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Guidelines for Design, Manufacture, Inspection and Testing of Electronic Enclosures

A standard developed by IPC

Association Connecting Electronics Industries



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IPC-HDBK-630

Guidelines for Design, Manufacture, Inspection and Testing of Electronic Enclosures Assembly

Developed by the Requirements for Structural Enclosure Task Group
(7-31j) of the Product Assurance Committee (7-30) of IPC

Users of this publication are encouraged to participate in the
development of future revisions.

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Guidelines for Design, Manufacture, Inspection and Testing of Electronic Enclosures

1 PREFACE

1.1 Scope This document has been written to assist the designers, manufacturers and end users of electronic enclosures of electrical and electronic equipment to understand the best practices to meet requirements, ensuring the reliability and function of the end item assembly for its intended design life.

An electronic enclosure, for the purpose of this document, is defined as a chassis, box, top level assembly, high level assembly (HLA), functional unit, drawer, cabinet, or other designation forming a top level system assembly. An enclosure typically consists of a combination of printed board assemblies (PBAs), cable and wire harness assemblies and other electronics and/or mechanical components, and is typically tested as a functional unit. The enclosure includes the necessary mechanical and structural elements to protect and integrate the assembly into a finished system. Enclosures are often modular components or sub-systems of larger systems, designed for replacement in the end-use environment.

1.2 Purpose This handbook provides guidelines for the design, manufacture, inspection and test for electronic enclosures. It is not enough to understand the properties of the various components, materials and processes; the user should understand what is to be achieved by the set of selected components, materials and processes within the end use environment and how to verify that the desired results have been realized.

This document is intended to be used as a reference only. It is the responsibility of the user to determine the suitability, via appropriate testing, of the selected electronic enclosure and application method for a particular end use application. An electronic enclosure may have several functions depending on the type of application. The most common are:

- a. To protect the electronic assembly from the end use environment, such as vibration, shock and other movements detrimental to electronic assemblies
- b. To incorporate into the end use environment.

1.3 Applicability This handbook covers high reliability type end item equipment, such as Aerospace, Defense, Medical, Telecom, etc. Not all specialized technologies are covered in this handbook.

This handbook is for guidance only and cannot be cited as a requirement. If it is, the supplier does not have to comply.

The use of words like, “must,” “should” and “shall” have no special meaning in this guideline. They do not indicate a binding criterion.

1.4 Classification This standard recognizes that electrical and electronic assemblies are subject to classifications by intended end-item use. Three general end-product classes have been established to reflect differences in producibility, complexity, functional performance requirements and verification (inspection/test) frequency. It should be recognized that there may be overlaps of equipment between classes.

The product class should be stated in the procurement documentation package.

CLASS 1 General Electronic Products

Includes products suitable for applications where the major requirement is function of the completed assembly.

CLASS 2 Dedicated Service Electronic Products

Includes products where continued performance and extended life is required, and for which uninterrupted service is desired but not critical. Typically the end-use environment would not cause failures.

CLASS 3 High Performance Electronic Products

Includes products where continued high performance or performance-on-demand is critical, equipment downtime cannot be tolerated, end-use environment may be uncommonly harsh, and the equipment should function when required such as life support or other critical systems.

1.5 Measurement Units and Applications All dimensions and tolerances, as well as other forms of measurement (temperature, weight, etc.) in this standard are expressed in SI (System International) units with Imperial English equivalent dimensions provided in brackets. Dimensions and tolerances use millimeters as the main form of dimensional expression; Micrometers are used when the precision required make millimeters too cumbersome. Celsius is used to express temperature. Weight is expressed in grams.

1.6 Terms and Definitions Other than those terms listed below, the definitions of terms used in this standard are in accordance with IPC-T-50.

1.6.1 Supplier Supplier as referred to herein means the organization that ultimately delivers the completed product to the customer, and this supplier is responsible for proper flow-down of all applicable user defined contract requirements to lower-tier contractors and/or manufacturers. Note that the terms Supplier and Manufacturer are the same for the purposes of this document (e.g., As agreed between user and supplier - AABUS).

1.7 Health and Safety The use of some materials referenced in this standard may be hazardous. To provide for personnel safety, follow the applicable local and federal Occupational, Safety and Health Regulations.

Ergonomic factors should be considered and implemented into the design to ensure the product can be manufactured, operated and maintained without any undue risk of injury. The designer should make accommodation for all of the following:

- a. Product intended end use – how will the product be used in the field.
- b. Original manufacturing process – general lifting, moving, rework required.
- c. Maintenance/repair activity.

2 APPLICABLE DOCUMENTS

2.1 Department of Defense¹

MIL-A-46106 Adhesive-Sealants, Silicone, RTV, One Component

MIL-STD-167 Mechanical Vibrations of Shipboard Equipment

MIL-STD-186 Manufacturing Process, Protective Finishing for Army Missile Weapon Systems

MIL-STD-202 Test Method Standard - Electronic and Electrical Component Parts

MIL-STD-220 Test Method Standard - Method of Insertion Loss Measurement

MIL-HDBK-310 Global Climatic Data for Developing Military Products

MIL-HDBK-344 Environmental Stress Screening (ESS) of Electronic Equipment

MIL-STD-403 Preparation For and Installation of Rivets and Screws, Rocket, Missile, and Airframe Structures

MIL-HDBK-454 General Guidelines for Electronic Equipment

MIL-STD-461 Requirements for the control of Electromagnetic interference Characteristics of Subsystems and Equipment

MIL-STD-464 Electromagnetic Environmental Effects, Requirements for Systems

MIL-I-631 Insulation, Electrical, Synthetic-Resin Composition

MIL-T-713 Twine, Fibrous: Impregnated, Lacing and Tying

MIL-STD-740 Airborne and Structure-Borne Noise Measurements and Acceptance Criteria of Shipboard Equipment

MIL-STD-810 Test Method Standard - Environmental Engineering Considerations and Laboratory Tests

1. www.mil-standards.com

- MIL-STD-889** Dissimilar Metals
- MIL-S-901** Requirements for Shock Tests. H.I. (High-Impact) Shipboard Machinery, Equipment, and Systems
- MIL-E-917** Electric Power Equipment Basic Requirements
- MIL-Y-1140** Yarn, Cord, Sleeving, Cloth, and Tape-Glass
- MIL-HDBK-1250** Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies
- MIL-STD-1312** Fastener Test Methods
- MIL-STD-1474** Design Criteria Standard, Noise Limits
- MIL-STD-1523** Age Controls of Age Sensitive Elastomeric Material
- MIL-STD-2042** Fiber Optic Topology Installation Standard Methods for Naval Ships
- MIL-I-3158** Insulation Tape, Electrical Glass-Fiber (Resin)
- MIL-DTL-5541** Chemical Conversion Coatings on Aluminum and Aluminum Alloys
- MIL-STD-8516** Sealing Compound, Synthetic Rubber, Electric Connectors and Electric Systems, Chemically Cured
- MIL-DTL-18240** Fastener Element, Self-Locking, Threaded Fastener, 250 Deg. F Maximum
- MIL-I-19166** Insulation Tape, Electrical, High-Temperature, Glass Fiber, Pressure-Sensitive
- MS122076 - MS122115** Insert Cres Helical Coil Coarse Thread 1 dia. Nominal Length
- MIL-I-22129** Insulation Tubing, Electrical, Polytetrafluoroethylene Resin, Nonrigid
- MIL-PRF-23586** Sealing Compound (with Accelerator), Silicone Rubber, Electrical
- MIL-I-24391** Insulation Tape, Electrical, Plastic Pressure-Sensitive
- MIL-I-3190** Insulation Sleeving, Electrical, Flexible, Coated, General Specification
- MS33557** Nonstructural Rivets for Blind Attachment; Limitations for Design and Usage
- MS33522** Requirements for Rivets, Blind, Structural, Mechanically Locked and Friction Retainer Spindle, (Reliability and Maintainability) Design and Construction
- MS33540** General Practices for Safety Wiring and Cotter Pinning
- MIL-I-46058** Insulating Compound, Electrical (for Coating Printed Circuit Assemblies)
- MIL-A-46146** Adhesives - Sealants, Silicone, RTV, Noncorrosive
- MIL-DTL-53022** Primer, Epoxy Coating, Corrosion Inhibiting Lead and Chromate Free
- MIL-DTL-53030** Primer Coating, Epoxy, Water Based, Lead and Chromate Free
- MIL-DTL-53039** Coating, Aliphatic Polyurethane, Single component, Chemical Agent Resistant
- MIL-DTL-64159** Coating Water Dispersible Aliphatic Polyurethane, Chemical Agent Resistant
- MIL-DTL-81706** Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys
- MIL-A-83377** Adhesive bonding (structural) for Aerospace and other systems
- MIL-PRF-85045** General Specification for Cables, Fiber Optics

MIL-C-85485 Cable, Electric, Filter Line, Radio Frequency Absorptive

MIL-DTL-83528 General Specification for Gasketing Material, Conductive, Shielding Gasket, Electronic, Elastomer, EMI/RFI

2.2 U.S. Federal Standards²

FED-STD-H28 Screw-Thread Standards for Federal Services

FED-STD-595 Federal Standard: Colors used in Government Procurement

2.3 Telcordia³

Telcordia GR-20 Generic Requirements for Optical Fiber and Optical Fiber Cable

Telcordia GR-409 Generic Requirements for Indoor Fiber Optic Cable

2.4 TIA⁴

TIA 568-B.3 Optical Fiber Cabling Components Standard

2.5 NASA⁵

EEE-INST-002 Instructions for EEE Parts Selection, Screening, Qualification and Derating.

SP-8063 Lubrication, Friction, and Wear, NASA Space Vehicle Design Criteria

NASA 1228 Fastener Design Manual

2.6 ISTA⁶

ISTA-STD-0020 Global Method for Standardizing the Establishment of Insulated Shipping Container Performance

2.7 IPC⁷

IPC/WHMA-A-620 Requirements and Acceptance for Cable and Wire Harness Assemblies

IPC-CC-830 Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies

IPC-A-610 Acceptability of Electronic Assemblies

IPC-T-50 Terms and Definitions for Interconnecting and Packaging Electronic Circuits

J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies

2.8 SAE International⁸

AS7928 Terminals, Lug and Splices, Conductor, Crimp Style, Copper, Insulated, Rectangular Tongue, for Thin Wall Wire, Type II, Class 1 for 150 °C Total Conductor Temperature

AS21919 Clamp, Loop Type, Cushioned Support

AS23190 Straps, Clamps, and Mounting Hardware, Plastic and Metal for Cable Harness Tying and Support

AS25274 Cap, Electrical (Wire End, Crimp Style, Type II, Class 1) for 105 °C Total Conductor Temperature

2. www.fas.gsa.gov/pub/fedspecs/

3. www.telcordia.com

4. www.tiaonline.org

5. nepp.nasa.gov

6. www.ista.org

7. www.ipc.org

8. www.sae.org

AS39029 General Specification for Contacts, Electrical Connector

AS50881 Wiring, Aerospace Vehicle

AS81044 Wire, Electrical, Crosslinked Polyalkene, Crosslinked Alkane-Imide Polymer, or Polyarylene Insulated, Copper or Copper Alloy

AS83519 Shield Termination, Solder Style, Insulated, Heat-Shrinkable, Environment Resistant With Preinstalled Leads for Cables Having Tin or Silver Plated Shields (Class I)

AS85049 Electrical General Specification for Connector Accessories

2.9 IEC⁹

IEC 61000 Electromagnetic Compatibility

2.10 American Society of Mechanical Engineers¹⁰

ASME B1.1 Unified Inch Screw Thread Series

ASME B107.14 Hand Torque Tools

ASME Y14.100 Engineering Drawing Practices

2.11 ASTM¹¹

ASTM D495 Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation

ASTM D635 Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position

ASTM D638 Standard Test Method for Tensile Properties of Plastics

ASTM D4066 Standard Classification System for Nylon Injection and Extrusion Materials

ASTM D5363 Standard Specification for Anaerobic Single-Component Adhesives

ASTM D5948 Standard Specification for Molding Compounds, Thermosetting

3 ENGINEERING DESIGN

3.1 General The engineering design process is the execution of a plan, a sequence of events, to enable engineering teams to create functional systems or products. Typically it is a strategic approach considering many elements such as design objectives and requirements, product function, synthesis, analysis, product performance, testing and evaluation. In addition to functional requirements, enclosure design often necessitates the consideration of aesthetic, safety, economic and environmental aspects of the product's intended end use. Further, the design process should address reliability, heat dissipation, testability, the ease of manufacture and the ability to service or repair the unit. The output of the engineering design process is the definition or specification of an object satisfying a set of defined requirements. The design output is typically manifested as "engineering outputs documents" such as drawings, purchase specifications, or computer aided design (CAD) database models.

Section 3 outlines the basis for considering different methods & materials which are used in construction of electronic enclosures. The information herein provides guidance on why engineering design would choose specific materials and provides reasoning behind use of those materials. Advantages & disadvantages are outlined so consideration is provided for various aspects of the material.

9. www.iec.ch

10. www.asme.org

11. www.astm.org

3.1.1 Engineering Drawings Unless otherwise specified by or approved by the user, engineering drawings should conform to ASME Y14.100, "Engineering Drawing Practices," and the referenced documents cited therein. The types of drawings to be provided should be as agreed to between the user and the supplier. The user should specify if any of the drawings require specific user approval.

