The history of aluminum fusion welding is quite recent, since it apparently lies entirely within the twentieth century. As recently as 1905, aluminum welding was still limited to forge welding. This "autogeneus soldering" employed a soldering pipe for the heat source and hammering to effect the bond. Fusion welding with oxyacetylene arrived in 1906 (49).

At first, the weld strengths attainable in certain alloys undoubtedly depended on the welding process. The oxyacetylene and oxyhydrogen processes were the recognized fusion welding processes for almost the first thirty years of aluminum welding. By 1934, the arc welding process, using flux-coated aluminum electrodes, was well enough developed for commercial application. From the mid 1930's through the World War II years, aluminum was welded by the carbon arc process, but references to weld strengths of carbon arc aluminum are scarce. The mechanized carbon arc process was said to produce better quality welding that gas welding. Moreover, it was faster. The greater flux consumption, however, kept the overall cost about the same as the cost of gas welding (9).

In 1940, Northrop Aircraft, Inc. developed the helium-shielded tungsten-arc process and applied it

to the commercial welding of magnesium. The Linde Company acquired the Northrop invention in 1942 and undertook further development. The Linde efforts led to the commercial introduction of helium or argon shielded tungsten-arc process in another year or so. In 1948, the Air Reduction Company introduced the inert gas-shielded metal-arc process. With the advent of gas shielding, a big growth of aluminum welding began. The inert gas-shielded arc processes made it possible to weld nearly any aluminum alloy. Inert gas arc welding has almost entirely replaced the earlier processes for aluminum welding.

Table 8 gives the nominal composition of some aluminum filler alloys now in common use. A few of them date back several decades (9).

If we assume that the first alloy welded was commercially pure aluminum (1100 alloy), welded autogenously or with similar filler, we should expect joint strengths of about 11,000 psi. We can place the commercial use of 3S (3003) alloy joints at about 1916. If they were welded with 1100 filler, as was recommended in the early days, joint strengths should have been about 14,000 psi (9).

TABLE 8

Nominal Compositions of some Aluminum Filler Alloys

	Per Cent Alloying Element by Weight							
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	
1100	1.0 max	Si+Fe	*						
4043	5.2							0.20 max	
4145	10.0		4.0						
5052					2.5	0.25		0.20 max	
5154					3.5	0.25		0.20	
5554				0.7	2.7	0.12		0.13	
5356				0.12	5.0	0.12		0.15 max	
5183				0.7	4.7	0.15		0.12	
5556				0.7	5.1	0.12		0.12	0.15 Zr
5180				0.5	4.0		2.2	0.10 max	
5039		0.25		0.4	3.8	0.12	2.8	0.15	0.10 V
2319			6.3	0.3					0.15 Zr

* - Not intentionally added, and usually controlled to a maximum.

In the 1920's, the aluminum of five percent silicon alloy came into use as a casting alloy. It was also recommended as a weld filler in crack-prone alloys and in highly restrained assemblies. This is the versatile filler we now know as 4043. We can assume that it was used even then to weld 3003 alloy sheet and plate, with joint strengths of about 16,000 psi.

During the 1920's, some heat-treatable alloys were available and were being welded. Apparently, they were not often heat-treated after welding. However, Al-Si-Mg alloy 51S (6051) gave as-welded joint strengths of 26,000 psi when oxyacetylene welded with 4043 filler. Al-Cu-Mg alloy 17S (2017) was reported to have an as-welded tensile strength of 40,000 psi, but the welds were probably too brittle for commercial use.

The aluminum-magnesium alloys had little application prior to the 1930's. The Al - 2.5% Mg - 0.25% Cr alloy 52S (5052) was introduced in about 1936. When arc welded with 4043 flux-coated electrode, butt weld tensile strengths reported in 1938 were 27,000 psi. In 1945, the strength reported for inert gas-shielded tungsten-arc welds in 5052 plate was 30,000 psi, when 4043 filler was used.

From 1945 on, the aluminum fusion weldment properties

reported were almost entirely for the inert gas-shielded arc processes. Magazine articles on welding appeared much more frequently, probably because of the increased use of aluminum, and because welding was so readily done by inert-gas arc. We need no longer interpolate weld strengths by matching available plate and filler alloy because reported data are available. Tables 9a and 9b list the strengths of welds reported from 1930 to 1966. The bulk of the data are for inert gas-shielded welds reported since 1945 (9,49).

Through 1950, certain heat-treatable alloys gave the highest as-welded joint strengths. In 1951, the 5% Mg alloy 56S (5056) brought the Al-Mg alloys into use. Then Al-Mg-Mm alloys 5086, 5083 and 5456, with their corresponding filler, boosted the strengths of as-welded joints well into the 40,000 psi range. In the early 1960's, the weldable heat treatable Al-Zu-Mg alloys entered the picture with still higher weldments strengths. Of those commercially available, alloy 7039 produces the strongest untreated welds.

Selection of the arc welding method to use in joining aluminum depends largely upon the individual application. Factors such as thickness or gage of metal, design of parts, components or assemblies, production

TABLE 9a

Strengths of As-welded Joints Reported During Certain Years

Year Reported	Alloys Plate	Alloys Filler	Butt Weld TS,psi
1930	6051	4043	26-27,000
1938	5052	4043	27,100
1945	5052	4043	30,000
1945	6061	4043	31,000
1946	2024	4043	27-33,000
1948	6061	4043	28-32,000
1949	2024	4145	38,200
1951	2014	4043	40,700
1952	5056	5056	41,000
1953	2024	4145	44,000
1955	5083	5083	41,000
1958	5456	5456	42-46,000
1958	5083	5183	42,000
1962	5456	5556	42-47,000
1966	7039	5039	48-52,000

TABLE 9b

Strengths of Heat-Treated Welds

Reported During Certain Years

Year Reported	Alloys		Butt Weld TS,psi
	Plate	Filler	
1930	6051	4043	32-33,000
1945	6061	4043	44,000
1949	6061	4145	46,300
1949	2024	4145	50,800
1949	2024	2024	55,700
1953	2024	4145	48,000
1958	2014	4043	56,000
1958	2014	2014	59,000
1961	2219	2319	65,500
1961	2014	2319	69,700
1966	7039	5039	63,000

quantities and available equipment must be considered.

The best welding methods for aluminum are the tungsten inert gas arc (TIG) and the metal inert gas arc (MIG) processes. Both use inert gas (argon,helium or mixtures) to keep air away from the arc and molten weld pool, thus eliminating the use of a welding flux (30,26).

The TIG process is preferred for welding aluminum sections less than 1/8 of an inch in thickness. This method can also be used on heavier sections but the MIG process is usually chosen for its higher welding speed and economy. There are many others that can be used as resistance welding, adhesive bonding, etc., but the MIG and the TIG processes are the ones used widely, and we can say that they have proven merits in welding aluminum. Chilean Navy Shipyards have a certain experience in the use of the MIG process, mainly in repairs, welds, and aluminum plating in superstructures. TIG equipment has been also ordered.

As we can see, personnel (welders, engineers) training in these two processes is needed. This can be done through training provided by the suppliers of the equipment or through Institutions recognized by Classification Societies.

This step is basic to avoid future problems if aluminum

or other many materials weldable by these process are going to be used in the fabrication of large structures.

7.3 Physical Properties

This section discusses some physical properties which affect welding of aluminum.

7.3a Melting Point of Aluminum

Pure aluminum melts at 1,220°F, while weldable commercial aluminum alloys start to melt at 1,050°F. This compares with steel melting at about 2,800°F, and copper melting at approximately 1,980°F. Unlike these metals, there is no color change in aluminum during heating. However, it is possible to know when the aluminum is near its melting point at welding temperature by watching the weld pool. The TIG weld pool, for example, develops a glossy appearance, and a liquid pool or spot forms under the arc when the metal becomes molten.

7.4 Problems in Welding Aluminum

Instead of describing in detail the different methods of welding, it is more important to consider the problems associated with the welding process, such as distortion, porosity, buckling, incomplete fusion, inadequate penetration, cracking, inclusion, fatigue, etc.

Due to the improvements in nondestructive testing techniques employing x-ray, ultrosonic and other devices,

an increasing number of small defects can be detected. Many of these defects would have gone unnoticed in previous years. Unfortunately, however, the ability to judge the effect of a given defect has not kept pace with test equipment discoveries. Because of the disparity, acceptance standards are usually based on the best products which can be repeatedly produced under laboratory or nearly ideal field conditions (56). This causes more repair work most of the time with detrimental results. It is necessary to find some way to determine what defects, in what scope, how big and so on, could be accepted for a specific structure. It is important to establish realistic inspection standards that consider not only the existence of defects, but also the severity and importance of these defects.

If we look at the development of new structures, such as missiles, space rockets, planes, deep diving submarines, etc., we see that a great deal of problems were solved, such as NASA's sponsored research programs in fusion welding, high-strength heat treated aluminum alloys to improve weld quality performance and reliability on space vehicles. If we are thinking of building huge ships completely out of aluminum, alot of problems can be considered solved for actual uses of this material, but

new problems are going to arise, such as methods and costs of fabrication, suitability as material for ship structure, fatigue and corrosion resistance characteristics of base plates and weldments, as well as structures fabricated with this material, etc.

Among the different problems found in aluminum welded joints are: inadequate penetration, inadequate fusion, undercutting, slag inclusion, concavity and convexity, all of which are avoidable and must be guarded against. Others, such as porosity, heat affected zone and distortion are not avoidable, but can be minimized.

7.4a Porosity

Aluminum alloys are subject to certain types of weld defects, especially porosity. Every attempt should be made to minimize porosity. Sources of porosity in aluminum weldments can be classified as: contamination of shielding gas, contamination of the joint or filler metal surfaces and composition of base plate and filler metal.

1. Shielding Gas Contamination

It has been found that shielding gas contamination can be one of the major sources of porosity in aluminum weldments, also that commercial shielding gas is normally, acceptably pure as received (23). Reports have been new problems are

of fabrication,

fatigue and

plates and

with thin

Among the

welded joints

fusion,

convexity,

against. Other

distortion

7.4a

Aluminum

weld defects,

be made to

aluminum

of shielding

metal

metal.

1.

It

can be

acceptabl

written by investigators of NASA saying that it was always necessary to intentionally contaminate the shielding gas to produce an appreciable amount of porosity in welds made in the laboratory with proper procedures. The same investigators studied the effect of individual gas contaminants by making welds in an atmospheric-control chamber containing various levels of gas contamination. The metal studied was 1/4 inch thick, 2219-T87 aluminum alloy, welded in the horizontal position by the G.T.A. process using 1/16 inch diameter, 2319 aluminum alloy filler wire. The conclusion was that: increasing hydrogen concentration increased porosity, increasing water vapor increased porosity, increasing oxygen did not increase porosity, and increasing nitrogen had little effect on porosity.

Figure 5 (23) shows the contamination levels where occurrence of a weld-quality change is initially observed. The figure indicates that 250 ppm. of either hydrogen or water vapor was necessary before significant quality changes were observed.