The type of engineering drawings may include some, but not necessarily all, of the drawing types described below:

- a. **Layout Drawing** – This type of drawing depicts design development requirements. It is similar to a detail, assembly, or installation drawing, except that it presents pictorial, notational, or dimensional data to the extent necessary to convey the design solution used in preparing other engineering drawings.
- b. **Detail Drawing** – A detail drawing provides the complete end-product definition of the part or parts depicted on the drawing. A detail drawing establishes item identification for each part described thereon.
- c. **Assembly Drawing** – An assembly drawing defines the configuration and contents of the assembly or assemblies depicted thereon. If the assembly drawing contains detailed requirements for one or more parts used in the assembly, it is a detail assembly drawing.
- d. **Installation Drawings** – An installation drawing provides information for properly positioning and installing items relative to their supporting structure and adjacent items, as applicable.
- e. **Altered Item Drawing** – An altered item drawing delineates the physical alteration of an existing item under the control of another design activity or defined by a nationally recognized standard.
- f. **Control Drawings** – A control drawing is a drawing disclosing engineering form, fit, function and performance requirements for the acquisition of interchangeable purchased items of existing designs, or items specially developed by vendors to the control drawing requirements. This category of drawing can be further sub-divided into;
 1. Procurement control drawing.
 2. Vendor item control drawing.
 3. Source control drawing.
 4. Envelope drawing.
- g. **Interface Drawing** – An interface drawing depicts physical and functional interfaces of related or co-functioning items. It does not establish item identification.
- h. **Identification Cross Reference Drawing** – An identification cross reference drawing is an administrative type drawing which assigns unique identifiers to provide a cross reference to the original incompatible identifier. The drawing does not establish item identification.
- i. **Electrical/Electronic Diagrams** – An electrical/electronic diagram depicts the elements or functions of electrical or electronic items using standard symbols in accordance with ANSI/IEEE 91 and IEEE 315 and connecting lines or data in tabular form.
- j. **Schematic Diagram or Circuit Diagram** – This is one form of an electrical/electronic diagram. A schematic diagram depicts the electrical connections and functions of a specific circuit arrangement without regard to the physical shape, or location of the elements.
- k. **Connection Diagram or Wiring Diagram** – This is one form of an electrical/electronic diagram. A connection diagram or wiring diagram depicts the general physical arrangements of electrical connections and wires between circuit elements in an installation or assembly. It contains the details necessary to make or trace connections involved.
- l. **Wiring List** – A wiring list consists of tabular data and instructions necessary to establish wiring connections. Wiring lists serve the same basis purpose as a connection diagram or wiring diagram; their tabular format allows their use in manufacturing requirements planning (MRP) database driven software systems (e.g., SAP, etc.).
- m. **Special Application Drawings** – A special application drawing includes the following types of drawings used for the manufacture of cable and wire harness assemblies;
 1. **Wiring Harness Drawing** – A wiring harness drawing specifies the engineering requirements and establishes item identification for a wiring harness.
 2. **Cable Assembly Drawing** – A cable assembly drawing depicts an electrical cable assembly of defined length, specifies the engineering requirements and establishes item identification for that assembly.

3.1.2 Content of Assembly Drawings Assembly drawings should include the following information, as a minimum, in addition to any information specified in ASME Y14.100 and the documents referenced therein. If the information is not

available from an industry recognized current standard, or from a current military specification, it need not be duplicated on the engineering drawings unless otherwise specified by the user. Additional detailed information may be required for the specific application and this information should be provided on the engineering drawings.

- a. Marking information.
- b. Safety related items.
- c. Bill of Materials (BOM) or separate parts list (PL).
- d. Hardware stack-up.
- e. Torque values for threaded items that require a torque.
- f. Isometric assembly views.
- g. Reference to the product design requirements that apply.
- h. Any distribution restriction (e.g., ITAR) and/or classification markings.
- i. Drawings should be formatted in a generic fashion such that the drawings can be used by any manufacturer who can manufacture the product. Drawings should not flow down supplier/manufacturer procedures; drawings should flow down user requirements, using generally accepted industry standards whenever possible.
- j. Interface dimensions (with tolerance) shown as INT in a rectangular box.
- k. Applicable environmental criteria (e.g., shock, vibration, temperature, etc.).
- l. Inspection and test criteria; if in separate procedure identify the procedure number.
- m. Foreign Object Debris (FOD) controls, if not already flowed down through a document of higher order of precedence (e.g., purchase order, special purchase order conditions).
- n. Application issues.
- o. Special handling, storage and processing.
- p. Application issues.
- q. Manufacturing processes.
- r. Information on cable and/or wire harnesses.

3.1.3 Bill of Materials (BOM)/Parts Lists (PL) A manufacturing release Bill of Materials (BOM) may consist of several sections, each containing information necessary for the implementation of required manufacturing action as authorized by a covering job order. Sample data and formats include:

- a. Job order.
- b. Numeric Parts List.
- c. Indented Parts List.
- d. Priority Make List.
- e. Priority Buy List.
- f. Floor Stock Requirements.
- g. Inventory Requirement Cards.
- h. Production Purchase Requisition.
- i. Shop Order Control Cards.
- j. Automated Manufacturing Planning System Files.

Bill of Material requirements may change due to the following:

- a. Customer requirements changes.
- b. Engineering bill of material changes.

3.1.4 General Design Considerations The following section lists many of the elements that must be considered during the design of electronic enclosures. These elements are for reference purposes only. Applicable governmental safety standards, environmental requirements, regulatory compliance requirements and industry standards must be identified and implemented within all systems and product designs.

3.1.4.1 General Manufacturing and Assembly All enclosure design must take into consideration the actual assembly operations required to consistently and efficiently manufacture the enclosure. Ergonomic accessibility, tool clearances, visual clearances, must be addressed during all phases of the design process.

The design team must strive for optimal ease of assembly and repair. Design teams should employ manufacturing alignment guides and features, include keying features to prevent any component from being installed in the wrong location or orientation. In addition, 'blind' component placements, connector mating or fastening operations should be minimized.

When designing an electronic enclosure, the logical order of how the enclosure is assembled and tested must be taken into account. Assembly order consideration can reduce or eliminate difficult assembly operations, damage to parts being installed and unnecessary steps to correct in-process assembly defects.

3.1.4.2 Thermal Management The foremost recommendation for successful thermal design is to minimize the amount of heat that needs to be removed. This can be accomplished by conservative design practices making use of power efficient components, keeping the overall system power density low and avoiding the need for active cooling. Thermal consideration at all sub system levels should be predicted with sufficient accuracy during the early design phase so that the operating and reliability constraints will be met in the final product.

The design team should always develop an enclosure with consideration of end use thermal performance and capability in mind. Prototype models are developed to validate cooling approaches and determine design limitations. Numerical models can help establish the level of cooling possible and help in identification of unrealistic goals before the design proceeds.

For example, given an enclosure volume of 400 in³, and a maximum allowable internal temperature rise of 20 °C, it would be imprudent to assume that 50 Watts could be dissipated by free convection methods alone.

3.1.4.2.1 Conduction All systems, even if convectively cooled, will use conduction for heat transfer at the component and printed board (PB).

Wherever possible, use PB traces and plane regions for the input and output power distribution of high power devices. The thermal conductivity of copper is approximately 1000 times greater than that of glass epoxy.

3.1.4.2.2 Free Convection Free convection designs require a conservative approach striving to minimize the overall system power density. Free convection design challenges occur when either too much dissipation is attempted in a too small volume/space or when lack of clean airflow paths result in localized hot spots.

$$\text{Natural convection cooling} = \frac{Q}{V} < \frac{0.1 \text{ watts}}{\text{in}^3} \text{ for } \Delta T < 20^\circ \text{C}$$

Where:

Q = Thermal energy

V = Volume

ΔT = Change in temperature

For vertically mounted PB's, higher power density components should be located toward the bottom of the card for spatially uniform heat dissipation. Though this arrangement tends to increase the ambient temperature of the circuitry above it, it is the high power density components that typically have the smallest operating margins and require a local cooling solution.

Utilize open layouts with clean unobstructed channels or paths for airflow around components. Enclosures should be well vented at both the top and the bottom so that external air can flow freely through the enclosure. For instance, venting only the bottom of an enclosure is unlikely to provide much, if any, cooling advantage. Measurements of internal air temperatures are recommended only for detection of stagnation points and air re-circulation.

3.1.4.2.3 Forced Convection Many elements of forced convection designs are similar to those of free convection. Utilize open layouts with clean unobstructed paths for airflow around components.

Use air plenums and strategic venting to route the cooling air over components with significant power dissipation.

Required minimum vent area in square inches can be approximated by dividing the fan free air cubic feet per minute

$$(CFM) \text{ by two } (A_{vent} = \frac{CFM}{2}).$$

Refer to 3.1.4.2.6 for recommendations on the use of cooling fans.

3.1.4.2.4 Radiation Radiation may account for as much as 1/3 of all heat loss. Painting unfinished steel and aluminum external and internal surfaces can attain emissivity values approaching 1.0. The greater the emissivity, the more efficient the radiator becomes. Heat loss due to radiation is a function of a temperature differential between the 'hot' body and the 'cold' body. If two bodies are at the same temperature, no transfer of heat energy through radiation is possible. See Table 3-1 for typical values of emissivity.

Table 3-1 Typical Values of Emissivity (for reference only)

Polished Aluminum	0.06/0.09
Anodized Aluminum	0.80
Conversion Coated Aluminum	0.01
Paint of any color (flat/dull)	0.80/0.95
Aluminum Oxide	0.33

3.1.4.2.5 Component Heat Transfer Local ambient temperatures should be monitored only to establish internal airflow characteristics, evidence of air re-circulation and areas of stagnation. This information offers insight into cooling inefficiencies and problem areas. Care should be taken when comparing measured data to manufacturer's maximum operating ambient specifications (T_a). In general, measured local ambient temperatures should not be used as a measure of device T_a .

It is generally accepted that every 10 °C [50 °F] rise in component temperature halves the life expectancy. This rule of thumb stems from empirical work used in the development of MIL-HDBK-217. MIL-HDBK-217 states however that long-term nominal operating junction temperatures lower than 70 °C [158 °F] have zero effect on reliability. Though reliability is directly linked to component operating temperature, efforts to reduce junction temperatures below 70 °C [158 °F] under nominal operating conditions don't necessarily result in additional, significant reliability improvements.

The issue of heat dissipation is a key factor in long-term reliability when dealing with high power density electronic components. Heat is generated as a result of electrical energy being converted to thermal energy during circuit activities. The junction temperature of a component directly affects circuit performance and reliability. It is therefore very important that the junction temperature of critical devices be determined and operating margins be understood under worst case operating conditions.

3.1.4.2.6 Cooling Fans Free convection cooling is typically preferred to the use of cooling fans. An attempt should be made to maintain average internal air temperatures less than ambient temperature + 20 °C. When a decision is made to use a cooling fan, several points should be considered before an appropriate fan can be selected and implemented.

There are two basic types of fan applications to provide forced convection heat transfer - either evacuate the enclosure or pressurize the enclosure. When evacuating an enclosure, the main advantage is that air distribution inside is flexible (i.e., inlet air vents can be located to ensure proper cooling in desired locations). Inlet air velocities can be kept small by size and placement of inlet vents so that the need for filtering is minimized or eliminated completely. A primary disadvantage of an exhaust side fan is a reduction in long-term fan reliability due to a higher fan ambient temperature. The other approach is to pressurize the enclosure by orienting the fan to move air inward. The enclosure remains pressurized in this manner and the fan remains generally at room ambient conditions, improving fan life and reliability.

Note: It is important to be aware of the effect of high fan ambient temperatures on fan life expectancies. Some of the factors to be considered in fan selection include: required airflow, AC or DC power, voltage, speed, life expectancy, EMI/RFI, heat dissipation, locked rotor protection and audible noise.

3.1.4.2.7 Air Flow Requirements Before a fan can be specified, the approximate airflow required to dissipate the heat generated within an enclosure should be determined. Both the amounts of power to be dissipated and the air density must be known in order to determine the required airflow. The basic forced convection heat transfer equation is as follows:

$$Q = \Delta T C_p m_a$$

Where:

Q = total power or rate of heat dissipation or heat transfer (W).

C_p = air specific heat (0.24 Btu/lbm·°F)

M_a = mass flow rate = $\rho \cdot A_v$

ΔT = average difference between enclosure air and surrounding ambient air temperature.

ρ = air density = 0.075 lbm/ft³ @ STP

A_v = volumetric flow rate (CFM)

Therefore,

$$Q = \Delta T C_p p A_v$$

$$A_v = Q / \Delta T \cdot C_p \cdot p$$

Unit Conversion: $CFM = Q / (^\circ F)(Btu/lbm \cdot ^\circ F)(lbm/ft^3)$

$$Q = Btu/min$$

$$W = 3.412 \text{ Btu/hr} = 0.05687 \text{ Btu/min}$$

$$CFM = \frac{W(0.05687)}{\Delta T(0.24)(0.75)}$$

Finally,

$$CFM = \frac{3.159W}{\Delta T} \text{ W in watts, } \Delta T \text{ in } ^\circ F$$

$$CFM = \frac{1.76W}{\Delta T} \text{ W in watts, } \Delta \text{ in } ^\circ C$$

These equations can be used as an approximate guide to determine the necessary airflow to remove a given amount of heat at a desired temperature rise. The specific heat of air is considered constant in these equations.

It should be pointed out that it is the mass flow rate (not the volumetric flow rate) that determines the amount of cooling. For free convection cooled devices, airflow is somewhat self-compensating for the altitude influenced density change, but not for fan cooled devices. Therefore, as operating altitudes or air pressures vary so too does air density and the ultimate performance of a cooling system. If the atmospheric density at which the equipment is to operate deviates significantly from standard air density (sea level), the equations should be multiplied by the following correction factor, k (see Table 3-2):

Table 3-2 Correction Factor for Altitude

Altitude (ft)	Correction Factor (k)
0	1
1000	1.037
2000	1.075
3000	1.116
4000	1.157
5000	1.202
6000	1.248

In normal applications, the power to be dissipated is usually determined and fixed. The variable where a designer may compromise is in ΔT which, though dictated by the maximum permissible temperature rise in the smallest margin component, can be varied. Note: ΔT is an average value. If local 'hot spots' are present, better flow distribution should be investigated, often achievable by way of properly located inlet/outlet vents and/or internal baffling. As mentioned earlier, as a general goal, ΔT should remain below 20 °C [68 °F].