However, gas contamination can occur within the bottle, or sometimes between the bottle and the torch nozzle. Contamination could occur in a partially empty bottle, for instance. Or, it could occur due to defective connections in the tubing system. For these

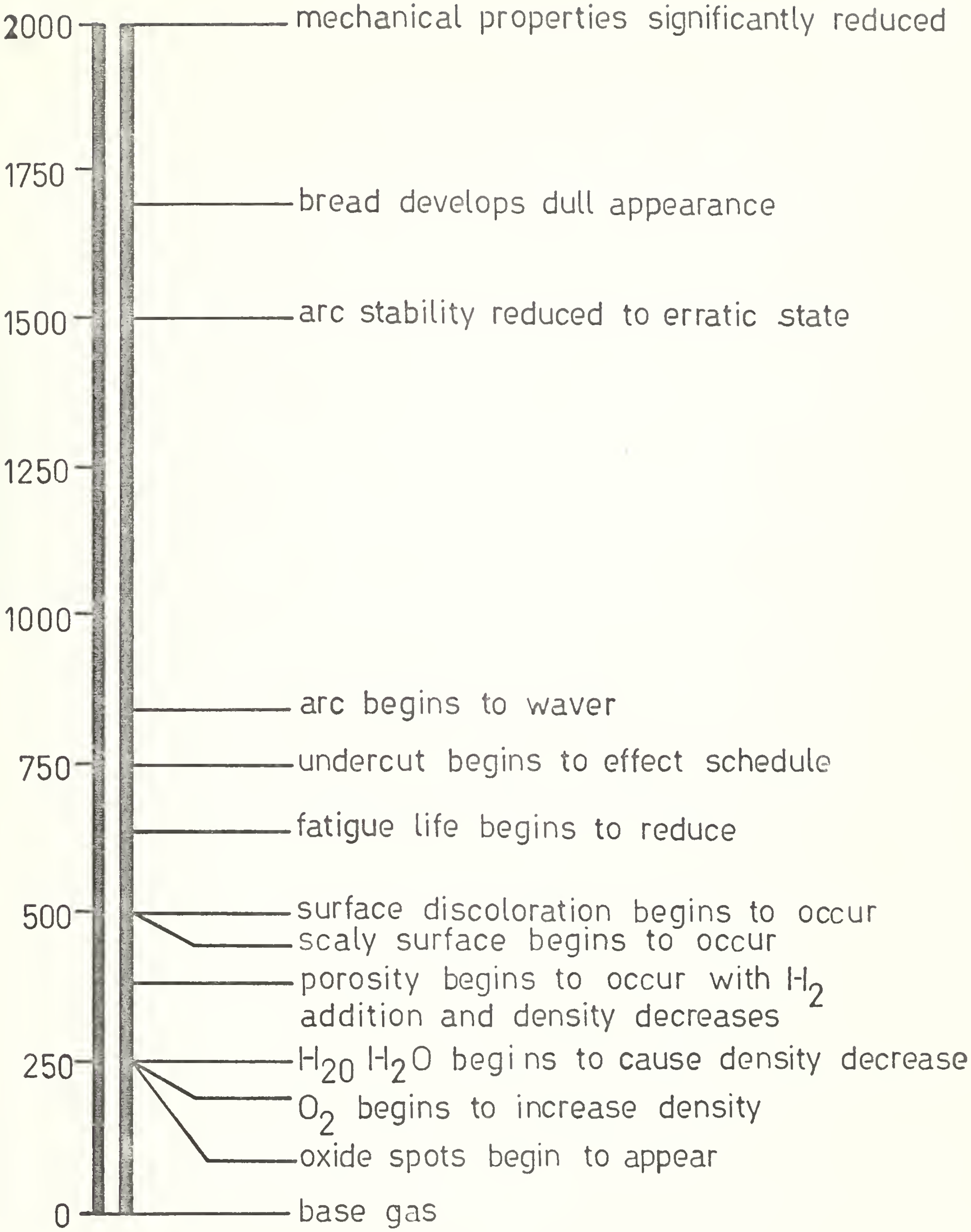


FIGURE 5. CONTAMINATION CONCENTRATION LEVELS AT WHICH SIGNIFICANT CHANGES OCCUR IN WELD QUALITY.

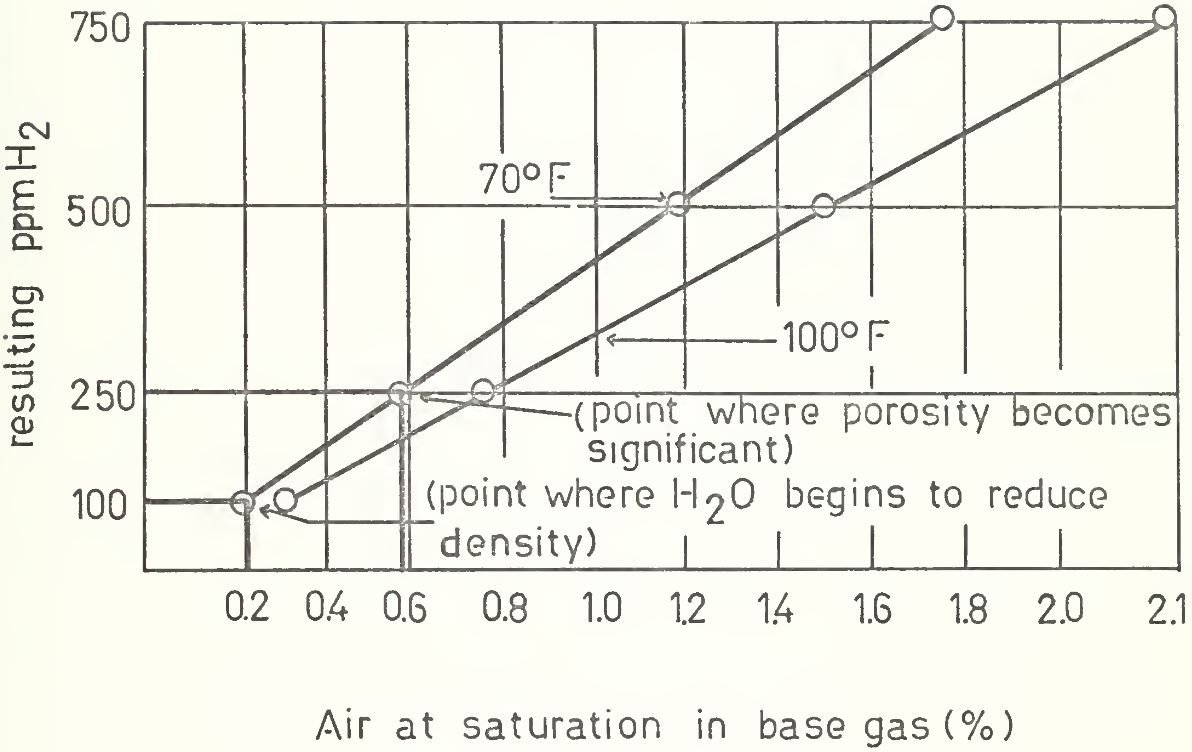


FIGURE 6. VOLUME OF WATER AVAILABLE TO WELDMENT FROM SATURATED AIR CONTAMINATION

reasons, a device to check the purity of gas at the torch nozzle may be advised. However, Figure 5 should be only a guide, remembering that these data are based on welds made in an atmospheric control chamber. Under open conditions, results could be expected to differ from these.

In these experiments, metallographic specimens were cross-sectioned and examined in the polished and etched conditions. Porosity was localized in the weld metal along each side of the weld bead.

2. Surface Contamination

It is believed that contamination of the base metal and the filler metal is an important factor causing porosity. Hydrogen gas is available by decomposition of hydrocarbon on the weld groove. It is assumed that hydrocarbon will decompose completely to gases by the welding arc and they will become gaseus contaminants (23). Boeing investigators claim that it is required less than 1 mg. of hydrocarbon per inch of weld to continuously generate 250 ppm hydrogen in the shielding gas. Since it is estimated that a single finger print would result in a 750 ppm hydrogen increase in the area contaminated, we see that this can cause significant increases in

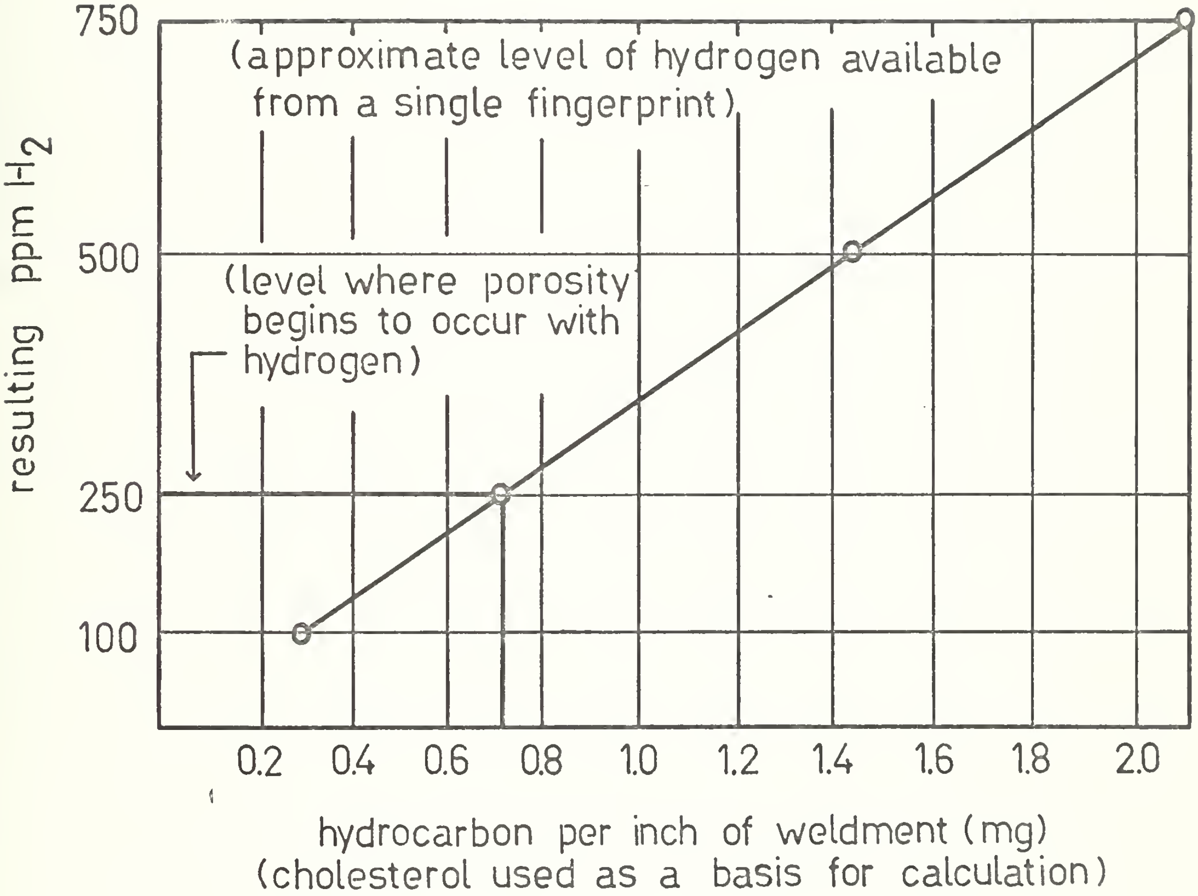


FIGURE 7. CALCULATED VOLUME OF HYDROCARBON AVAILABLE TO WELDMENT FROM HYDROCARBON CONTAMINATION.

porosity. It has been also proved that conventional and recommended surface treatments such as solvent degreasing, chemical cleaning, and water rising promote the formation of porosity. The best conditions were found in specimeneus welded in the as-machined condition. When possible to avoid potential defects due to surface contamination, it is recommended to machine surface immediately before welding to insure a clean surface (16).