To improve fan life, low speed fans (e.g., <4000 rpm) should be selected where appropriate. The primary mode of fan failure is bearing failure, not fan electronics. With this in mind, it is generally better to employ a larger, lower speed fan over a smaller, fast speed fan when space permits.

Audible noise can originate from several sources, some of which can be controlled by the enclosure designer. Aerodynamic noise is a result of turbulence caused by the fan blades. The predominant component of this noise is at the blade-passing frequency, the frequency at which blades pass the struts that connect the motor to the fan's outer casing. This is inherent in the fan design. Speed is therefore a major contributor to fan noise. The effect speed has on noise can be best defined by one of the fan laws:

$$dB_1 = dB_2 * 50 \log \left(\frac{RPM_1}{RPM_2} \right)$$

Where:

dB_1 = Fan noise initial

dB_2 = Fan noise final

RPM_1 = Fan speed initial

RPM_2 = Fan speed final

As an example, a 20% reduction in fan speed reduces fan noise by 5dB.

3.1.4.3 Structural-Born Noise Structural-born noise can be caused by unbalance that causes vibration. If this vibration is at a frequency that matches a resonant frequency of the enclosure, it can be amplified to an unacceptable level.

3.1.4.4 Mechanical Noise Mechanical noise can be caused by damaged or worn bearings and is properly mitigated only by fan replacement. As mentioned earlier, bearing selection is key in both extending life expectancy and limiting the degree of audible noise.

In an effort to minimize noise, the enclosure designer should consider the following:

- a. Avoid placing obstructions in high air-velocity areas close to the fan.
- b. Use mechanical isolators to reduce or eliminate structural-born noise.
- c. Design mounting structure resonant frequency to be at least 3dB from blade-passing frequency.
- d. Mount the fan on an interior surface of the enclosure rather than on an exterior surface.
- e. Design for the largest, slowest moving fan possible.

3.1.4.5 Design for Safety When designing electronic enclosures, care must be given to ensure the assembly meets all regulatory statutes and industry standards. The following are just a few of the elements that must be considered:

- a. Suspended mass.
- b. Sharp edges.
- c. High Voltage /Amperage protections.
- d. Tip hazard.
- e. Operator protections.

3.1.4.6 Shipping and Physical Shock Early in the enclosure design, the physical robustness of the enclosure must be considered. Provisions must be made to protect sensitive components or elements of the enclosure. For example, a sensitive movement device may require a shipping 'lock-down' feature be designed in to ensure the device will be protected during transport and the product can arrive at the end use location without physical damage. When practical, the designer should consider specifying the use of shock-sensing devices to indicate potential shipping damage.

If applicable, care should be taken to ensure packaging is designed to prevent damage to the final product during shipment. It is recommended that packaging requirements are documented and validated to adequately protect the product. Common practices used to validate packaging include, but are not limited to, drop-testing as well as shake and vibration testing.

In addition to physical damage, the shipping package design teams must consider environmental concerns. Accommodation must be made protect enclosures from moisture, corrosives and other contaminants, especially for items intended for international ocean surface shipping.

3.2 Selection of Parts, Materials and Tools Normally, the parts and materials needed to manufacture assemblies, or otherwise needed to install the assemblies into their ultimate next-higher level assembly, will have been specified by the user activity, or otherwise, will have been defined on the applicable documentation (assembly drawings, wire lists, parts lists, etc.), which may or may not require user approval.

This handbook will provide some general guidance that may be useful when parts and materials have otherwise not been previously selected or otherwise mandated.

Tools needed are normally selected by the manufacturer. However, some tooling may have been selected or otherwise mandated by the user.

3.2.1 Standard Parts and Materials Whenever possible, standard parts and materials (items purchased to recognized commercial, industrial or military/NASA specifications) should be used. Such items should be suitable for their intended purpose.

3.2.2 Non-Standard Parts and Materials Any parts and materials not selected in accordance with 3.2.1 are considered non-standard and as such user approval may be required for their use.

3.3 General Fastening Through-bolting should be used wherever practicable. For electrical panels and other applications where frequent disassembly is required, blind nuts and captive fasteners should be used when practical. Similarly, these types of fasteners should be used when practical to prevent a loose fastener from dropping into electrical equipment. See Section 8 for more information on fasteners and fastening.

4 MATERIALS AND PROCESSES – METALS

4.1 Alloy Selection Primary considerations include mechanical properties such as tensile strength, modulus of elasticity and work resistance to mechanical fatigue. The material should be sufficiently stiff and strong to withstand applied forces and vibration in the service environment while still being readily formable and machinable.

The alloy should resist corrosion in the service environment. Protective surface treatments such as conversion coatings, platings, or paints may be used and metals differ in their capacities to accept such coatings. Dissimilar metals may introduce potential for galvanic corrosion depending on the surface treatments and galvanic series of the metals. The design should consider any other metals that may come into contact with the chassis, for example in threaded fasteners or other hardware.

Joining processes such as welding or brazing can affect mechanical properties (i.e., temper). With some alloys, mechanical properties may be restored or partially recovered through heat treatment.

4.2 Aluminum Alloys Aluminum is light, strong, resists corrosion and readily accepts chromate conversion coatings and paint. It is easily stamped, formed, machined, welded and dip-brazed.

4.2.1 Form Aluminum wrought products are those that have been subjected to plastic deformation by hot and cold working mill processes such as rolling, extruding and drawing, either singly or in combination, transforming cast aluminum ingots into the desired product form. Commercial wrought aluminum products are divided into flat rolled products (i.e., plate, sheet and foil); bar, rod and wire; tubular products; shapes and forgings. Flat rolled products are classified by thickness. Plate is classified as flat rolled products with thicknesses >6.35 mm [>0.25 in], while sheet and foil have thickness ranges of 0.15 to 6.32 mm [0.006 to 0.249 in] and <0.15 mm [<0.006 in], respectively.

4.2.2 Alloys Most alloys are only available in certain product forms. A standard four digit numbering system has been established to designate wrought aluminum and aluminum alloys (see Table 4-1).

Table 4-1 Wrought Aluminum Alloy Designation System

Alloy Series	Principle Alloying Element
1xxx	99.000% Minimum Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

4.2.3 Temper The temper designation system classifies the mechanical work and/or thermal treatment given to all forms of wrought and cast aluminum and aluminum alloys. It does not apply to ingots. The temper designation follows the alloy designation, the two being separated by a hyphen. A letter specifies basic temper.

4.3 Steel Though stronger than aluminum, sheet steel is less common in fabricated electronic enclosures. It is more difficult to form, stamp and machine than aluminum. Steel cannot be dip brazed and should be joined by welding or mechanical means. Welding requires special skills, and if left unpainted, the “heat tint” from welding may be cosmetically objectionable. Welding typically affects mechanical properties, which may not be restorable by heat treatment

4.3.1 Carbon Steel Carbon steels are the most important group of engineering alloys, with relatively low cost and wide range of properties, and account for 85% of the steel produced in the United States. They are defined as steels having no specified minimum quantity for any alloying element, other than the commonly accepted amounts of manganese ($<1.65\%$), silicon ($<0.60\%$) and copper ($<0.60\%$), and containing only an incidental amount of any element other than carbon, manganese, silicon, and copper.

Mn, Cu, S & P). Carbon steels are divided into categories according to carbon content: low carbon steels contain up to 0.30% C, medium carbon steel contain 0.30-0.60% C and high-carbon steels contain from 0.60-1.0% C.

In general, plain-carbon steels have the following limits:

1. They cannot be strengthened past 100 ksi without a significant loss of toughness and ductility.
2. Large sections cannot be made martensitic throughout, and thus are not thoroughly hardenable.
3. Rapid quench rates are necessary for full hardening.
4. They have poor impact resistance at low temperatures.
5. They have poor corrosion resistance and oxidize at elevated temperatures.

Because of these limitations, low alloy steels have been developed. Low alloy steels are a category of ferrous materials that exhibit mechanical properties superior to plain carbon steels, resulting from additions of alloying elements such as Ni, Cr and Mo. The total alloy content can range from 2.07% up to levels just below that of stainless steels, which contain a minimum 10% Cr. For many low-alloy steels, the primary function of the alloying elements is to increase hardenability in order to optimize mechanical properties and toughness after heat treatment.

4.3.2 Stainless Steel Stainless steels are iron-based alloys containing at least 10.5-12% chromium. Other elements (i.e., Mo, Cu, Ti, Al, Nb, N, S & Se) are added to impart other desired qualities. They are widely used in engineering applications for their excellent corrosion resistance which results from the chromium content.

Small amounts of chromium (up to 5%) improve the corrosion resistance of steels, but do not make them stainless. A minimum of 10.5-12% chromium is required to form a stable, passive chromium oxide surface layer that protects the underlying metal from corrosion.

4.3.2.1 Austenitic Stainless Steels Austenitic stainless steels are essentially ternary iron-chromium-nickel alloys containing 16-25% Cr and 7-35% Ni. Other elements (i.e., Mo, Cu, Si, Al, Ti & Nb) are also added to impart added corrosion or oxidation resistance. Sulfur and selenium are added to improve machinability. These alloys are classified austenitic as a result of their microstructure being mainly austenite at all normal heat treatment temperatures. Austenitic stainless steels are widely used for the corrosion resistance, good mechanical properties and formability. They are essentially non-magnetic in the annealed condition and can be hardened only by cold working. Types 302 and 304 are the most widely used of all the stainless steels for ambient and elevated temperature service.

4.3.2.2 Ferritic Stainless Steels Ferritic stainless steels are essentially iron-chromium alloys containing 12-30% chromium. These alloys are classified as ferritic as a result of their structure being ferrite at all normal heat treatment conditions. The ferritic stainless steels are ferromagnetic and have good ductility and formability, but are not as widely used as the austenitic grades because of lower elevated temperature strength. Ferritic stainless steels can be divided into two groups based on chromium content. Group 1 contains alloys with chromium contents of 15-18% and approximately 0.06% carbon. Type 430 (17% Cr & 0.06% C) is a typical example. Group 2 contains alloys with chromium contents of 25-30% chromium and approximately 0.08% carbon. Type 446 (25% Cr & 0.08% C) is an example.

4.3.2.3 Duplex Stainless Steels Duplex stainless steels have a mixed structure of ferrite and austenite. The amount of each phase is a function of the composition and heat treatment. Most alloys have equal amounts in the annealed condition. The major alloying elements are chromium (21-30%) and nickel (3.5-7.5%), but Mo (up to 4%), N, Cu, Si and W may be added to control the amounts of phases and to impart certain corrosion resistance characteristics.

4.3.2.4 Martensitic Stainless Steels Martensitic stainless steels are Iron-chromium alloys containing 10.5-18% chromium with enough carbon to produce the hard martensitic structure after heat treating and quenching. Carbon content can be up to and exceed 1.2%. Additions of N, Ni and Mo in combination with lower carbon levels improve the toughness of these alloys. Sulfur and selenium additions improve machinability. These alloys possess the highest strength and hardness of all stainless steels, but have poor corrosion resistance. Martensitic stainless steels are ferromagnetic and can be hardened by heat treatment. Tempering after quenching is often performed to improve toughness and ductility. Type 410 is a general purpose heat-treatable martensitic alloy used for pump shafts, bolts, bushings, etc.

4.3.2.5 Precipitation Hardening Stainless Steels Precipitation hardening stainless steels are chromium-nickel grades with additions of aluminum and copper for precipitation hardening. They may be austenitic, semi-austenitic, or martensitic. Type 17-7PH is an example of the semi-austenitic type. It has approximately the same composition as type 304, but contains

stainless, but has 1.2% aluminum for precipitation hardening. Type 17-4PH is an example of the martensitic type. It contains copper as a precipitation-hardening element.

4.4 Other Metals Rarely, electronic enclosures may be fabricated from sheet copper, titanium, or other metals. The expense and difficulty in working with these materials limits their use to specialized applications.

4.5 Castings

4.5.1 General Castings may provide more mechanical strength than sheet metal construction, particularly for applications with high stress, shock (g-loads), or vibration. Castings may be formed with stronger fins, brackets, or mounting features, and are preferred when the enclosure should be pressurized, backfilled with inert gas, or sealed for operation at altitude. Additional information can be found in MIL-HDBK-454 Guideline 21.

Thin-walled castings are common, but casting construction usually entails some weight penalty when compared with sheet metal. Due to limitations of the process, castings may not be preferred when the design requires enclosed spaces such as air plenums.

Molds require initial non-recurring cost, and challenging applications may require considerable process development, including trial and error.

Die casting should not be used for load-bearing applications.

4.5.2 Casting Drawings The casting drawing can be a particularly sensitive issue in the electronics company. Many electronic companies have a variety of problems associated with castings received from the foundry that do not embody the features that the designer thought had been incorporated into the drawing set. Foundries have a language peculiar to themselves and the constraints of foundry practice on design callouts is not clearly understood by most electronic packaging designers. An attempt will be made to define some of the principle casting design considerations.

4.5.2.1 Viewing Casting drawings generally should depict two sets of views. One set incorporates the cast and machined contour dimensions, the other specifies the machine hole dimensions only. Both sets should be separated by a vertical division line so that the cast and machined contour portion can be distinguished from the machined hole portion. Simple castings may have both sets combined into one, provided clarity and legibility are not affected.

It is general policy to produce separate casting and machined drawings. If the design plan is to do very minor machining or drilling to the casting, a combined drawing may be considered. When combined casting and machining drawings are made, great care should be exercised to make sure that the dimensioning cannot be misinterpreted in a manner which would make the casting unusable (see Figure 4-1).

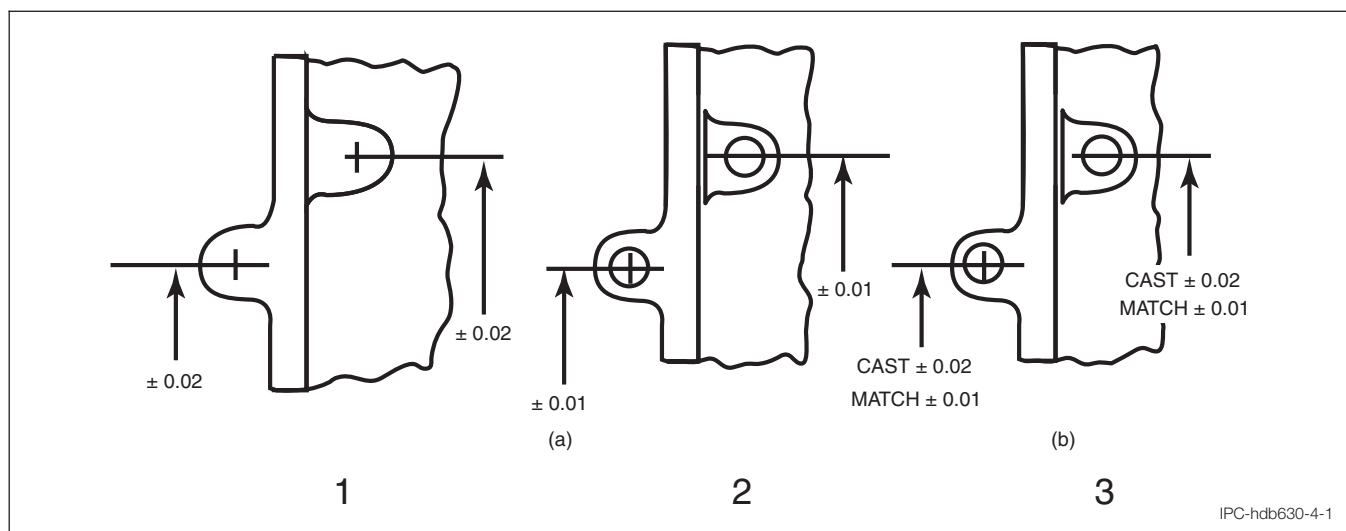


Figure 4-1 Casting Views

1. Casting Drawing
2. Machining Drawing
3. Combination Drawing

4.5.2.2 Casting Contour One cast surface not subsequently machined should be selected while as many other cast surfaces as practical are dimensioned in each of the three mutually perpendicular planes. These are the cast datum surfaces and should be selected on the basis of accessibility and stability (those which will give the broadest base and are least apt to be affected by working and springing when clamped in a fixture.).

All box locations should be dimensioned in the contour views. In addition, all cored holes should be indicated in the contour views and labeled “Cored Hole.”

4.5.2.3 Cast Surfaces All surfaces shown cast may be machined to meet drawing dimensions unless otherwise specified. This is often necessary in order to remove fins, risers, gates, test coupons and temporary stiffeners used to prevent warping. When a specific area should remain “as cast” (no machining permitted) for functional purposes, then an applicable note should be specified on the drawing.

4.5.2.3.1 Casting Surfaces for Electrical Grounding As-cast surfaces should not be used for electrical grounding points. For aluminum castings, the use of skim machining to remove the as cast finish, followed by a chem-film treatment (e.g., MIL-DTL-5541 Class 3) is the preferred approach.

4.5.2.4 Casting Dimensioning Castings, unlike machined parts, have a tendency to vary uniformly in all directions. For this reason, chain dimensioning is preferable to base line dimensioning. If base line dimensioning is used, the base line should be chosen as near the casting center as possible as this reduces the requirements for large tolerances on long dimensions, which in turn might produce a false indication of probable accuracies obtainable.

Figure 4-2 illustrates the difference in dimensioning methods. The mirror-image cores (E and F) should be dimensionally identical. However, by using the method in Figure 4-2(a) the tolerance build-up in core F would appear as being much greater than E. The method used in Figure 4-2(b) provides about equal tolerances in E and F.

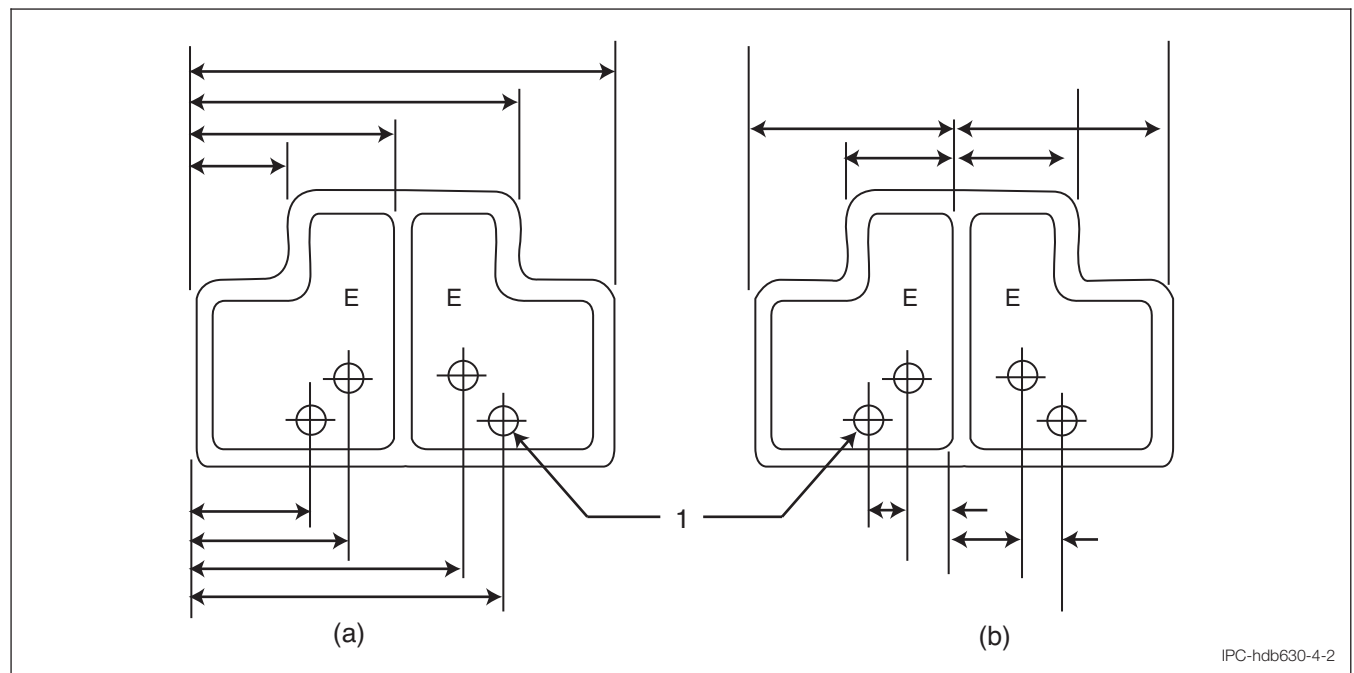


Figure 4-2 Chain vs. Baseline Dimensioning

- a. Baseline Dimensioning
- b. Chain Dimensioning

Figure 4-3 shows two identical bosses on a casting, but because the baseline system of dimensioning was used, boss “(a)” has a larger tolerance than boss “(b),” even though the thickness of the bosses in the actual casting would probably not vary more than ± 0.25 mm [± 0.010 in].

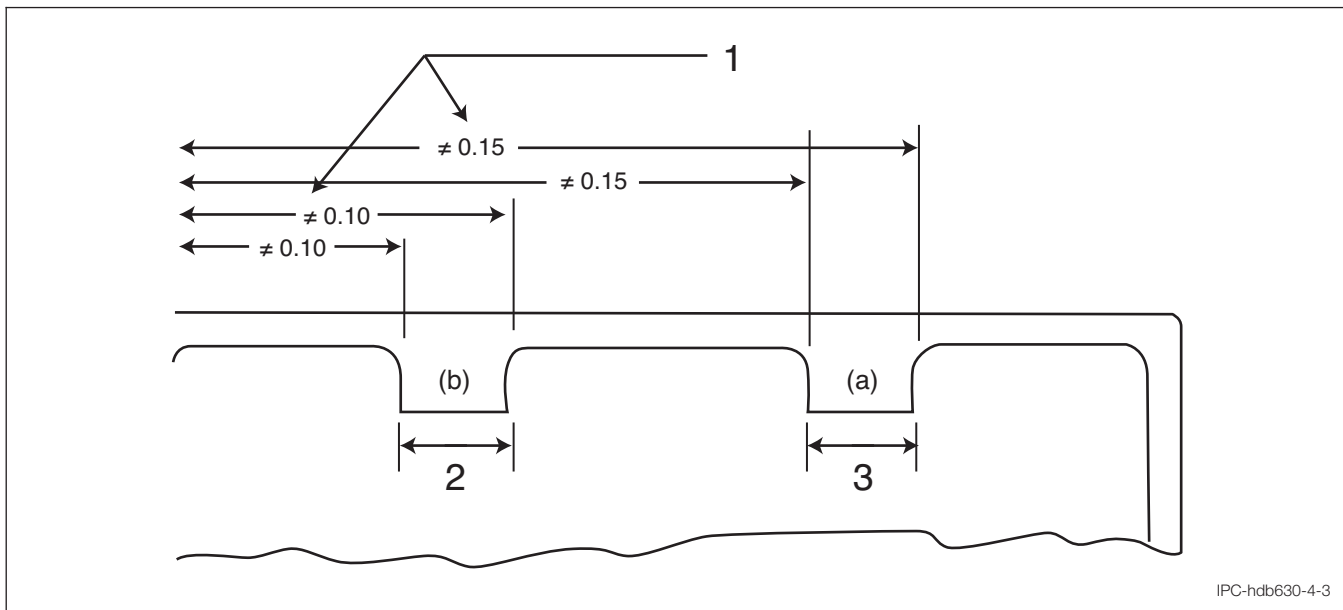


Figure 4-3 False Tolerances

1. Based on tolerance required per inch of length
2. Cumulative Tolerance = ± 0.020 in
3. Cumulative Tolerance = ± 0.030 in

4.5.2.5 Machining Stock No matter how a casting is dimensioned, the size will vary per inch of distance from the theoretical center. This differs from a part machined from solid stock, where a feature 254 mm [10 in] from a given point can be milled as accurately as a feature 25.4 mm [1 in] from that same point. Because of this basic difference and the fact that machining of a casting should generally use one feature as a baseline from which all other machined features in a given plane are measured, greater amounts of stock should be provided in the casting. Boss lengths should be elongated in the long direction of a casting. For example, see Figure 4-4.

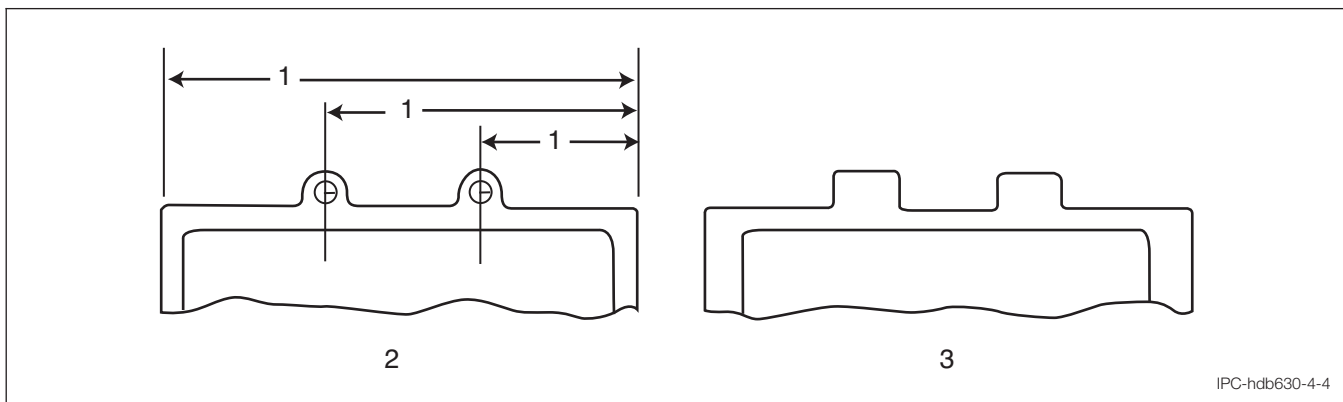


Figure 4-4 Adequate Stock Allowance

1. Machined
2. Desired Product (To be cast and machined)
3. Casting Design (Anticipates machining and casting variation and provides Adequate stock for machining)

4.5.2.6 Machining Cast surfaces should not be located from machined surfaces. Parts should be located in accordance with the three plane concept for machining. When adequate flat surfaces do not exist on a casting, which would allow repeatable measurements to be made for both machining and inspection, datum point dimensioning should be used.

4.5.2.7 Accuracy The parting lines between any two mold pieces, including cores, should be considered in establishing tolerances. Suggested practice for minimizing the effects of parting lines is to dimensionally relate, as isolated groups, only those features formed by the same part or mold, and then establish relationships between groups with as few dimensions as possible (see Figure 4-5). The numbered callouts shown in Figure 3-5(c) indicate the probable orders of accuracy obtainable in various castings because of accuracy obtainable in various parts of castings because of parting line effects.