3. Composition of Base Plate and Filler Metal

There is not enough data to make any conclusions on the role of base plate and filler metal composition in porosity formation. It is only known that base plate and filler metal composition are not likely to be significant sources of porosity as long as shielding gas and surface contamination are controlled at low levels and base plates and filler metals are carefully prepared to meet the present specifications with no gross hydrogen contamination (24).

7.4b Effects of Porosity Level on Weld-Joint Performance

Ultimate tensile strength of a transverse-weld specimen decreases with increasing porosity. Theoretically, this loss in strength should be approximately proportional to the loss of sectional area due to porosity. Some porosity. It has been [illegible] and recommended [illegible] degreasing, chemical [illegible] the formation [illegible] found in specim[illegible] When possible [illegible] contamination, [illegible] immediately before [illegible]

3. Composition [illegible]

There is [illegible] on the role of [illegible] in porosity [illegible] and filler metal [illegible] significant [illegible] gas and surface [illegible] levels and [illegible] prepared to [illegible] hydrogen content [illegible]

7.4b Effects [illegible]

Ultim[illegible] specimen [illegible] this loss [illegible] to the lo[illegible] experimental results disagree with this theory, showing that a five percent loss of sectional area caused as much as 30 percent reduction in strength, believed to be due to a large number of very fine pores which were not counted as lost of sectional area (Only pores 1/64 inch in diameter were counted.).

Fatigue life decreases with porosity, however, no data is available to measure these effects quantitatively for different aluminum alloys (16,24).

Figure 8 shows experimental results, made at Bottelle Memorial Institute, of strength versus pore area for 2219-T87 aluminum alloy.

Proved that hydrogen contamination is a major factor in producing porosity, some attempts were made to find methods of reducing porosity such as proper surface preparation, cleanliness precautions during the handling of the material, hydrogen getters, molten Puddle stirrer and cryogenic cooling. Among the last three methods, no significant reduction of porosity was obtained. It was, therefore, concluded that more experimental study should be carried out before conclusive statements can be made about this problem (24).

7.4c Heat Affected Zone in Aluminum Welding

Another major problem we find in aluminum welding

experimental results
that a five percent
as 30 percent
to a large
counted as lost
in diameter very

Fatigue life

no data is
for different

Figure

Memorial
aluminum

Proved

in producing
methods of
preparation,
of the
and cryogenic
significant
therefore,
be carried
about this

7.4c

Another

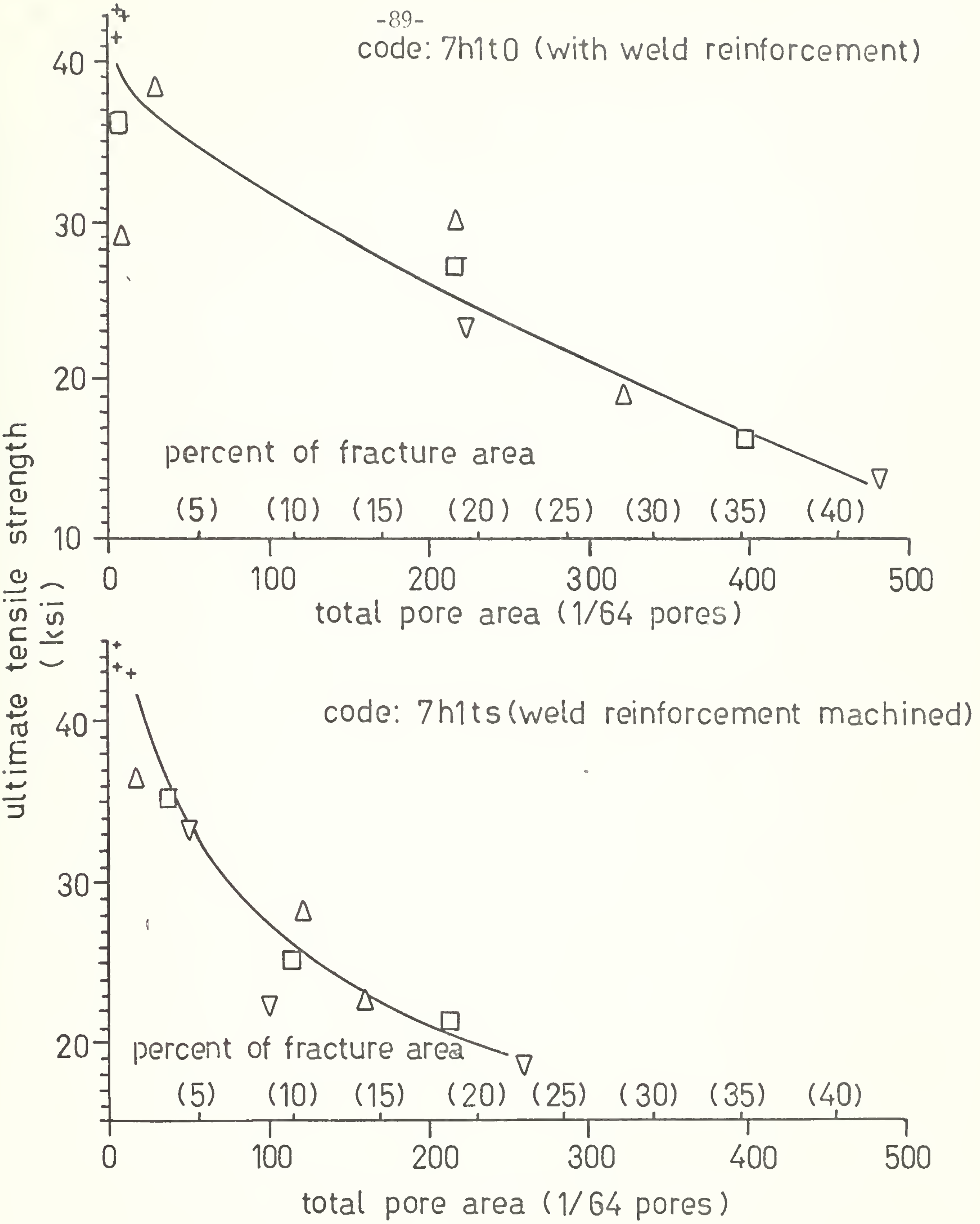


FIGURE 8. STRENGTH VERSUS PORE AREA, 2219-T87, HORIZONTAL WELD 1 4 IN. TRANSVERSE TEST

is the detrimental effects in strength caused by the heat input during welding.

Heat input is defined as:

$$\frac{V \times I \times 60}{S \times T} \quad (\text{Joules}/\text{m}^2),$$

where

V = arc voltage, volts

I = welding current, amper

S = arc travel speed, i.p.m.

T = plate thickness, inches

It has been proved by experimental analysis that ultimate tensile strengths of welded joints decreased as welding heat input increased, regardless of the welding process or the material thickness. The higher weld strength obtained by using low heat input is believed to be due to a reduced thermal effect and the geometrical effect of a narrow weld, both contributing to results in a heat-affected zone with higher strength metallurgical structures. A joint with a very narrow weld-metal area, but with a heat-affected zone with lower strengths than the base metal, still has nearly the same fracture strength as the base metal (57).

This loss in strength is critical when loads are applied normal to the direction of welding and has little effect when the major stress acting on a joint is parallel to the joint.

Electron beam welding process is the more successful mean to produce narrow weld metal areas and heat affected zones, but it is not actually available as an industrial process for joining large assemblies, the reason being that electron beam welding must be made in a vacuum chamber limiting its use to small joints (1).

Attempts have been made to reduce the heat conducted in the base plate during welding by means of cryogenic cooling, keeping in mind to obtain the same effect as the reduction of welding heat input (58). The result showed an increase in strength in a range from five to ten percent which was considered insignificant unless it occurs in a very critical range (16). The main efforts are to be made in reducing heat input. Attempts, such as cryogenic cooling, molten-puddle stirring, and relating different parameters affecting welding, were studied, but each of them was highly sophisticated, requiring very closely controlled conditions and highly trained personnel. However, the results have not yet been satisfactory or

reliable.

7.4d Distortion

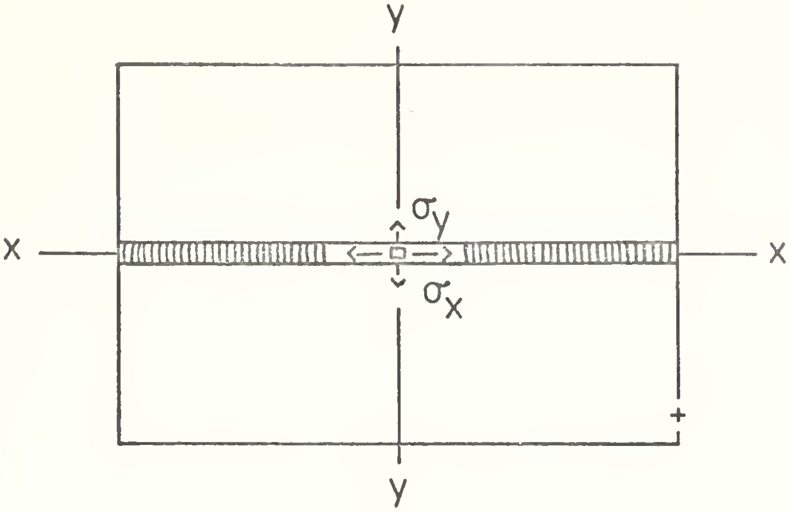
Residual stresses are those that would exist in a body if all external loads were removed. Residual stresses in metal structures occur for many reasons during various manufacturing stages, including rolling, casting, machining, flame cutting, and welding.

When a weldment is locally heated by the welding heat source, the temperature distribution in the weldment is not uniform and it changes as welding progresses. During the welding cycle, complex strains occur in the weld metal and base metal regions near the weld, both during heating and cooling. The strains produced during heating are accompanied by plastic upsetting. The stresses resulting from these strains combine and react to produce internal forces that cause bending, buckling, and rotation. It is these displacements which are called distortion.

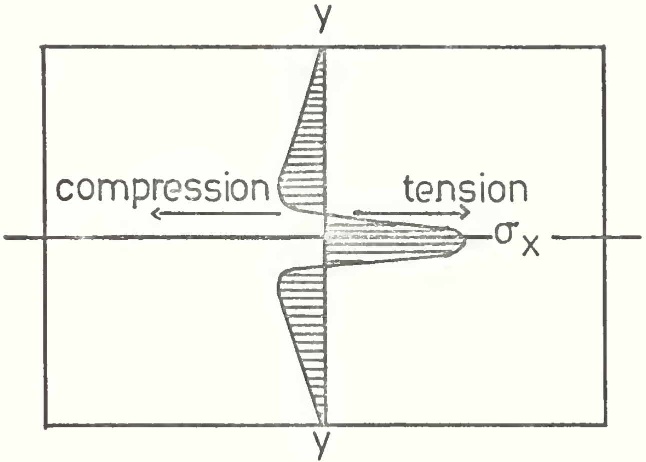
The residual stresses in a welded joint are caused by the contraction of the weld metal and the plastic deformation produced in the base matal region near the weld. Residual stresses are those which occur in a joint, free from any external constraint. Locked-in stresses are those induced by an external constraint.

Figure 9 shows a typical distribution of residual stresses in a butt weld (17). The stresses parallel to the weld direction are designated σ_x and those transverse to the weld are designated σ_y. Tensile stresses of high magnitude are produced in the region of the weld, tapered off rapidly and becoming compressive at a distance several times the width of the weld. The weld metal and heat-affected zone try to shrink in the direction of the weld, and the adjacent plate material prevents this shrinkage. σ_y tensile stresses of relatively low magnitude are produced in the middle of the joint, and compressive stresses are observed at the end of the joint. If the contraction of the joint is restrained by the external constraint, the distribution of σ_y is as shown by the dotted line in Figure 9 . An external constraint, however, has little influence on the distribution of σ_x residual stresses.

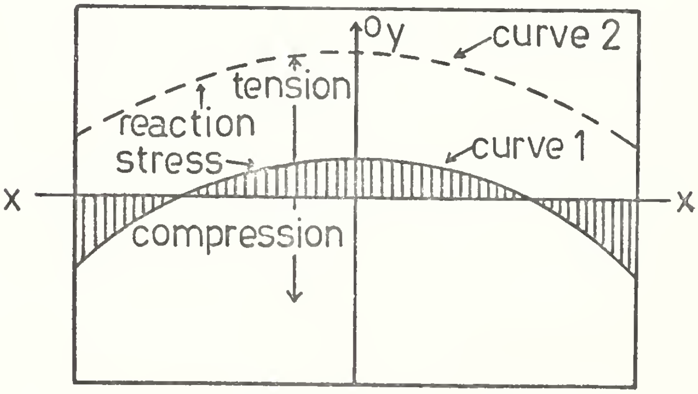
The magnitude and distribution of residual stresses in a weld are determined by expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle and temperatures versus yield-strength relationships of the base metal and the weld metal. Research in carbon-steel weldments has shown that the maximum residual weld stress is as high as the yield stress of the weld metal, as a good



(a) butt weld



(b) distribution of σ_x along yy



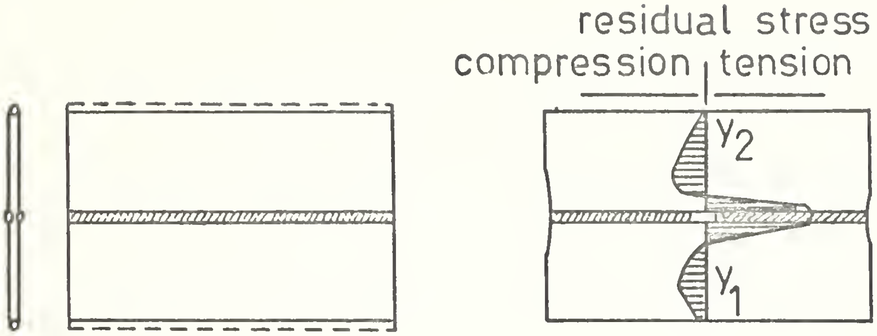
(c) distribution of σ_y along xx

FIGURE 9 TYPICAL DISTRIBUTION OF RESIDUAL STRESSES IN BUTT WELD

approximation. The distortion found in fabricated structures is caused by three fundamental dimensional changes which occur during welding: transverse shrinkage which occurs perpendicular to the weld line, longitudinal shrinkage which occurs parallel to the weld line and an angular change that consists of rotation around the weld line. These dimensional changes are shown in Figures 10 & 11. Distortions which occur in practical weldment are far more complex than the ones shown.

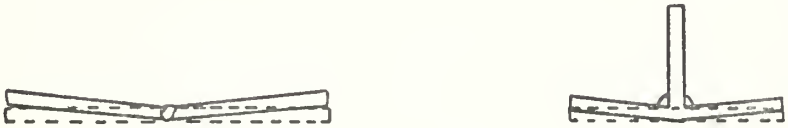
Figure 13 shows how residual stresses are formed in a weld. Along section A-A which is ahead of the welding arc, the temperature change due to welding, DT, is almost zero. Along section B-B which crosses the welding arc, the temperature distribution is very steep. Along section C-C which is the same distance behind the welding arc, the distribution of temperature change shows a lesser slope. Along section D-D, which is very far from the welding arc, the temperature change due to welding again diminishes.

Stresses in areas underneath the welding arc are close to zero, because molten metal does not support loads. Stresses in areas somewhat away from the arc are compressive, because the expansion of these areas is restrained by surrounding areas which are heated to



(a) transverse shrinkage in a butt weld

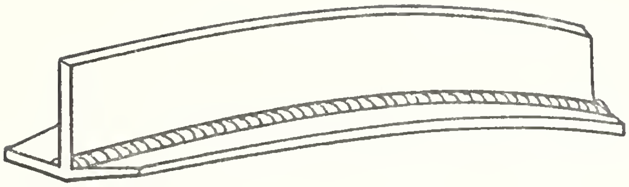
(b) longitudinal shrinkage in a butt weld (distribution of longitudinal residual stress O is also shown)



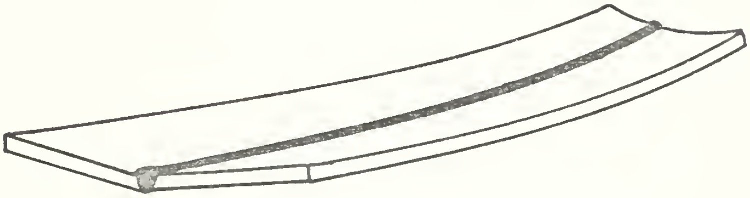
(c) angular change in a butt weld

(d) angular change in fillet weld

FIGURE 10. FUNDAMENTAL DIMENCIONA CHANGES THAT OCCUR IN WELDMENTS



(a) longitudinal distortion of a build-up beam



(b) longitudinal bending distortion of a single-vee butt weld

(c) buckling distortion·

FIGURE 11. DISTORTIONS INDUCED BY LONGITUDINAL SHRINKAGE

lower temperatures. Since the temperatures of these areas are quite high and yield strength of the material is low, stresses in these areas are as high as the yield strength of the material at corresponding temperatures. The amount of compressive stress increases with increasing distance from the weld or with decreasing temperature. However, stresses in areas away from the weld are tensile, and balance with compressive stresses in areas near the weld. In other words,

$$\int \sigma_x \, dy = 0$$

neglecting the effect of σ_y and τ_{xy} on the equilibrium condition. Stresses which are distributed along section C-C are shown in Figure 13. Since the weld metal and base metal regions near the weld have cooled, they try to shrink, which causes tensile stresses in areas close to the weld. As the distance from the weld increases, the stresses first change to compressive and then become tensile;along section D-D, high tensile stresses are produced in areas near the weld, while compressive stresses are produced in areas away from the weld.

To analyse residual stress and distortion completely

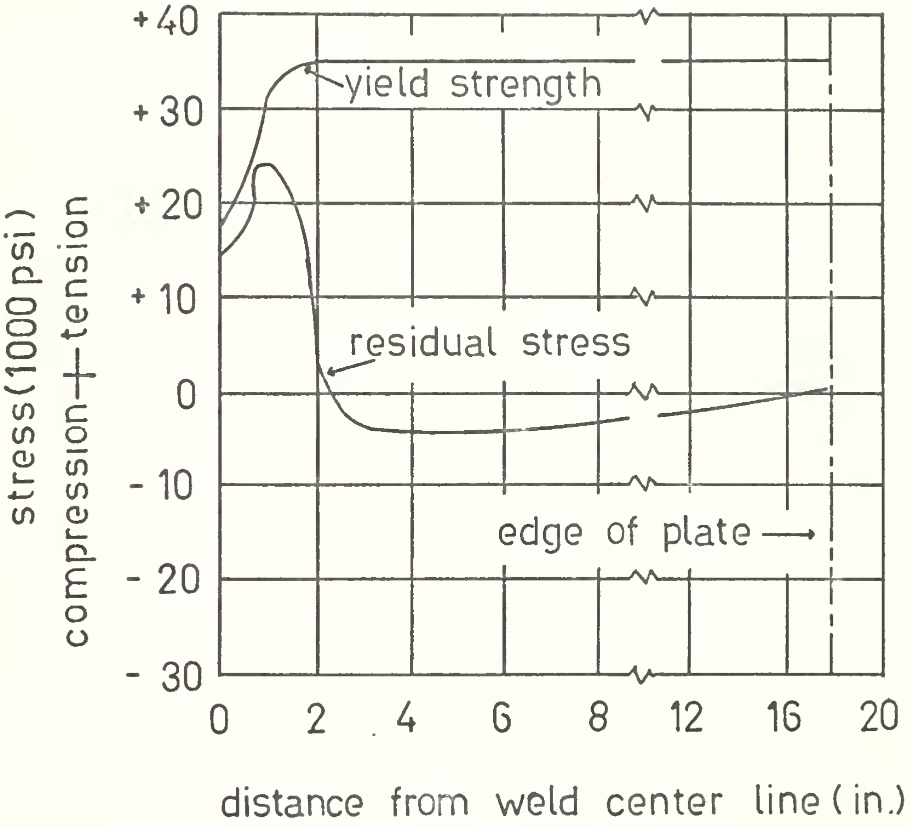
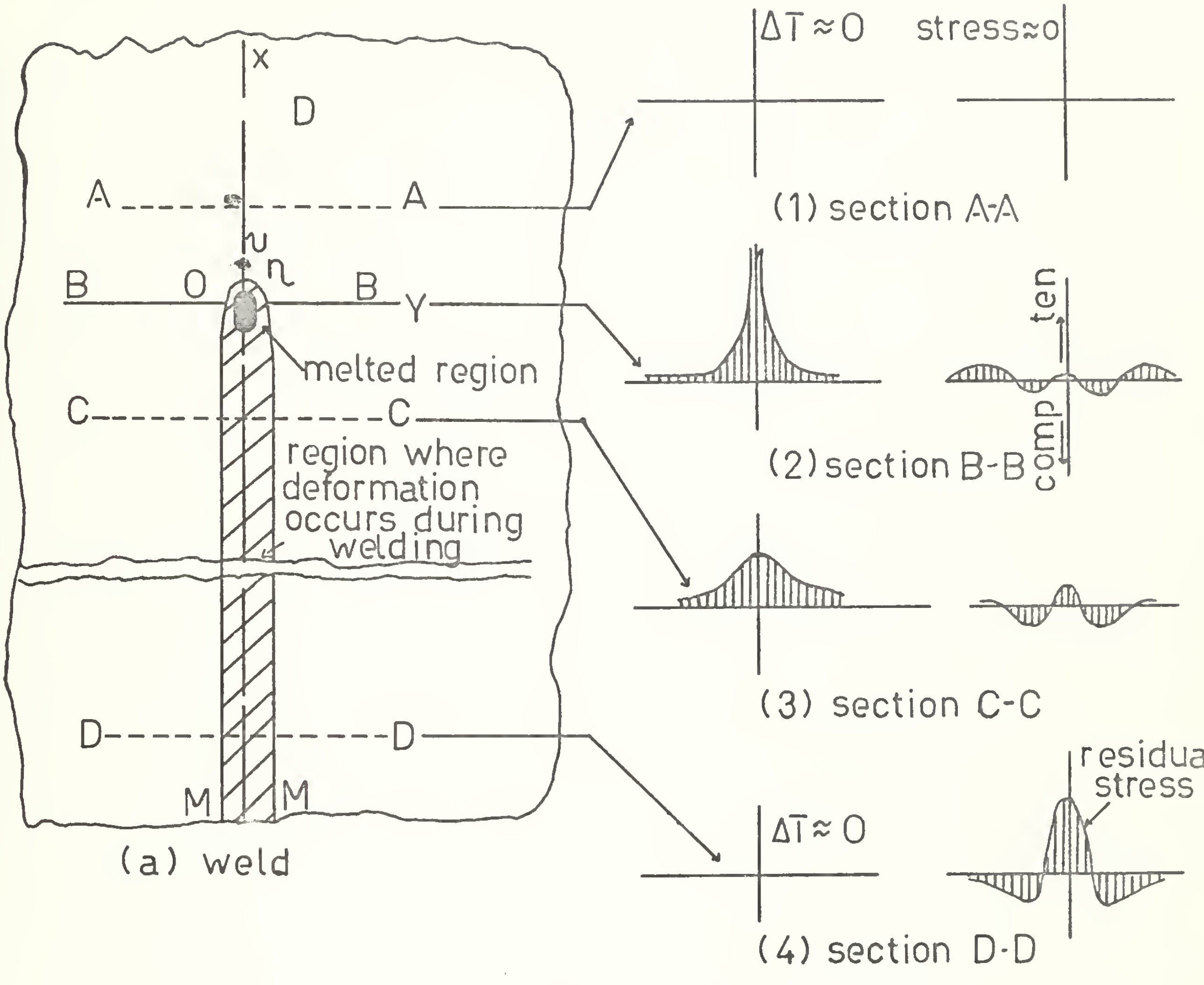


FIGURE 12. DISTRIBUTION OF YIELD STRENGTH AND LONGITUDINAL RESIDUAL STRESSES IN A WELDED 5456-H321 PLATE



(a) weld

(b) temperature change c stress x

FIGURE 13. SCHEMATIC REPRESENTATION OF TEMPERATURE AND STRESSES DURING WELDING

by mathematics, it is necessary to analyse the heat flow, thermal stresses during welding and determine the distribution of incompatible strains that are produced during the welding thermal cycle and finally determine residual stresses and distortion produced by the incompatible strains.