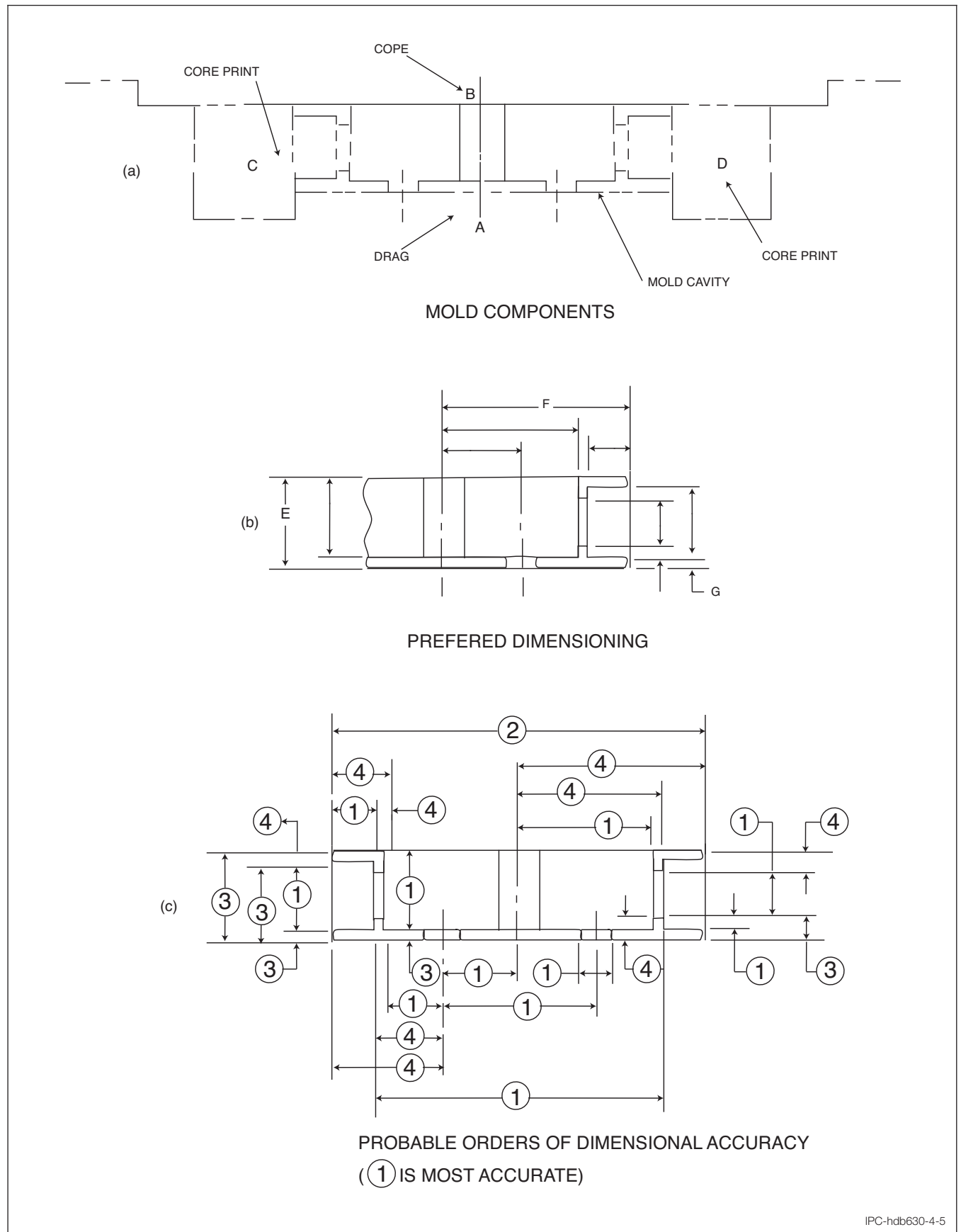


Figure 4-5 Effect of Accuracy Due to Different Mold Pieces

4.5.2.8 Tolerances

Typical casting tolerances are shown in Table 4-2.

Table 4-2 Casting Tolerance

TYPE OF CASTING			SAND		PERMANENT MOLD (b)		DIE		PLASTER MOLD		INVESTMENT		SHELL MOLD	
CONDITION			NORM	MIN	NORM	MIN	NORM	MIN	NORM	MIN	NORM	MIN	NORM	MIN
Linear (c)	Per inch or fraction of dimension	Al & Mag Steel	0.005	0.003	0.005	0.003	0.003	0.002	0.005	0.003	0.005	0.005	0.005	0.002
			0.008	0.005							0.005	0.005	0.005	0.002
	Minimum per dimension (up to 7 in)	Al & Mag Steel	0.03	0.02	0.01	0.01							0.02	0.01
			0.06	0.03									0.03	0.02
Angular (d)			1°	½°	1°	¼°	1°	¼°	1°	¼°	⅛°	¼°	1°	⅛°
Surface Texture: micro inches AA(e)			500		125		63		63		63		125	
Mismatch (f)			0.016		0.012		0.01		0.01		0.005		NONE	0.01

4.5.2.8.1 Critical/High Stress Locations Casting drawings should clearly define any/all critical/high stress locations as well as the minimum mechanical strength requirements at those identified locations. It is also common to identify any/all weld repair keep-out zones, which are often the same as critical/high stress locations.

4.6 Machined Metal (Hog-Out Construction) Machined assemblies offer many of the advantages and disadvantages of castings. For small quantities, unit costs may be lower than for castings.

4.6.1 Hog-Out of Thick Plate Stock (>6 inches) The machining of thick plate stock may require post machining heat treatment to ensure that uniform material properties are achieved. A multi-machine process may be required to deal with distortion due to heat treatment (e.g., 80% machining, followed by heat treatment and finished with completion of machining).

4.7 Welding There are many different types of welding processes that may be used for welding end-item enclosures. This section of the handbook will address only the most commonly used welding processes.

A significant amount of tutorial information on welding is readily available, and industry has developed various standards that define welding processes, weld symbols, weld materials, welding equipment, weld procedure qualification requirements, weld inspector qualification requirements and additional requirements pertaining to welding. One major source of welding information/standards is available from the American Welding Society (AWS) at <http://www.aws.org>.

The AWS definition for a welding process is “a materials joining process which produces coalescence of materials by heating them to suitable temperatures with or without the application of pressure or by the application of pressure alone and with or without the use of filler material.”

AWS has grouped the processes together according to the “mode of energy transfer” as the primary consideration. A secondary factor is the “influence of capillary attraction in effecting distribution of filler metal” in the joint. Capillary attraction distinguishes the welding processes grouped under “Brazing” and “Soldering” from “Arc Welding,” “Gas Welding,” “Resistance Welding,” “Solid State Welding” and “Other Processes.”

The welding processes, in their official groupings, are shown by Table 4-3. This table also shows the letter designation for each process. The letter designation assigned to the process can be used for identification on drawings, tables, etc.

4.7.1 Arc Welding The arc welding group includes eight specific processes, each separate and different from the others but in many respects similar.

4.7.1.1 Carbon Arc Welding (CAW) The carbon arc welding (CAW) process is the oldest of all the arc welding processes and is considered to be the beginning of arc welding. The Welding Society defines carbon arc welding as “an arc welding process which produces coalescence of metals by heating them with an arc between a carbon electrode and the work-piece. No shielding is used.

Table 4-3 AWS Welding Processes and Letter Designation

Group	Welding Process	Letter Designation
<i>Arc welding</i>	Carbon Arc	CAW
	Flux Cored Arc	FCAW
	Gas Metal Arc	GMAW
	Gas Tungsten Arc	GTAW
	Plasma Arc	PAW
	Shielded Metal Arc	SMAW
	Stud Arc	SW
	Submerged Arc	SAW
<i>Brazing Oxyfuel Gas Welding</i>	Diffusion Brazing	DFB
	Dip Brazing	DB
	Furnace Brazing	FB
	Induction Brazing	IB
	Infrared Brazing	IRB
	Resistance Brazing	RB
	Torch Brazing	TB
	Oxyacetylene Welding	OAW
	Oxyhydrogen Welding	OHW
	Pressure Gas Welding	PGW
<i>Resistance Welding</i>	Flash Welding	FW
	High Frequency Resistance	HFRW
	Percussion Welding	PEW
	Projection Welding	RPW
	Resistance-Seam Welding	RSEW
	Resistance-Spot Welding	RSW
	Upset Welding	UW
<i>Solid State Welding</i>	Cold Welding	CW
	Diffusion Welding	DFW
	Explosion Welding	EXW
	Forge Welding	FOW
	Friction Welding	FRW
	Hot Pressure Welding	HPW
	Roll Welding	ROW
	Ultrasonic Welding	USW
<i>Soldering</i>	Dip Soldering	DS
	Furnace Soldering	FS
	Induction Soldering	IS
	Infrared Soldering	IRS
	Iron Soldering	INS
	Resistance Soldering	RS
	Torch Soldering	TS
	Wave Soldering	WS
<i>Other Welding Processes</i>	Electron Beam	EBW
	Electroslag	ESW
	Induction	IW
	Laser Beam	LBW
	Thermit	TW

Pressure and filler metal may or may not be used.” It has limited applications today, but a variation or twin carbon arc welding is more popular. Another variation uses compressed air for cutting.

4.7.1.2 Shielded Metal Arc Welding (SMAW) The development of the metal arc welding process soon followed the carbon arc. This developed into the currently popular shielded metal arc welding (SMAW) process defined as “an arc welding process which produces coalescence of metals by heating them with an arc between a covered metal electrode and the work-piece. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.”

4.7.1.3 Submerged Automatic/Arc Welding (SAW) Submerged automatic welding utilizing bare electrode wires was used in the 1920s, but it was the submerged arc welding (SAW) process that made automatic welding popular. Submerged arc welding is defined as “an arc welding process which produces coalescence of metals by heating them with an arc or arcs between a bare metal electrode or electrodes and the work piece. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod.” It is normally limited to the flat or horizontal position.

4.7.1.4 Gas Tungsten Arc Welding (GTAW) The need to weld nonferrous metals, particularly magnesium and aluminum, challenged the industry. A solution was found called gas tungsten arc welding (GTAW) [also known as tungsten inert gas (TIG) welding] and was defined as “an arc welding process which produces coalescence of metals by heating them with an arc between a tungsten (non-consumable) electrode and the work piece. Shielding is obtained from a gas or gas mixture.”

4.7.1.5 Plasma Arc Welding (PAW) Plasma arc welding (PAW) is defined as “an arc welding process which produces a coalescence of metals by heating them with a constricted arc between an electrode and the work piece (transferred arc) or the electrode and the constricting nozzle (non-transferred arc). Shielding is obtained from the hot ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas.”

4.7.1.6 Gas Metal Arc Welding (GMAW) Another welding process also related to gas tungsten arc welding is known as gas metal arc welding (GMAW) (MIG). It was developed in the late 1940s for welding aluminum and has become extremely popular. It is defined as “an arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work piece. Shielding is obtained entirely from an externally supplied gas or gas mixture.” The electrode wire for GMAW is continuously fed into the arc and deposited as weld metal. This process has many variations depending on the type of shielding gas, the type of metal transfer and the type of metal welded.

4.7.1.7 Flux-Cored Arc Welding (FCAW) A variation of gas metal arc welding has become a distinct welding process and is known as flux-cored arc welding (FCAW). It is defined as “an arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work piece. Shielding is provided by a flux contained within the tubular electrode.” Additional shielding may or may not be obtained from an externally supplied gas or gas mixture.

4.7.1.8 Stud Arc Welding (SW) The final process within the arc welding group of processes is known as stud arc welding (SW). This process is defined as “an arc welding process which produces coalescence of metals by heating them with an arc between a metal stud or similar part and the work piece.” When the surfaces to be joined are properly heated they are brought together under pressure. Partial shielding may be obtained by the use of ceramic ferrule surrounding the stud.

4.7.1.9 Oxy Fuel Gas Welding (OFW) Oxy fuel gas welding is “a group of welding processes which produces coalescence by heating materials with an oxy fuel gas flame or flames with or without the application of pressure and with or without the use of filler metal.”

There are four distinct processes within this group and in the case of two of them, oxyacetylene welding (OAW) and oxy-hydrogen welding (OHW), the classification is based on the fuel gas used. The heat of the flame is created by the chemical reaction or the burning of the gases. In the third process, air acetylene welding, air is used instead of oxygen, and in the fourth category, pressure gas welding (PGW), pressure is applied in addition to the heat from the burning of the gases. This welding process normally utilizes acetylene as the fuel gas. The oxygen thermal cutting processes have much in common with this welding process.

4.7.2 Resistance Welding (RW) Resistance welding is “a group of welding processes which produces coalescence of metals with the heat obtained from resistance of the work to electric current in a circuit of which the work is a part, and by the application of pressure.” In general, the difference among the resistance welding processes has to do with the design of

the weld and the type of machine necessary to produce the weld. In almost all cases the processes are applied automatically since the welding machines incorporate both electrical and mechanical functions.

4.7.2.1 Resistance Seam Welding (RSEW) Resistance seam welding is a type of resistance welding that utilizes roller type electrodes in lieu of fixed electrodes to apply pressure and heat to form the weld joint. This process is used to form seam welds between metals. In this process, a series of spot welds is made without retracting the electrode wheels or releasing the welding pressure. Weld speed, current magnitude, current waveform, cooling system and the electrode parameters such as force, shape and diameter are all interrelated and should be tightly controlled to produce a quality weld.