The problem of determining the distribution of incompatible strains is very complex, however. When the material undergoes plastic deformations, the stress-strain relationship is not linear. Furthermore, plastic properties of the material change with temperature.

Because the difficulty in determining the distribution of incompatible strains, no analysis has been made in which both heat flow and stress field are treated as two-dimensional problems. If the distribution of incompatibility is determined, residual stresses and distortions can be calculated theoretically (59).

7.5 Further Analysis of Distortion Problems

Distortion problems in steel have extensive data available, but rather limited information is available on residual stresses and distortions in weldments in aluminum alloys. The following work is an attempt to extend the steel information to aluminum that may be verified by experiments.

Let us consider thin plate, long enough to compare with the width of the plate to neglect the end effects. The plate is assumed simple-supported at the ends , $x = o,L$. Mura (18) conducted a mathematical analysis of buckling type distortions of long strips due to welding. His work is summarized below as a background.

The plate has the length L, the width 2a, and the origin of coordinate is taken at the middle point of the left end. The shrinkage strain of the welded material is assumed as ϕ , then the stress distribution is obtained as follows:

(1) $$\sigma_x = E \int_o^{\bar{c}} (\phi \, d\bar{y} - \phi) \quad \text{at} \quad |y| \leq c$$

$$\sigma_x = E \int_o^{\bar{c}} \phi \, d\bar{y} \quad \text{at} \quad |y| > c$$

assume, $\sigma_y = \tau_{xy} = 0$ everywhere,

$\bar{y} = y/a$, $\bar{c} = c/a$

Neglecting the end effects, the stresses do not depend on x, the equation of equilibrium is simplified to:

$$\frac{\partial \tau_{xy}}{\partial y} = 0 \quad , \qquad \frac{\partial \sigma_y}{\partial y} = 0$$

$$\tau_{xy} = \sigma_y = 0 \qquad \text{at} \qquad y = \pm a$$

therefore, they must vanish everywhere.

From the stress relations as:

$$\epsilon_x = \frac{\sigma_x}{E} + \phi \quad , \qquad \epsilon_y = - \frac{y}{E} \sigma_x + \phi \quad ,$$

$$\gamma_{xy} = 0$$

compatibility equation as:

$$\frac{\partial^2 \epsilon_x}{\partial y^2} + \frac{\partial^2 \epsilon_y}{\partial x^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y}$$

and from the condition for vanishment of total stress along the width of plate

$$\int_0^a \sigma_x \, dy = 0$$

Then it is possible to determine the stresses σ_x as (1), giving stress distribution shown in Figure 14.

$$T_x = \sigma_x \cdot t$$

The tension T" induced in the welded part for carbon steel and aluminum is as high as the yield stress of the material; this is not true for high strength steel (17).

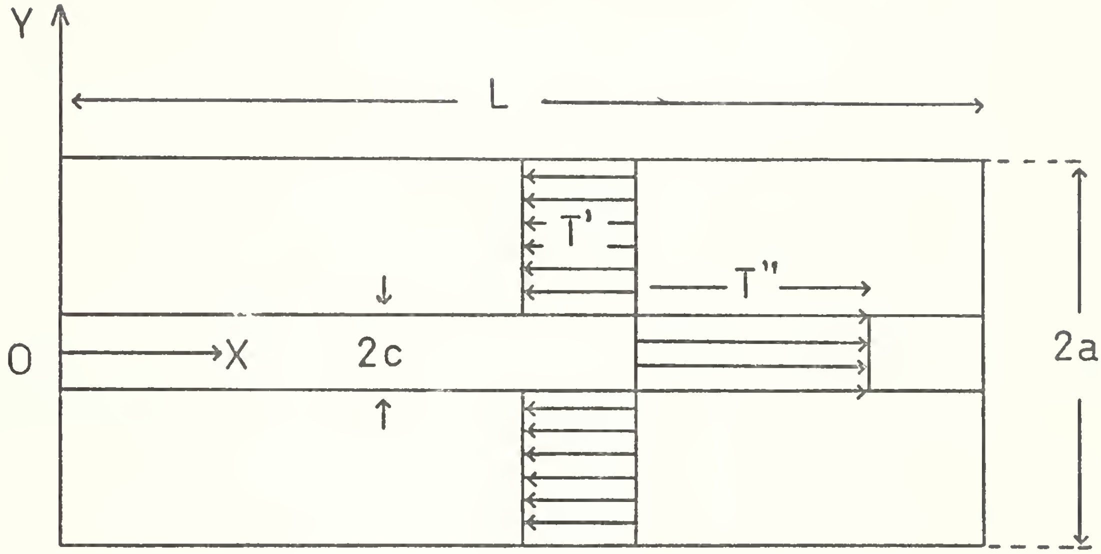


FIG. 14. RESIDUAL STRESS IN A LONG WELDED STRIP.

Denoting the deformation of the plate as w in the z direction, the equation of equilibrium can be written as:

$$(2) \qquad \frac{\partial^4 w}{\partial x^4} + \frac{2\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{T_x}{D} \frac{\partial^2 w}{\partial x^2}$$

Taken ϕ approximately a constant

$T_x = -T'$ constant in $1 \geq \bar{y} \geq \bar{c}$

$T_x = T''$ constant in $\bar{c} > \bar{y} \geq 0$

$D = E\, t^3/12(1-\nu^2)$

T' and T" are related from (1)

$$(3) \qquad T' = T'' \frac{c}{a-c}$$

The boundary conditions for free edges $\bar{y} = \pm 1$ are,

$$(4)\qquad \frac{\partial^2 w}{\partial y^2} + \lambda \frac{\partial^2 w}{\partial x^2} = 0$$

$$(2 - \nu)\frac{\partial^3 w}{\partial x^2 \partial y} + \frac{\partial^3 w}{\partial y^3} = 0$$

Solving equation (2) independently in the domains $1 \geq \bar{y} \geq c$ and $\bar{c} \geq \bar{y} \geq 0$, the quantities with one dash and two dashes refer to each domain respectively, and assuming the solutions of (2) in the two domains as the forms:

$$(5)\qquad \begin{aligned} w' &= y' \sin \omega_x \\ w'' &= y'' \sin \omega_x \end{aligned}$$

where $\omega = \frac{m\pi}{L}$, m, integer

The function Y depends only on y, and must satisfy the equations:

$$\begin{gathered}\frac{d^4Y'}{dy^4} - 2 \cdot \omega^2 \frac{d^2Y'}{dy^2} + \omega^2 \left(\omega^2 - \frac{T'}{D}\right) Y' = 0 \\ \frac{d^4Y''}{dy^4} - 2\,\omega^2 \frac{d^2Y''}{dy^2} + \omega^2 \left(\omega^2 + \frac{T''}{D}\right) Y'' = 0\end{gathered} \tag{6}$$

with solutions:

$$\begin{gathered}Y' = A' \cosh \alpha_1 y + B' \cosh \alpha_2 y + C' \sinh \alpha_1 y + D' \sinh \alpha_2 y \\ Y'' = A'' \cosh \beta_1 y + B'' \cosh \beta_2 y + C'' \sinh \beta_1 y + D'' \sinh \beta_2 y\end{gathered} \tag{7}$$

where,

$$\alpha_1 = \sqrt{\omega^2 + \omega\mu'} \;,\quad \beta_1 = \sqrt{\omega^2 + i\omega\mu''}$$

$$\alpha_2 = \sqrt{\omega^2 - \omega\mu'} \;,\quad \beta_2 = \sqrt{\omega^2 - i\omega\mu''}$$

(8)

$$\mu' = \sqrt{\frac{T'}{D}} \;,\quad \mu'' = \sqrt{\frac{T''}{D}}$$

$$\mu' > \omega \;,\quad i = \sqrt{-1}$$

From symmetry of Y" for the x axis, C" and D" must vanish. The conditions of (4) for w" offer the relations between A', B', C', and D'.

$$A' (\alpha_1^2 - \nu \omega^2) \cos h \alpha_1 a + B' (\alpha_2^2 - \nu \omega^2) \cos h \alpha_2 a$$

$$+ C' (\alpha_1^2 - \nu \omega^2) \sin h \alpha_1 a + D' (\alpha_2^2 - \nu \omega^2)$$

$$\sin h \alpha_2 a = 0$$

(9)

$$A' \left\{ \alpha_1^3 - (2 - \nu) \omega^2 \alpha_1 \right\} \sin h \alpha_1 a +$$

$$B' \left\{ \alpha_2^3 - (2 - \nu) \omega^2 \alpha_2 \right\} \sin h \alpha_2 a +$$

$$C' \left\{ \alpha_1^3 - (2 - \nu) \omega^2 \alpha_1 \right\} \cos h \alpha_1 a +$$

$$D' \left\{ \alpha_2^3 - (2 - \nu) \omega^2 \alpha_2 \right\} = 0$$

The solution (7) must satisfy the condition of continuity for the deformation, moment and shear force at the boundary of the two domains, $y = c$.

$$w' = w'' \quad , \quad \frac{\partial w'}{\partial y} = \frac{\partial w''}{\partial y}$$

(10)

$$M'_y = M''_y \quad , \quad Q'_y + \frac{\partial M'_{xy}}{\partial x} = Q''_y + \frac{\partial M''_{xy}}{\partial x}$$

The above conditions (10) give relations:

$$A' \cos h\alpha_1 c + B' \cos h\alpha_2 c + C' \sin h\alpha_1 c +$$

$$D' \sin h\alpha_2 c = A'' \cos h\beta_1 c + B'' \cos h\beta_2 c$$

(11)

$$A'\alpha_1 \sin h\alpha_1 c + B'\alpha_2 \sin h\alpha_2 c + C'\alpha_1 \cos h\alpha_1 c +$$

$$D'\alpha_2 \cos h\alpha_2 c = A''\beta_1 \sin h\beta_1 c + B''\beta_2 \sin h\beta_2 c$$

$$A'\alpha_1^2 \cos h\alpha_1 c + B'\alpha_2^2 \cos h\alpha_2 c + C'\alpha_1^2 \sin h\alpha_1 c +$$

$$D'\alpha_2^2 \sin h\alpha_2 c = A''\beta_1^2 \cos h\beta_1 c + B''\beta_2^2 \cos h\beta_2 c$$

$$A'\alpha_1^{\,3} \sin h\alpha_1 c + B'\alpha_2^{\,3} \sin h\alpha_2 c + C'\alpha_1^{\,3} \cos h\alpha_1 c +$$

$$D'\alpha_2^{\,3} \cos h\alpha_2 c = A''\beta_1^{\,3} \sin h\beta_1 c + B''\beta_2^{\,3} \sin h\beta_2 c$$

The algebraic determinant for the coefficients A', B', C', D', A" and B" is obtained from the equations (9) and (11). Considering the smallness of c compared with a, the determinant is reduced to:

$$\left\{\bar{\mu}^2 - (1-\nu)^2\bar{\omega}^2\right\} + \left\{\bar{\mu}^2 + (1-\nu)^2\bar{\omega}^2\right\}$$

$$\cos h\sqrt{\bar{\mu}\bar{\omega} + \bar{\omega}^2}\ \cos\sqrt{\bar{\mu}\bar{\omega} - \bar{\omega}^2} +$$

$$\frac{\bar{\omega}\left\{(1-2\nu)\bar{\mu}^2 - (1-\nu)^2\bar{\omega}^2\right\}}{\sqrt{\bar{\mu}^2 - \bar{\omega}^2}} \sin h\sqrt{\bar{\mu}\bar{\omega} + \bar{\omega}^2} \tag{12}$$

$$\sin\sqrt{\bar{\mu}\bar{\omega} - \bar{\omega}^2} - \frac{\sqrt{\bar{\mu}\bar{\omega} - \bar{\omega}^2}}{\bar{\mu}\bar{\omega}}\left\{\bar{\mu} + (1-\nu)\bar{\omega}\right\}^2$$

$$\cos h\sqrt{\bar{\mu}\bar{\omega} + \bar{\omega}^2}\ \sin\sqrt{\bar{\mu}\bar{\omega} - \bar{\omega}^2} - \frac{\sqrt{\bar{\mu}\bar{\omega} + \bar{\omega}^2}}{\bar{\mu}\bar{\omega}}$$

$$\left\{ \bar{\mu} - (1-\nu)\,\bar{\omega} \right\}^2 \sin h\sqrt{\bar{\mu}\,\bar{\omega} + \bar{\omega}^2} \quad \cos\sqrt{\bar{\mu}\,\bar{\omega} - \bar{\omega}^2} = 0$$

where $\bar{\mu} = \sqrt{\frac{T'\,a^2}{D}} = \frac{a}{t}\sqrt{\frac{12(1-\nu^2)\,\sigma_{x'}}{E}}$

$$\sigma_{x'} = \frac{c}{a-c}\,\sigma_{x''} \quad , \quad \bar{\omega} = a\,\omega = \frac{a\,m\,\pi}{L}$$

$$\sigma_{x''} \approx \sigma_y$$

The wave length divided by the width of the plate is denoted by

$$(13) \quad \bar{\lambda} = \frac{\pi}{\bar{\omega}} = \frac{2}{m}\,\frac{L}{2a}$$

The relation between $\bar{\mu}$ and $\bar{\lambda}$ is obtained from (12) and (13) and is shown in Figure 15, by the curve A. The plate under uniform longitudinal compression without residual stresses is shown by the curve B.

$\bar{\mu} = \sqrt{T'a'/D \quad T'}$; residual compression

$\bar{\lambda} = \eta/\bar{w}$ $\quad\bar{\lambda}$; wavelength/width of plate

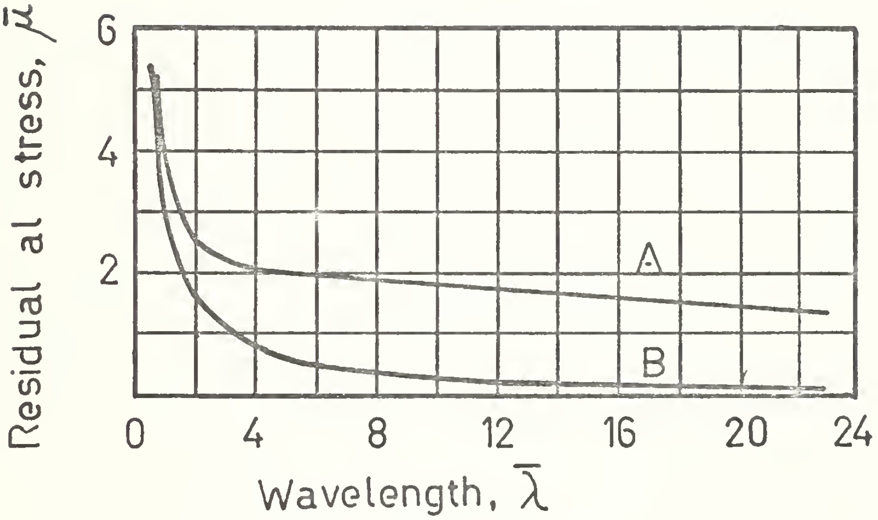


FIG. 15. RELATIONSHIP BETWEEN WAVELENGTH AND RESIDUAL STRESS IN A LONG WELDED STRIP.

For the same value of $\bar{\lambda}$, the corresponding $\bar{\mu}$ for the curve (a) is always higher than that for the B curve, because of the effect of tension acting in the middle part of the plate on buckling.

From knowing the residual stress σ', $\bar{\mu}$ is determined. Then $\bar{\lambda}$ is determined. Wavelength values L_1, L_2, L_3 for $m = 1, 2, 3, \ldots$. The longest wave L_1 is obtained under $m = 1$. For a given residual stress σ' and for a width a, a plate longer than L_1 is going to buckle. Therefore, L_1 is considered as the critical size of the plate to cause buckling due to residual stress.

From the expression for $\bar{\mu}$,

$$\bar{\mu} = \sqrt{T' \frac{a^2}{D}}$$

where:

$$T' = \sigma_{x'}\ t$$

$$\sigma_{x'} = \frac{\sigma'' c}{a-c}$$

$$D = \frac{E\ t^3}{12(1-\nu^2)}$$

and assuming $\sigma'' \approx \sigma_y$ of the material, we can express $\bar{\mu}$ as:

$$\bar{\mu} = \frac{a}{t}\sqrt{\frac{12(1-\nu^2)\,\sigma_y\, c}{E(a-c)}} \qquad \text{or,}$$

$$= \frac{a}{t}\sqrt{\frac{12(1-\nu^2)\,\sigma_y}{E}}\;\sqrt{\frac{c}{a-c}}$$

We see that for a plate of the same dimensions, $\bar{\mu}$ will be a function of the yield strength, modulus of elasticity and c is the width of the plate under tensile stress due to residual stress caused by welding.

The author has considered plates of steel and aluminum of different thickness and different widths, and solved for $\bar{\mu}$ and $\bar{\lambda}$. The zone under tensile stress c has been considered as equal to c_{steel}, equal to $2c_{steel}$ and equal to $3c_{steel}$, assuming c for steel is approximately 3t. The results are shown in Table 10. L_1/a is plotted against $\bar{\mu}_{al}$ for the different values of c in Figures 16 through 18.

TABLE 10

Analytical Results of Buckling Conditions of Aluminum vs. Steel

a	t	$C_{al} = C_s$				$C_{al} = 2C_s$		$C_{al} = 3C_s$	
		$\bar{\mu}_{steel}$	$\bar{\mu}_{al}$	$\bar{\lambda} c_s$	$\bar{\lambda} c_{al}$	$\bar{\mu}_{al}$	$\bar{\lambda} c_{al}$	$\bar{\mu}_{al}$	$\bar{\lambda} c_{al}$
5"	1/16"	1.82	2.2	10	3.4	3.12	1.4	3.9	0.95
	1/8"	1.25	1.5	26	18	2.22	2.5	2.84	1.8
	1/4"	0.95	1.11	38	35	1.73	15.0	2.38	2.4
10"	1/16"	2.5	3.05	2.1	1.4	4.31	0.8	5.34	0.7
	1/8"	1.72	2.08	12	5.0	3.0	1.5	3.76	1.1
	1/4"	1.25	1.50	26	17.5	2.22	3.5	2.84	1.8
20"	1/16"	3.52	4.25	1.2	0.9	6.04	0.6	7.44	0.5
	1/8"	2.42	2.92	2.2	1.6	4.15	0.9	5.15	0.75
	1/4"	1.72	2.08	12	4.5	3.00	1.5	3.76	1.1