4.7.2.2 Resistance-Spot Welding (RSW) Resistance welding is one of the oldest of the electric welding processes in use by industry today. The weld is made by a combination of heat, pressure and time.

As the name resistance welding implies, it is the resistance of the material to be welded to current flow that causes a localized heating in the part. The pressure exerted by the tongs and electrode tips, through which the current flows, holds the parts to be welded in intimate contact before, during and after the welding current time cycle. The required amount of time current flows in the joint is determined by material thickness and type, the amount of current flowing and the cross-sectional area of the welding tip contact surfaces.

4.7.3 Other Welding Processes This group of processes includes those, which are not best defined under the other groupings. It consists of the following processes: electron beam welding (EBW), laser beam welding (LBW), thermit welding (TW) and other miscellaneous welding processes in addition to electrosag (ESW) welding which was mentioned previously. These processes will not be discussed in the handbook.

4.7.4 Deciphering Weld Symbols When welds are specified on engineering and fabrication drawings, a cryptic set of symbols is used as a sort of shorthand for describing the type of weld, its size and other processing and finishing information (see Figure 4-6). The complete set of symbols is given in a standard published by the American National Standards Institute and the American Welding Society: ANSI/AWS A2.4, Symbols for Welding and Nondestructive Testing.

The horizontal line—called the reference line—is the anchor to which all the other welding symbols are tied. The instructions for making the weld are strung along the reference line. An arrow connects the reference line to the joint that is to be welded. In the Figure 4-6 example, the arrow is shown growing out of the right end of the reference line and heading down and to the right, but many other combinations are allowed.

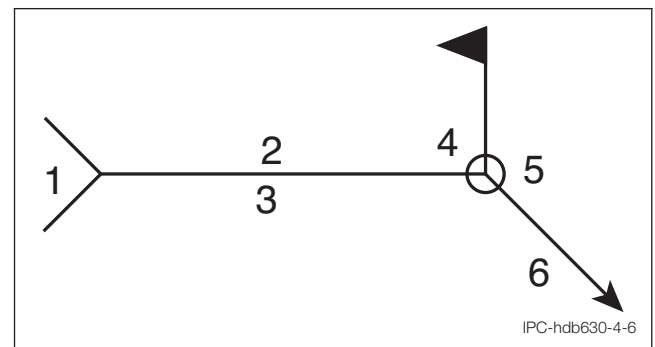


Figure 4-6 The Structure of the Welding Symbol

1. Tail
2. Weld info for other side
3. Weld info for arrow side
4. Field weld symbol
5. Weld-all-around symbol
6. Arrow to joint

4.7.5 Classification of Welds Contract documents/drawings sometimes assign a classification designation to welds to classify the weld regarding the impact to the user in event the weld fails to meet specified requirements. The classification designations are assigned to define the minimum level of non-destructive inspection and/or testing that applies, depending on the type of classification. One such classification methodology is included in MIL-STD-2219, Fusion Welding for Aerospace Applications. This document is available from <http://assist.daps.dla.mil/>. It is noted that this specification has recently been superseded by AWS-D17.1.

Class A: Critical Application – A weldment is critical where a failure of any portion would cause loss of system, loss of major component, loss of control, unintentional release of critical stores, or endangering of personnel.

Class B: Semi-Critical Application – A weldment is semi-critical when a failure would reduce overall efficiency of the system but loss of the system or endangering of personnel would not be experienced.

Class C: Non-Critical Application – A weldment is non-critical where a failure would not affect the efficiency of the system or endanger personnel.

4.7.6 Procedure and Personnel Qualification To ensure that final welds meet contract requirements and are of the requisite quality, it is important that the welding process is well documented in a welding procedure. The welding procedure

should be qualified as being capable of producing the desired weld joints in a consistent manner using specified weld joint designs, filler material, welding parameters, etc.

Qualification ensures that qualified procedures are used by properly trained and qualified personnel. Only qualified personnel, procedures and nondestructive test equipment should be used in fabrication and inspection.

4.7.7 Post Weld Cleaning Completed weldments should be free of visible oxides, flux, spatter, scale, slag, or other foreign matter. Welding flux should be completely removed by appropriate methods. Removal of material during the cleaning operation should not exceed the allowed tolerances of the end product specification.

4.7.8 In-Process and Final Visual Inspection of Welds In-process inspection, prior to welding should be performed to verify the parts to be welded are clean, the weld joint design/dimensions are as specified and fixturing, if required, is used to prevent distortion due to the weld process.

Final inspection should be performed to verify the weld joint conforms to specified requirements; in particular for type of weld (e.g., fillet, full penetration, etc.), weld throat size, weld length, spacing between welds and final contour, including post grinding if applicable. Cleanliness, including freedom from slag should be verified. The completed weld should agree with the weld symbol/designation shown on the drawing and there should be no missing welds.

4.8 Brazing Brazing is a method of joining two pieces of metal together with a third, molten filler metal. The filler metal may be in the form of a filler rod (similar to welding rod in concept) or the braze metal may be clad onto sheet metal stock such as aluminum.

The joint area is heated above the melting point of the filler metal but below the melting point of the metals being joined; the molten filler metal flows into the gap between the other two metal pieces by capillary action and forms a strong metallurgical bond as it cools. Brazed joints have great tensile strength - they are often stronger than the two metals being bonded together. Brazed joints may not be as strong as welded joints but they are stronger than solder joints made with conventional lower-temperature solders.

For end-item enclosures, the primary use of brazing is for attaching heat sink fins to heat sink base metal, for making connections within magnetic components, for connecting one or more sections of bus bars together and for brazing sub-assembly chassis pieces together.

Brazing comprises a group of joining processes where coalescence is produced by heating to a temperature above 450 °C (840 °F), and by using a filler metal that has a liquidus temperature above 450 °C (840 °F), and below the solidus temperature of the base metals. The filler metal is distributed between the metal parts which are spaced closely together. Brazing is similar to soldering, except that soldering uses a filler metal (solder that melts at less than above 450 °C (840 °F)).

The brazing process employs the following primary steps:

- a. The parts being brazed are heated to the required temperature by various heating methods; torch, furnace, salt bath, induction coil, etc. to the melting temperature of the braze filler metal but less than the melting temperature of the metals being joined.
- b. Once the filler metal and the parts being brazed reach the desired temperature, the filler metal, held in the joint by surface tension, spreads into the joint and wets the base metal surfaces.
- c. The parts are allowed to cool until the filler metal solidifies. The filler metal during solidification is held in the joint by capillary attraction and holds the parts together by metallurgical reaction and atomic bonding.

Basically, no melting of the base metal occurs in brazing; however, the temperatures involved can affect the properties of the metals being joined. For example, base metals whose properties were obtained by cold working may soften or undergo grain growth depending on the temperature. Brazing temperatures may also alter metal properties that were obtained by heat-treatment. Normally, metals brazed in the annealed condition are not impacted by brazing temperature.

Process control of brazing temperature is critical to ensuring a proper braze joint; in particular, the temperature should be high enough to ensure complete melting of the braze filler metal, but not too high such that it melts the base metal.

The reader should consult ASM Handbook, Volume 6, Welding, Brazing and Soldering for a significant amount of additional information on the brazing process.

4.8.1 Types of Brazing The following types of brazing are commonly used.

4.8.1.1 Torch Brazing Torch brazing is normally used for repairs, one-of-a-kind brazing jobs and short production runs. Any joint that can be accessed by the torch and heated to required brazing temperature by the torch and/or auxiliary heating can be brazed using this technique. Normally torch brazing is accomplished using the same type of torch, controls and gases as used for fusion welding.

4.8.1.2 Induction Brazing In the induction brazing process, heat is applied to a water-cooled coil using high frequency (5 to 5000 KHz) AC current. The frequency of the power source determines the type of heat that will be induced in the parts. The higher frequency sources produce “skin-effect” heating while the lower frequency sources provide heating to thicker areas. Induction heat has the advantages of speed (normally the joint is brazed from 10 to 60 seconds), accuracy and consistency. Each part is identically positioned in the induction coil and the filler material is carefully regulated. This type of system consistently and quickly delivers a precise amount of heat to a small area. The brazing coils are a unique design for each different braze joint. Brazing in a protective atmosphere such as argon generally produces the cleanest joints.

4.8.1.3 Furnace Brazing Furnace brazing is used primarily where the parts to be brazed can be assembled with the brazing filler metal can be preplaced near or in the joint. Heating is usually produced by electrical resistance although other types of fuel can be used. Flux is normally used unless the oven can accommodate a reducing atmosphere such as hydrogen or other reducing gasses. In some cases, both flux and a reducing gas are used. Fluxes should never be used when brazing with a vacuum atmosphere.

4.8.1.4 Resistance Brazing Resistance brazing is most applicable to simple joints in metals that have high electrical conductivity. In resistance brazing, the parts are heated locally. Filler metal that is preplaced between the parts is melted by the heat obtained from the flow of current through the electrodes and the parts. The same equipment used for resistance welding may be used for resistance brazing. The flux used is conductive. Normally, fluxes are insulators in their “off-the-shelf” condition. They become conductive when wet.

4.8.1.5 Dip Brazing In the dip brazing process, the assembly is immersed in a suitable molten bath to accomplish the brazing. The bath can be molten brazing filler metal, molten chemical flux, or molten chemical salts. The most commonly used process employs molten chemical salts. The molten metal is contained in a “pot” style furnace that is heated via various methods. In the molten braze filler metal method, parts being joined together and immersed in flux-covered molten filler metal, which flows into the joints when the parts reach the bath temperature. The flux cleans the parts and protects the brazing filler metal by preventing oxidation and the loss of volatile elements from the bath. Since it is difficult to heat and contain metals at high temperatures filler metals that require a brazing temperature above 1000 °C (1830 °F) are rarely used. Based on this, the choice of filler metal is restricted to straight brasses and silver-based filler metals.

In the molten-flux method, the brazing filler metal is located in or near the joints and is heated to the required temperature by immersion into a bath of molten-flux.

The molten salt bath process is the most commonly used process; it is primarily used for brazing aluminum. The type of salt used for a particular application depends on the ease with which the parent-metal surface oxides can be removed and on the temperature required for brazing. For aluminum brazing, the molten flux at 593 °C [1100 °F] provides heat transfer and fluxes the joints. Braze time varies, but is normally less than two minutes.

This process allows simultaneous joining of multiple joints with varying base metal thicknesses.

The assembly is subjected to pre-heat prior to dip brazing; normally the heat is applied from an oven.

4.8.2 Braze Procedure Qualification and/or Brazing Personnel Qualification Brazing procedures should be qualified and personnel who perform brazing operations should be trained and qualified/certified.

4.8.3 In-Process and Final Visual Inspection of Brazing In-process inspection, prior to brazing, should be performed to verify the parts to be brazed are clean, the braze joint design/dimensions are as specified, and fixturing, if required, is used to prevent distortion due to the brazing process.

Final inspection should be performed to verify the braze joint conforms to specified requirements. There should be no visual indication of incomplete braze joints or un-melted braze filler metal (if used).

5 MATERIALS AND PROCESSES – NON-METALS

5.1 Selection and Application Nonmetallic materials should be selected and qualified with each application by consideration of the following, as a minimum:

- a. Design engineering properties.
- b. Application operational requirements.
- c. Compatibility with other materials used
- d. Material hazards and restrictions specified in Section 4.
- e. Environmental and health restrictions mandated by applicable federal, state and local regulation.

5.1.1 Composition and Processing Specifications for composition and processing should be used to ensure a product that is reproducible and meets all physical, chemical and mechanical requirements.

5.1.2 Compatibility Nonmetallic materials should be evaluated and tested, or documented on the basis of detailed history for compatibility with temperature, pressure, radiation and fluid or gas environments. Tests for compatibility with hazardous fluids and gases such as oxygen or hydrogen should consider energy sources available in the proposed application that could initiate adverse reactions.

5.2 Special Considerations

5.2.1 Chlorinated Fluorocarbons (CFCs) All materials should be free of CFCs as mandated by federal or state regulations.

5.2.2 Shelf-Life Limitations Many nonmetallic materials should have a shelf life specified by the manufacturer. All materials so specified may be controlled by a shelf life control program and should not be used beyond expiration dates unless based on test information supplied by the manufacturer (or test information obtained by the user for the production lot(s) of concern).

5.3 Polymer Materials

5.3.1 Application The selection of all materials should be made such that the system can operate in the specified environments with limited or no maintenance over the specified lifetime with an acceptable level of deterioration and degradation. Therefore, the selection of suitable materials, appropriate processing methods and appropriate protective treatments should be made such that design allowables are adequate for the system's anticipated worst case environments.

5.3.2 Part Design Considerations To insure a quality final product, it is necessary to start out with quality components. Injection molded parts can be molded to a high quality standard by focusing on these areas of plastic technology:

- a. Correct Part Design.
- b. Accurate Selection of Material.
- c. Proper Plastic Processing.

When designing plastic components it is important to maintain uniform wall thickness. The already cooled section will not yield to the shrinking action of the cooling interior mass causing voids in the thick portion of the part. Concentrated stress at the junction of high & low shrinkage areas may cause a part to crack or fail.

5.3.2.1 Draft Plastic parts should be designed with a taper or draft in the direction of mold movement to allow part ejection or removal from the mold. Since plastics shrink when cooled, it is common for parts to shrink (or grip tightly) to cores. A good definition for draft would be: the degree of taper of a side wall or rib needed to allow the molded plastic part to be removed from the metal mold. Without proper draft, plastic parts may be difficult to remove from the mold. A draft angle of 1/2° is regarded as minimum for most applications. Draft angles of 1 1/2 to 2° per side are considered normal for plastic injection molding.

5.3.2.2 Ribs The use of ribs is a practical way and economical means of increasing the structural strength of a part. But there are guidelines that govern adding ribs without causing sink marks or surface blemishes to your parts.