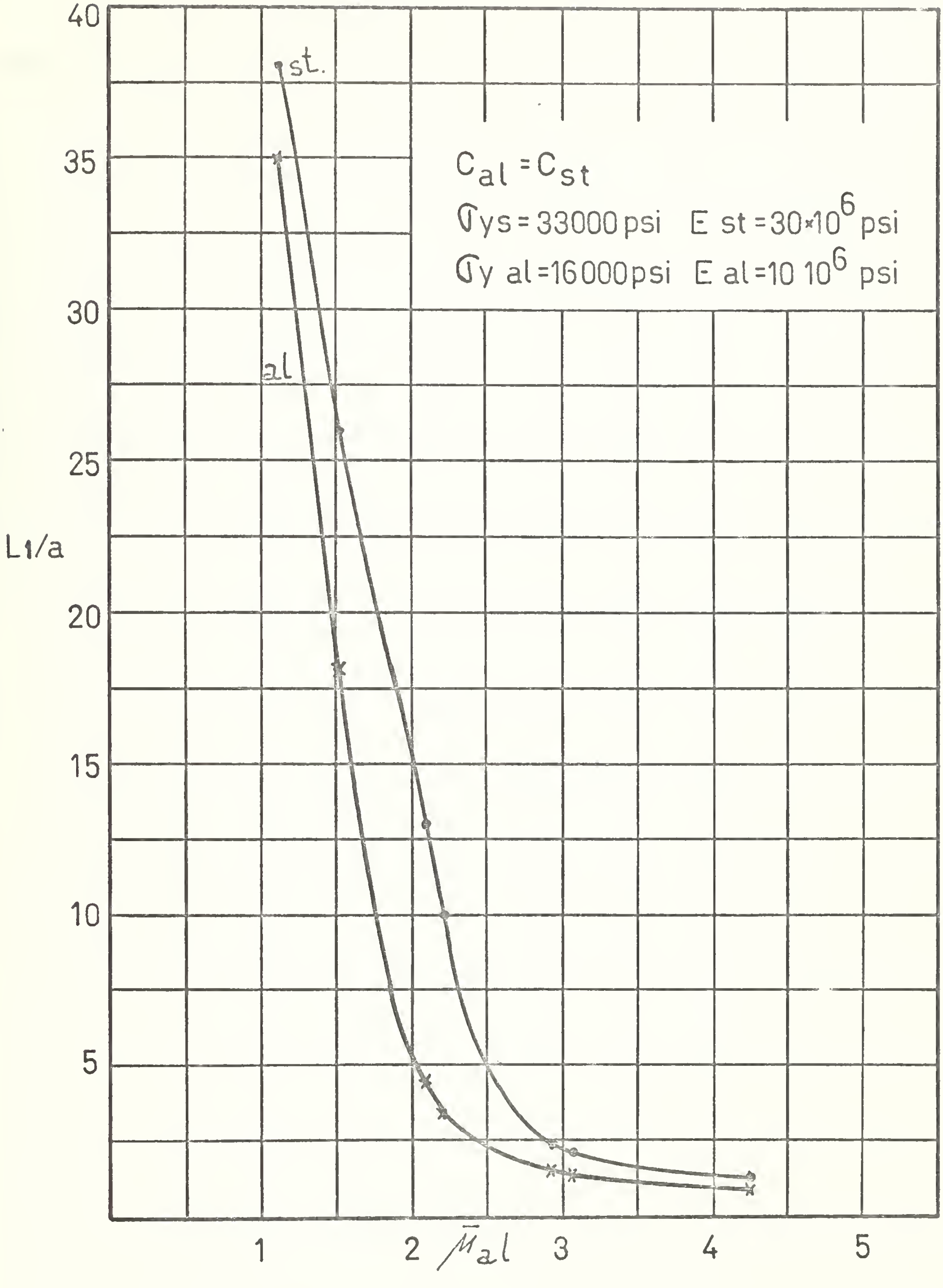


FIG 16 CURVE OF L1/a FOR ALUMINUM VS. STEEL

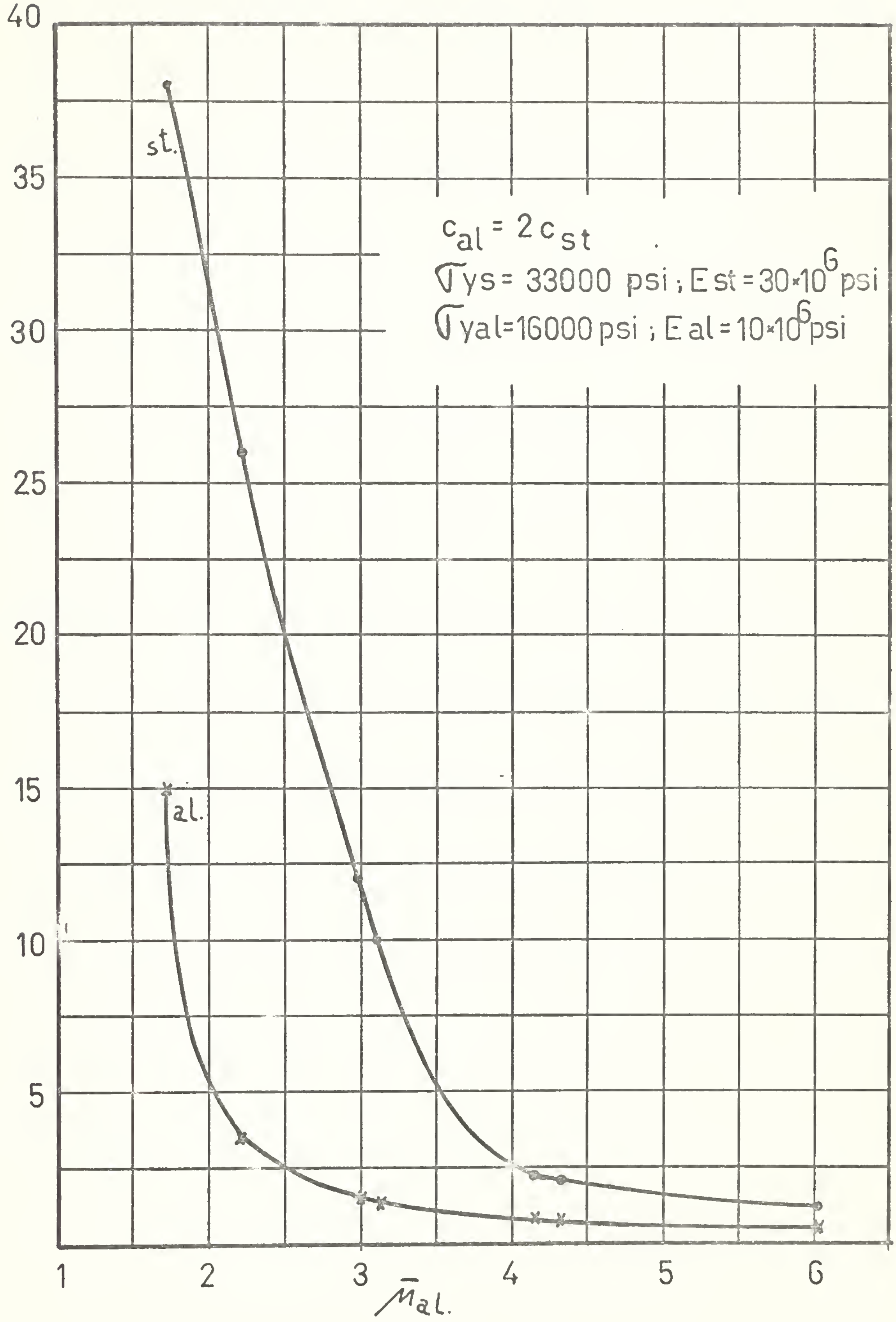


FIG 17. CURVE OF L1/a FOR ALUMINUM VS. STEEL.

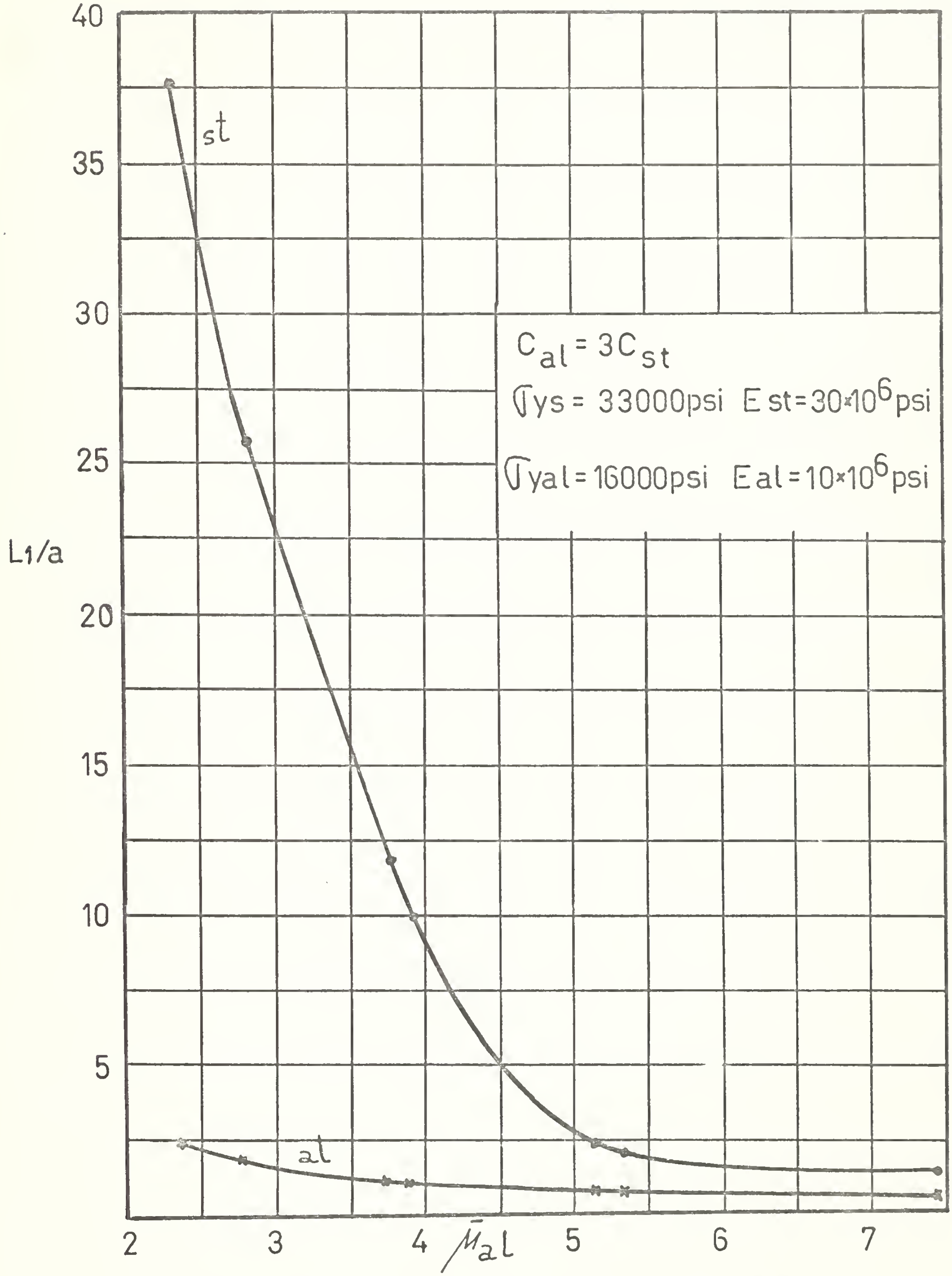


FIG 18. CURVE OF L1/a FOR ALUMINUM VERSUS STEEL.

In the author's opinion, the assumption $c_{al} = 2c_{steel}$ seems to be close to the real case. There is a range of $\bar{\mu}$ of aluminum from 1.8 to 3.7 which gives a large difference for buckling conditions of aluminum compared to steel, where the ratio of $\bar{\lambda}_c$ of steel over $\bar{\lambda}_c$ of aluminum goes from 5 to 8.1. This is due to the abrupt change in values of $\bar{\lambda}$ in the shoulder of the curve A in Figure 15.

Looking at the expression for ,

$$\bar{\mu} = \frac{a}{t} \sqrt{\frac{12(1-\nu^2)\,\sigma_y}{E}} \sqrt{\frac{c}{a-c}} \; ,$$

we see that for a given alloy, the first square root in the expression of $\bar{\mu}$ will be a constant. Then we deal with the expression of:

$$\frac{a}{t} \sqrt{\frac{c}{a-c}}$$

which, for the values of σ_y and E of aluminum used in the calculations, will tell the designer that for values of

$$13.6 \leq \frac{a}{t} \sqrt{\frac{c}{a-c}} \leq 28.1,$$

high buckling conditions are to be expected for aluminum compared to steel. Also expected is an increase in the amount of stiffeners members in the structure, a decrease in the weight savings and an increase in the total cost. These values of $\bar{\lambda}_c$ have been read from curve 15, therefore, it will be necessary to solve equation (12), in order to make a more detailed analysis. It is also very important to verify these results experimentally (not included in the scope of this work). However, the analysis given in this report will provide a valuable guide for the experimental work.

CONCLUSIONS

From the preceding chapters several types of conclusions and recommendations can be made. They refer to: 1) Economics aspects; 2) Extensions of the use of aluminum to large ships; 3) Technical problems found in aluminum welding; 4) Methods that best suit the industrial welding of aluminum; 5) Feasibility of the use of aluminum in Chilean shipyards and 6) Recommendations to achieve welding capabilities in welding aluminum for the Chilean shipyards.

1. We have seen that one of the most important applications of aluminum in shipbuilding has been in the superstructure of large ships, where good advantage is taken of its light weight properties. A few small ships have been constructed with aluminum hulls. However, aluminum hulled ships have no overall economic advantages over its steel counterpart. Initial construction costs run about 20% higher than steel construction, but this is offset by the increase in payload due to higher displacement for the same weight. The overall utility of an aluminum ship is, thus, approximately the same as a steel ship.