- a. Rib thickness should be less than wall thickness. A rib thickness of 60% to 80% of nominal wall thickness is recommended.
- b. To increase stiffness increase the number of ribs or “gusset plates,” another feature designed to strengthen the plastic part.
- c. For a given stiffness, it is better to increase the number of ribs, not the height.
- d. For thick ribs “core out” the rib from the back. This creates a hollow space underneath the part and maintains a uniform wall thickness.
- e. Height: maximum height of three times nominal wall thickness of part.
- f. Spacing: minimum of two times nominal wall thickness of part between ribs.

5.3.2.3 Holes Holes are easy to produce in molded parts. Core pins that protrude into the mold cavity make the holes when the part is molded. Through holes in the molded parts are easier to produce than blind holes, which do not go all the way through a part. Blind holes are made by core pins supported on one end only. The pins can be deflected and pushed off center by the pressures of the molten plastic material during the molding process. A good rule of thumb: the depth of the blind hole should be about twice the diameter of core pins up to 3/16” and up to four times the diameter of core pins over 3/16”. The guidelines for blind and through holes are:

Blind Hole:

$L = 2D$ for Diameters Less than 3/16” dia. core pins $L = 4D$ for Diameters More than 3/16” dia. core pins

Through Hole:

$L = 4D$ for $D < 3/16$ ” dia. core pins $L = 6D$ for $D > 3/16$ ” dia. core pins

The distance from the edge of a hole to a vertical surface (i.e., rib) or the edge of a part should be twice the part thickness (or more), or at least one diameter of the hole. This same rule applies between holes - at least two part thicknesses or one hole diameter should be specified. As easy as it is to make holes in molded parts it does not come without some concerns for the strength of the part. For every cored or molded hole there will be a weld line. The weld lines are caused by the flow of the melted plastic around the core pins. These weld lines are not as strong as the surrounding plastic material and also may detract from the overall appearance of the molded part. The part designer should consider these points when designing holes in a molded part.

The coring of holes is easy when the axis is parallel to the parting line. But when holes and other features run perpendicular to the parting line then retractable cores (or cams) are required. Split pins and cores (called passing steel shutoffs) can be used to create some of the features. The designer should be aware of the problems of side action cores and the added expenses associated with these types of molds. With a little understanding of how the mold opens and where the parting line will exist, these costly features can be modified. Rule of thumb: whenever possible all design features should be incorporated in the same direction of the mold opening so that cam action can be avoided.

5.3.2.4 Bosses Bosses are used for locating, mounting and assembly purposes. There are boss design guidelines that should be followed to insure the highest quality in molded parts. Again, one of the main points to consider is nominal wall thickness. Too many times bosses are designed with thick wall sections that can affect the appearance of the plastic part and the final product.

Rule of thumb: the wall thickness around a boss design feature (t) should be 60% of the nominal part thickness (T) if that thickness is less than 3.17 mm [1/8 in].” If the nominal part thickness is greater than 3.17 mm [1/8 in]” the boss wall thickness should be 40% of the nominal wall.

Boss diameter, wall thickness and height design parameters. While boss heights vary by design, the following guidelines will help avoid surface imperfections like sink marks and voids: the height of the boss should be no more than 2 1/2 times the diameter of the hole in the boss. Please observe the “60/40” rule (see above) for the wall thickness at the bottom of the boss.

5.3.2.5 Radii In the design of injection molded parts, sharp corners should be avoided. Sharp corners act as stress risers or concentrators, reducing part strength and causing premature failures. Sharp corners may also affect plastic flow, producing parts with objectionable surface flow patterns.

- a. **Corners** – The inside radius should be at least half the part wall thickness
- b. **Bosses & Ribs** – Nominal radius should be one quarter of the nominal part thickness, with a minimum radius of 0.381 mm [0.015 in] (i.e., 2.54 mm [0.100 in] wall, 0.635 mm [0.025 in r])

The outside radius should equal the inside radius plus the part thickness (i.e., 2.54 mm [0.1 in] wall and inside radius of 1.27 mm [0.050 in] equals outside radius of 3.81 mm [0.150 in])

5.3.2.6 Insert Molding Tips Another problem concerning high stress occurs with molded-in inserts. The plastic melt heats the metal of the inserts. During the cooling stage of injection molding, the plastic part cools, but the plastic boss surrounding the metal insert is reheated by the heat from the insert. This allows the plastic to continue to shrink around the insert, causing excessive hoop stress that will eventually cause the boss to crack. The better design and process would be to use ultrasonic insertion or a hot probe (such as a heat staking unit) after the molded part has cooled throughout.

5.3.3 Molded Plastic Enclosures Plastic enclosures can be designed in a wide variety of sizes and using a wide range of engineered materials. Typical materials are polycarbonate, polystyrene, Acrylonitrile Butadiene Styrene (ABS) plastics.

5.4 Elastomers

5.4.1 Application Elastomeric components should be hydrolytically stable, should not subject to reversion, and possess adequate resistance to aging, low temperature, ozone, heat aging, working fluids, lubricants and propellants for the system. Elastomeric materials in contact with hydrazine should be limited.

5.4.2 Cured Elastomers Cured elastomers that are age sensitive should be controlled by MIL-STD-1523. All cured elastomeric materials should be cure dated either on the item itself or on the packaging. A first in, first out system should be maintained. Cured elastomeric materials should be protected from sunlight, fuel, oil, water, dust and ozone. A maximum storage temperature of 37.8 °C (100 °F) is recommended; the maximum storage temperature should not exceed 51.7 °C (125 °F).

5.4.3 Non-Cured Elastomers Materials that are procured in non-cured state such as sealants and potting compounds should be held in controlled temperature storage not to exceed 26.7 °C (80 °F). Some specific materials require storage at reduced temperatures and should be stored as recommended by the manufacturer. A first in, first out, system is recommended as the most effective method for tracking and maintaining adequate storage times. Overage materials may be used if testing can insure that the material is adequate for the intended uses.

5.4.4 Silicone Elastomers Some one-part silicone products including commercial adhesives/sealants, as well as those meeting the requirements of MIL-A-46106, give off acetic acid during cure. These materials can cause corrosion to copper, aluminum and steel. Alcohol liberating sealants should be used instead of acetic acid liberating sealants.

5.5 Foamed Plastics

5.5.1 Application Foamed plastics should be applied in a manner as to preclude damaging fragile components or exerting undue stress on adjacent surfaces. They should be hydrolytically stable and should not be subject to reversion.

5.5.2 Outgassing and Flammability Only a few foamed plastics meet outgassing and flammability requirements. Often such materials require baking at elevated temperatures to reduce outgassing to acceptable levels.

5.5.3 Special Considerations Foamed plastics should not be used for metal skin reinforcement in structural components, nor as a core material in sandwich structural components other than all plastic sandwich parts, low density filler putties, or syntactic foam.

5.6 Plastics Plastics which serve as electrical insulation should be selected in accordance with 5.7.

Plastics which do not serve as electrical insulation (structural parts, and so forth) should meet all physical and mechanical properties required for plastic insulating materials, including non-flammability and non-toxicity; however, these plastics may not need to meet the arcing and tracking resistance requirements.

5.7 Insulation Materials Various types of materials are suitable for use in the manufacture assemblies, and when installing these assemblies into their next-higher assembly. The following guidance is recommended regarding insulation materials.

5.7.1 Arc and Tracking Resistance Structural insulators, such as laminates, molding compounds, encapsulating materials, bus bar coverings and similar materials subject to arcing conditions should have an arc resistance of not less than 130 seconds and a track resistance of not less than 70 minutes for low voltage (< 2000 V) equipment. For equipment rated at 2000 V and higher a minimum track resistance of 300 minutes is recommended.

Arc resistance may be determined via ASTM D495, and tracking resistance may be determined by ASTM D638.

5.7.2 Laminated Plastics Laminated plastics in the form of sheets, rods, or tubes are recommended for use where rigid materials with dielectric properties are needed. Such laminates should meet the temperature, mechanical and electrical requirements of each application.

Other forms of plastics should be used only when suitable for the particular application.

Laminates should be chosen to meet the minimum requirements for toxicity, flame resistance and arc and tracking resistance.

Machined edges on glass based laminates may require sealing to prevent moisture infusion.

5.7.3 Molded Thermosetting Plastics Molded thermosetting plastics are generally used in electrical equipment where a rigid dielectric is needed and where the form or shape is such that fabrication of the part out of sheet stock is too costly, or the part too complex in design. The molding compound should meet minimum requirements for toxicity, flame resistance and arc resistance and the mechanical and electrical requirements for each application.

See ASTM D5948 for some recommended molding compounds.

Consideration should be given to specifying the color of thermosetting plastics depending on the voltage rating. For example, red color is normally used for voltages rated at 2000 V or higher and gray color is used for lower voltages.

5.7.4 Thermoplastics In general, thermoplastics are not recommended for any molded part because of temperature rating considerations.

However, if the application is such that only a thermoplastic material can be used, then polyamide (nylon) (ASTM D4066), or polycarbonate (ASTM D3935), molding compounds are recommended as long as they are suitable for the application.

5.7.5 Classes and Definitions of Insulating Materials Temperature classes of insulating materials have traditionally been established by definition based on a chemical composition of the materials. Methods of temperature classification based on the results of thermal evaluation tests are coming into use. Since the temperature classification of a material that has been accepted for a long time will have been established by field experience, its life temperature characteristics determined by test provides a basis for comparison with the thermal life of a new material.

The purpose of assigning each material to a definite temperature class, therefore, is to facilitate comparisons between materials and to provide a single number to designate each class for purposes of standardization. The life expectancy under the test conditions may be shorter than, and has no direct relation to, the life expectancy of the material in actual service. The classes and definitions of insulating materials are grouped according to the classifications noted below. New classifications may be created, and new materials may be developed for existing classifications. Therefore, the listing in the subsequent paragraphs may not be all inclusive.

5.7.5.1 Class 90 Materials or combinations of materials such as cotton, silk and paper without impregnation. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 90 °C [194 °F].

5.7.5.2 Class 105 Materials or combinations of materials such as cotton, silk and paper when suitably impregnated or coated or when immersed in a dielectric liquid such as oil. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 105 °C [221 °F].

5.7.5.3 Class 130 Materials or combinations of materials such as mica, glass fiber, and so forth, with suitable bonding substances. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 130 °C [266 °F].

5.7.5.4 Class 155 Materials or combinations of materials such as mica, glass fiber, and so forth, with suitable bonding substances. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 155 °C [311 °F].

5.7.5.5 Class 180 Materials or combinations of materials such as silicone elastomer, mica, glass fiber, and so forth, with suitable bonding substances such as appropriate silicone resins. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 180 °C [356 °F].

5.7.5.6 Class 200 Materials or combinations of materials such as mica, glass fiber, asbestos, and so forth, with suitable bonding substances. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 200 °C [392 °F].

5.7.5.7 Class 220 Materials or combinations of materials which by experience or accepted tests can be shown to have the required thermal life at 220 °C [428 °F].

5.7.5.8 Class 240 Materials or combinations of materials which by experience or accepted tests can be shown to have the required thermal life at 240 °C [464 °F].

5.7.5.9 Class over 240 Materials consisting entirely of mica, porcelain, glass, quartz and similar inorganic materials. Other materials or combinations, of materials may be included in this class if by experience, or accepted tests they can be shown to have the required thermal life at temperatures over 240 °C [464 °F].

5.8 Lubricants

5.8.1 Application NASA SP-8063 can be used as a guide in the design and application of lubricants.

5.8.2 Application Documents Application documents for dry film lubricants should define surface finish requirements for surfaces to be coated. The use of film lubricants are recommended for applications requiring minimum levels of friction, maximum life and maximum load-bearing capability.

5.8.3 Lubricant Selection of a lubricant should consider life cycles, including installation, test and utilization, as well as a design margins.

5.9 Other Materials

5.9.1 Adhesives Adhesives for general use should be qualified to MIL-A-46146. Adhesives for structural applications should be qualified to MIL-A-83377 for the specific materials to be bonded.

5.9.1.1 Adhesive Bonding Structural bonding should meet the requirements of MIL-S-83377. All bonding processes and materials selected for structural components should be validated and verified to meet the desired properties for the entire life of the component. This is accomplished through the test of tag-end test specimens under the simulated service conditions, except for high temperature nozzle bonds, or through hardware qualifications and acceptance tests plus lap shear witness coupons processed concurrently using the same material cleaning method and cure cycles.

5.9.2 Silicone Silicone greases are not recommended as a thermal couplant except in hermetically-sealed assemblies. Silicone contamination of surfaces can result in the loss of adhesion and/or surface solderability. Caution should be exercised to minimize/eliminate any potential for silicone contamination. If concerns exist, select non-silicone based materials, if possible.

5.9.3 Coatings Conformal coatings should be qualified to MIL-I-46058 or IPC-CC-830. Conformal coating should not be considered as an absolute environmental barrier.

5.9.4 Encapsulants Materials and processes used to encase components and assemblies in plastic or elastomeric resins for electrical insulation, protection from environmental conditions and protection from mechanical damage should be qualified by component or assembly-level testing or past experience under equivalent or more limited thermomechanical and radiation stresses.

5.9.5 Sealing Materials Some assemblies may need to function in a humid environment or otherwise in applications where water or other liquid can exist. In such cases, it may be necessary to provide a means of sealing off components such as connectors, etc.

Materials used for sealing should be elastomeric and reversion resistant. Materials should also be fully cured at the time of delivery of the assembly. If not fully cured, the material may out-gas unacceptable chemicals, or otherwise may not have developed the necessary mechanical and sealing properties needed for the application.