CONCLUSIONS

From the preceding chapters [illegible] conclusions and recommendations [illegible] ter: 1) Economics aspects; 2) [illegible] aluminum to large ships; 3) [illegible] in aluminum welding; 4) [illegible] industrial welding of aluminum; 5) [illegible] the use of aluminum in [illegible] mendations to achieve [illegible] minum for the [illegible]

1. We have seen that [illegible] tions of aluminum in ships [illegible] structure of [illegible] of its light weight [illegible] been considered [illegible] hulled ship [illegible] its steel [illegible] about 20% [illegible] offset by [illegible] ment for [illegible] aluminum [illegible] ship.

2. The extension of the use of aluminum in complete hulls of large ships will not be possible until more knowledge is obtained about the behavior of aluminum structures under water pressure and dynamic loads. Buckling characteristics of aluminum structures under compressive loads, deflection allowances, fatigue limits, distortion, etc. should be studied on both an experimental and a theoretical basis. For example, deflection has been limited to 50% over the steel deflection by the American Bureau of Shipping. This is an arbitrary factor based on a lack of knowledge in aluminum ships with high L/D ratios, and problems with machinery systems, piping, etc. As experience is gained from aluminum hulls with larger L/D ratios, the present limitations can be adjusted accordingly.

3. Welding problems in aluminum play an important role because of the large effects of the quality of the weld on the overall strength of the structure. Porosity has detrimental effects on the ultimate strength of a joint, decreasing strength as porosity increases and lowering fatigue properties. Porosity can be reduced by avoiding contamination with H_2, i.e., good results are obtained by making the weld immediately

after machining the material to a final dimension. It has recently been determined that former methods of chemical cleaning were, in fact, additional sources of contamination. Other proposed methods of reducing porosity are to use molten puddle stirrer, hydrogen getters and cryogenic cooling, but these methods prove to be of little practical value.

Another aluminum welding problem is to minimize the heat affected zone adjacent to the weld, because increasing heat input reduces the ultimate tensile strength of welded joints, regardless of the welding process or the material thickness. Some attempts have been made to minimize the extent of the heat affected zone, such as cryogenic cooling. However, the results have not yet been satisfactory or reliable.

Distortion is another major welding problem in aluminim welding due to stresses resulting from the welding thermal effects. Research on carbon-steel weldments has shown that the maximum residual weld stress is as high as the yield stress of the weld metal. This also seems to be true for aluminum alloys. It has been shown that, due to physical characteristics of aluminum and mechanical properties, the critical length

for aluminum weldments in plates is in the order of 1/2 to 1/8 of the critical size of steel plates, which decreases the spacing between stiffner members in a ship structure to approximately 1/2 to 1/8 of steel spacing for the same material dimensions. This is to be verified experimentally, which is not in the scope of this work.

4. Welding methods which presently best suit the joining of aluminum are Tungsten Inert Gas and Metal Inert Gas processes (TIG and MIG) giving a high production rate, (for MIG), clean heat source, adaptability to vertical weldments, and do not require cleaning after welding.

5. It has been shown that, in some cases, aluminum can compete with steel but has no particular economical advantages, therefore its use is recommended where its light weight, high strength and corrosion resistance properties are important design factors. One must also keep in mind the associated problem found in welding aluminum.

Use of aluminum in Chilean shipyards will probably be confined to superstructure applications and conversion programs for two reasons: 1) limited technical capabilities of a new developing shipyard indicates that conversions are feasible while the complete construction of an

aluminum hull is not; 2) aluminum is attractive primarily in reducing superstructure weight, such as the conversion of conventional cruisers where considerable additional weight, high above the waterline, will reduce the overall stability significantly.

6. Presently the Chilean shipyard industry has the capability to perform such conversion programs, but its experience with aluminum is limited. In order to achieve the welding capability to successfully handle the problems mentioned above, it is recommended that training of welders and engineers be undertaken immediately.

LIST OF REFERENCES

1. "Welding Handbook"; American Welding Society
2. "Fusion Welding Aluminum"; Reynolds Metal Company, 1965
3. "Welding Aluminum"; American Welding Society, 1967
4. Jen Chia-Lich, Lo Chin-Ch'ang and Chen Wu-Chu, "Porosity in TIG Welded Aluminum and Aluminum-Magnesium Alloy Welds"; welding section of Department of Metallurgical Engineering, Tsing Hua University, Peking, China, 1966
5. Chester H. Holtyn; "Aluminum - The Age of Ships", SNAME, October, 1966
6. "Aluminum Boats", Kaiser Aluminum and Chemical Sales, Inc., January, 1964
7. L. Capel, "Aluminum Welding Practice", Utrecht Meeting, 1961; British Welding Journal, May, 1961
8. William H. Ailor, Jr.; "Evaluation of Aluminum after One Year Deep Sea Exposure", Reynolds Metals Company, July, 1967
9. F.E. Gibbs, "The Developments of Aluminum Filler Alloys"; Wire and Wire Products, April, 1968

10. J.J. Baron; "The Peculiarities of Aluminum Metallurgy and Its Impact on the Metallurgy of other Metals; Journal of the Institute of Metals, September, 1965

11. Herman E. Reitman; "Designer's Underestimate the Capacities of Welded, Strain Hardened Aluminum Columns"; Naval Engineers Journal, February, 1967

12. J.A. Bennett; "The Effect of a Fatigue Crack on the Fatigue Strength of an Aluminum Alloy", Naval Engineers Journal, February, 1966

13. Carl W. Leveau; "Aluminum in Ship Construction", SNAME, May, 1957

14. C.H. Holtyn; "Impact Energy Absorption Characteristics of Aluminum"; Reynolds Metal Company, November, 1962

15. C.H. Holtyn;" Technical Data on the PGM-84 Class of Gunboat", Reynolds Metal Company, May, 1965

16. Koichi Masubuchi; "Integration of NASA. Sponsored Studies on Aluminum Welding"; Redstone Scientific Information Center, September, 1967

17. Koichi Masubuchi, F.B. Simmons, R.E. Monroe; "Analysis of Thermal Stresses and Metal Movement during Welding", Redstone Scientific Information Center, July, 1968

18. Toshio Mura; "On the Buckling Deformations of Thin Plates due to Welding", 3rd Japan National Congress for Applied Mechanics, 1955

19. H. Kihara and K. Masubuchi, "Distortions and Residual Stresses due to Welding", Tokyo, The Sampo Publishing Company, 1955

20. K. Masubuchi; "Control of Distortion in Welded Structures", Commission X of the Internal Institute of Welding, April, 1968

21. S. Timoshenko; "Strength of Materials", New York, D. Von Nostrand Co., 1956

22. E.J. Rupert and J.F. Ruay; "Analytic and Statistical Study on the Effects of Porosity Level on Weld Joint Performance", Technical Summary Report on Contract NAS 8-11335 from Martin Marietta Corp., March, 1966

23. W.E. Strubelt; "Inert Gas Weldment Effects Study", Final Report on Contract NAS 8-20168 from Aerospace Group, Boeing Co., June, 1966

24. D.L. Cheever, P.A. Kammer, R.E. Monroe; "Weld-Base Metal Investigation", Contract NAS 8-11445 from Battelle Memorial Institute, July, 1965

25. Lambert Tall; "Residual Stresses in Welded Plates - A Theoretical Study"; Welding Research Supplement, January, 1964

26. Carl W. Leveau; "Aluminum and its Use in Naval Craft"; Naval Engineers Journal, April, 1965

27. Herman E. Reitman; "Welded Aluminum Column Restraint"; Naval Engineers Journal, April, 1967

28. B.G. Martin and C.J. Adams; "Detection of Lack of Fusion in Aluminum Alloy Weldments", Naval Engineers Journal, February, 1967

29. Koichi Masubuchi; "Use of Computers for Ship Structural Design and Fabrication"; SNAME, March 14, 1968

30. W. Muckle; "The Development of the Use of Aluminum in Ships", Northeast Coast Institution of Engineers and Shipbuilders, Transactions, 1963-1964, Vol. 80

31. J.H. Dudas and F.R. Collins; "Preventing Weld Cracks in High-Strength Aluminum Alloys"; Welding Research Supplement, June, 1966

32. W.H. Ailor; "Aluminum in Seawater"; Geomarine Technology, March, 1965

33. C.H. Holtyn; "Shipbuilding Guide to Aluminum Construction, Reynolds Metal Co., October, 1963

34. C.H. Coltyn; "Allowable Design Stresses, PGM 84-85" Reynolds Metal Co., August, 1963

35. Koichi Masubuchi; "Welding Problems in Shipbuilding", Marine Technology, SNAME, January, 1969

36. "Alcoa Aluminum Handbook"; Aluminum Company of America, 1962

37. C.H. Holtyn; "isolation of Dissimilar Metals"; Reynolds Metals Co., July, 1962

38. Charles W. Covey, "Aluminaut"; Naval Engineers Journal, April, 1965

39. Hugh L. Logan; "The Stress Corrosion of Metals", John Wiley and Sons, Inc., New York, September, 1966

40. Herbert H. Uhlig; "Corrosion and Corrosion Control", John Wiley and Sons, Inc., New York, November, 1962

41. N.D. Tomashou, "Theory of Corrosion and Protection of Metals", MacMillan Co., New York, 1966

42. W. Muckle; "The Design of Aluminum Alloys Ships' Structures", Cornell Maritime Press, Cambridge, Maryland, 1963

43. "Geografia Economica De Chile", Corporacion de Fumento Dela Produccion - Chile, 1965

44. C.H. Holtyn; "Aluminum, From Boats to Ships", Reynolds Metals Co., April, 1963

45. "Corrosion and Protection of Metals under Stress", Reports of Central Scientific Research Institute of Technology and Machinery, No. 31, 1950

46. Ivo Fioriti and John Vasta, "Materials for Hydrofoils", Naval Engineers Journal, August, 1963

47 Robertson, W.D., and Tetelman; "Strengthening Mechanism in Solids"; ASM, Metals Park, Ohio, 1962

48. Mears, Brown and Dix, "Symposium on Stress Corrosion Cracking of Metals"; p.323

49. Kent R. Vanhorn; "Aluminum"; American Society for Metals, Metals Park, Ohio, 1967

50. T.G. Lindsay, "Economics Benefits from Using Aluminum for Merchant Ships Hull", SNAME, 1959

51. "Corrosion of Metals"; American Society for Metals, 1958

52. "Tentative Code for the Selection of Wrought Aluminum Alloys for Ship Structures", SNAME

53. "Correct Use of Aluminum Alloys"; Buship Instruction 9110.37A, October 14, 1958

54. Friedrich Bleich; "Buckling Strength of Metal Structures"; McGraw-Hill, New York, 1952

55. "Bureau of Ships Instruction 9110.46 Ser. 443-71", February 19, 1960

56. Koichi Masubuchi; "Welding in Modern Industry"; Unpublished manuscript

57. R.V. Hoppes; "Welding Study on 2219-T87 Aluminum Alloy", Technical Information Report No. TIR-15-64, R-MEMW",Manufactoring Engineering Laboratory Marshall Space Flight Center, NASA, April 27, 1964

58. D.Q. Cole, L.W. Davis, and P.E. Anderson; "Development of Controls for Time-Temperature Characteristics in Aluminum Weldments"; Contract NAS 8-11930 from Harvey Aluminum, Inc., October, 1966

59. Koichi Masubuchi, "Analytical Investigation of Residual Stresses and Distortion due to Welding", Welding Journal, Research Supplement, 39, No 12, 1960, pp. 525s - 537s

thesF264
Aluminum as a shipbuilding material.
3 2768 002 06556 7
DUDLEY KNOX LIBRARY