Various sealing materials are available. Examples include cured synthetic rubber (operating range -51 to 93 °C [-60 °F to +200 °F]) (MIL-STD-8516) which acts as a deterrent to fatigue, corrosion and contamination, as well as an aid in reducing arc-over between electrical connector pins.

Another example is a silicone rubber sealing compound with accelerator (operating range [-62 to 204 °C [-80 °F to +400 °F]) (MIL-PRF-23586), for use in applications where tear resistance is not critical. Proper curing is essential and in some cases, vacuum de-airing may be needed to eliminate air bubbles. Volatile by-products formed during cure should be removed. Factors affecting the rate and degree of cure are numerous, such as; catalyst concentration, humidity, diluents (if used to lower the viscosity), thickness of section area exposed for the release of volatiles and post-cure employed. Because of the high volume expansion of RTV silicones they are not recommended for use for the total filling of confined items. Pressures developed during heating are of a high order. Literature pertaining to the manufacturer's product should be thoroughly understood prior to consideration of RTV silicones, and all applications for use of this material should be thoroughly evaluated prior to use.

5.9.6 Cleaning Prior to Application All processes involving these materials require careful surface preparation to ensure adequate adhesion. Each qualified material should be associated with one or more documents describing its application and usage. Each application document should detail the specific cleaning procedure for all surfaces to be coated (or bonded) and a maximum time period between surface preparation and coating (or bonding), after which, surfaces should be reprocessed. Materials covered by this section should be qualified with the specific surface preparation procedure described

5.9.7 Special Considerations

5.9.7.1 Glass Transition Temperature The secondary or glass transition temperature of silicone-based adhesives or sealants subjected to application of cryogenic temperatures during test or usage should be a minimum of 1.1 °C (30 °F) lower than the usage qualification temperature.

5.9.7.2 Processing Requirements Processing requirements for encapsulation should consider as a minimum the following: surface preparation or cleaning, resin or elastomers preparation, processing temperatures (including exothermic heat of reaction), shrinkage during cure and rework or repair requirements.

6 MATERIALS NOT RECOMMENDED FOR USE

Various materials exist that are not recommended for use because of potential personnel hazards, restrictions by Government regulations, or for other reasons. Some of these materials may have been specifically prohibited from use by the user. The following are examples of non-recommended materials. This list may not be all inclusive.

- a. Items with exposed surfaces of cadmium or pure zinc.
- b. Mechanical and electronic parts within electronic boxes with pure (>97%) tin coated internal or external surfaces not including drawn wire products.
- c. Pure magnesium or beryllium.
- d. Parylene (paraxylylene) coatings containing chlorine.
- e. Corrosive (acetic acid evolving) silicone sealants, adhesives or coatings.
- f. Wood and other materials that are not inherently moisture and fungus resistant.
- g. Combustible materials, or materials that can generate toxic outgassing or toxic products of combustion such as PVC (vinyl) and CPVC materials.
- h. Metals with low resistance to stress corrosion cracking.
- i. Graphite loaded lubricants and gaskets.
- j. Sulfur containing packaging material.

k. Hazardous materials such as mercury, asbestos, etc., (see 6.1 through 6.8).

1. Toxic pyrolytic materials (see 6.1).
2. Flammable materials (see 6.2).
3. Fragile or brittle materials (see 6.3).
4. Mercury (see 6.4).
5. Asbestos (see 6.5).
6. Polychlorinated biphenyls (PCB) (see 6.6).
7. Polyvinyl chloride (PVC) (see 6.7).
8. Cadmium and cadmium plating (see 6.8).
9. Freon solvents.
10. Radioactive materials.

6.1 Toxic Pyrolytic Materials Toxic pyrolytic materials include those materials which emit toxic gases or other harmful products when exposed to high temperatures, including fire.

Toxicity of materials can be determined by performing a pyrolysis test. One such test method is DTIC AD 297457, Procedure for Determining Toxicity of Synthetic Compounds.

6.2 Flammable Materials Flammable materials include any material in a form which will ignite or explode from an electric spark, flame, or from heating, and which, if so ignited, will independently support combustion in the presence of air. Material flammability can be determined by various test methods. Some example test methods include; DTIC AD 297457, ASTM D5948, Standard Specification for Molding Compounds - Thermosetting and ASTM D635, Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position.

6.3 Fragile or Brittle Materials Fragile materials include any materials which are fragile in the form, size and manner in which they would be used.

Brittle materials, in general, fall within this category from the point of use as structural members. However, certain brittle materials may be used in small quantities, within a part, when the materials is so mounted, constrained or otherwise disposed within the part that it will not be strained under any processing, environmental and handling conditions to which the part reasonably may be subjected. (For example, glass and ceramic terminals seals and bushings have been employed successfully in packaging certain semiconductor devices).

Any material in a frail form which is not positively protected against mechanical damage as used in a part or subassembly is considered fragile.

Cast iron, semi-steel, porcelain and similar brittle materials should not be used as frames, brackets, mounting panels, spacers, or enclosures.

6.4 Mercury Mercury is highly toxic to humans and is corrosive to metals. Therefore, equipment, components and assemblies should be free of mercury. Mercury should not be used in the manufacture or testing of assemblies.

Manufacturers should evaluate materials to confirm that they do not contain intentionally added mercury. For example, some potting compounds may use a catalyst that contains mercury as a method of minimizing the presence of air bubbles during the potting process.

6.5 Asbestos Materials containing asbestos should not be used since asbestos is a known human health hazard.

6.6 Polychlorinated Biphenyls (PCB) PCBs are a type of organic compound that should not be used because they are an environmental pollutant. Historically, their main use was within components such as certain types of capacitors and transformers.

6.7 Polyvinyl Chloride (PVC) PVC, commonly referred to as vinyl, is hazardous to human health and the environment throughout its entire life cycle. PVC is useless without the addition of a plethora of toxic additives, which can make the PVC product itself harmful to consumers. These chemicals can leach out of PVC, posing risks to children and consumers.

New car smell? New shower curtain smell? That's the smell of poisonous chemicals out-gassing from the PVC. One of the most toxic additives is di-2-ethylhexyl phthalate (DEHP), a phthalate that is a suspected carcinogen and reproductive toxicant readily found in numerous PVC products.

When heated in a fire, PVC releases toxic hydrogen chloride gas, forming deadly hydrochloric acid when inhaled.

PVC cannot be effectively recycled due to the many different toxic additives used to soften or stabilize PVC, which can contaminate the recycling batch.

Based on the above, PVC, in particular, PVC (i.e., Vinyl) insulated wire should not be used.

6.8 Cadmium and Cadmium Plating Cadmium and its compounds are extremely toxic even in low concentrations, and will bio-accumulate in organisms and ecosystems.

When working with cadmium, it is important to do so under a fume hood to protect against dangerous fumes. For example, silver solder, which contains cadmium, should be handled with care. Serious toxicity problems have resulted from long-term exposure to cadmium plating baths.

Based on the above, manufacturers should evaluate the components, fasteners and other items they intend on using to verify that they do not contain cadmium. One common source of cadmium is fasteners that have been cadmium plated.

6.9 Other Non-Recommended Materials The following other types of materials should not be used:

- a. Linen.
- b. Cellulose acetate.
- c. Cellulose nitrate.
- d. Regenerate cellulose.
- e. Wood.
- f. Jute.
- g. Leather.
- h. Cork.
- i. Paper and cardboard.
- j. Organic fiberboard.
- k. Hair or wool felts.
- l. Plastic materials using cotton, linen or wood flour as a filler.

7 MATERIALS AND PROCESSES – COMPOSITES

7.1 Introduction A composite is a combination of engineered or natural occurring materials that when combined produce a material that has physical and chemical properties that can be tuned to match design requirements (i.e., weight, strength, environmental, etc.). The source materials are not intended to fully or partially dissolve in the end product.

7.1.1 Unique Issues for Composites Composites are different from metals in several ways. These include their largely elastic response, their ability to be tailored in strength and stiffness, their damage tolerance characteristics and their sensitivity to environmental factors. These differences force a different approach to analysis and design, processing, fabrication and assembly, quality control, testing and certification.

7.1.1.1 Elastic Properties The elastic properties of a material are a measure of its stiffness. This property is necessary to determine the deformations that are produced by loads. In composites, the stiffness is dominated by the fibers; the role of the matrix is to prevent lateral deflections of the fibers and to provide a mechanism for shearing load from one fiber to another.

7.1.1.2 Tailored Properties The properties of a composite laminate depend on the orientation of the individual plies. This provides the engineer with the ability to tailor a laminate to fit a particular requirement. For high axial loads predominantly in one direction, the laminate should have a majority of its plies oriented parallel to that loading direction. If the laminate is loaded mostly in shear, there should be a high percent of $\pm 45^\circ$ pairs.

For loads in multi-directions, the laminate should be quasi-isotropic. An all 0° laminate represents the maximum strength and stiffness that can be attained in any given direction, but is impractical for most applications since the transverse properties are so weak that machining and handling can cause damage. Fiber-dominated, balanced and symmetric, laminate designs that have a minimum of 10% of the plies in each of the 0° , $+45^\circ$, -45° and 90° directions are most commonly used.

Tailoring also means an engineer is not able to cite a strength or stiffness value for a composite laminate until he knows the laminate's ply percentages in each direction. Carpet plots of various properties vs. the percent of plies in each direction are commonly used for balanced and symmetric laminates. Similar plots for strength can also be developed.

7.1.1.3 Damage Tolerance Damage tolerance is the measure of the structure's ability to sustain a level of damage or presence of a defect and be able to perform its operating functions. The concern is with the damaged structure having adequate residual strength and stiffness to continue in service safely: 1) until the damage can be detected by scheduled maintenance inspection and repaired, or 2) if the damage is undetected, for the remainder of the product's life. Thus, safety is the primary goal of damage tolerance. Both static load and durability related damage tolerance should be interrogated experimentally because there are few, if any, accurate analytical methods.

There are basically two types of damage that are categorized by their occurrence during the fabrication and use of the part, i.e., damage occurring during manufacturing or damage occurring in service. It is hoped that the occurrence of the majority of manufacturing associated damage, if beyond specification limits, will be detected by routine quality inspection. Nevertheless, some defects or damage beyond specification limits may go undetected. Consequently, their occurrence should be assumed in the design procedure and subsequent testing (static and fatigue) performed to verify the structural integrity.

Service damage concerns are similar to those for manufacturing. Types of service damage include edge and surface gouges and cuts or foreign object collision and blunt object impact damage caused by dropped tools or contact with service equipment. A level of non-detectable damage should be established and verified by test that will not endanger the normal operation of the product's structure for two lifetimes. A certain level (maximum allowed) damage that can be found by inspection should be defined such that the vehicle can operate for a specified number of hours before repair or replacement at loads not exceeding design limit. This damage should also be tested (statically and in fatigue) to verify the structural integrity.

De-laminations can also be critical defects. However, unless they are very large, historically more than 50 mm [2 in] in diameter, the problem is mostly with thin laminates. Effects of manufacturing defects such as porosity and flawed fastener holes that are slightly in excess of the maximum allowable are usually less severe. They are generally accounted for by the use of design allowable properties that have been obtained by testing specimens with stress concentrations, e.g., notches. Most commonly these are specimens with a centered hole. Open holes are typically used for compression specimens while either open or filled holes (holes with an installed fastener) are used for tension testing. (Open holes are more critical than filled holes for compression. Filled holes may be more critical in tension, especially for laminates with ply orientations with a predominate number of plies in the load direction.) Consequently, the design allowables thus produced may be used to account for a nominal design stress concentration caused by an installed or missing fastener, at least to a 6.4 mm [0.25 in] diameter, as well as accounting for many other manufacturing defects.

7.1.1.4 Durability Durability of a structure is its ability to maintain strength and stiffness throughout the service life of the structure. A structure should have adequate durability when subjected to the expected service loads and environment spectra to prevent excessive maintenance, repair, or modification costs over the service life.

Thus, durability is primarily an economic consideration. Metallic structure can be very sensitive to durability issues; major factors limiting life are corrosion and fatigue. Metal fatigue is dictated by the number of load cycles required to start a crack (crack initiation) and the number of load cycles for the crack to grow to its critical length, reaching catastrophic failure (crack growth). Crack/damage growth rate is very dependent on the concentration of stress around the crack.

In composites, it has been demonstrated that one of the most common damage growth mechanisms is inter-cracking (delamination). This makes composites most sensitive to compression-dominated fatigue loading. A second common fatigue failure mode is fastener hole wear caused by high bearing stresses. In this failure mode the hole gradually elongates. The most serious damage to composite parts is low velocity impact damage which can reduce static strength, fatigue strength, or residual strength after fatigue.

The strain level of composites in most actual product applications to date has been held to relatively low values. Composites under in-plane loads have relatively flat stress-life (S-N) curves with high fatigue thresholds (endurance limits). These two factors combined have resulted in insensitivity to fatigue for most load cases. However, the greater variability found with composites requires an engineer to still characterize the composite's fatigue life to failure to correctly characterize its fatigue scatter.

7.1.1.5 Environmental Sensitivity When a composite with a polymeric matrix is placed in a wet environment, the matrix will absorb moisture. The moisture absorption of most fibers used in practice is negligible; however, aramid fibers (e.g., Kevlar) absorb significant amounts of moisture when exposed to high humidity. The absorption of moisture at the interface of glass/quartz fibers is a well-known degrading phenomena.

Key reasons for designing with composites:

- a. Light weight.
- b. Tailorable strength.
- c. Design flexibility.

Question to Answer: How does a composite enclosure differ from the traditional sheet metal enclosure?

- a. Strength to weight ratio.
- b. Different shapes.
- c. You can engineer the material to exactly match the anticipated forces and environment based on material selection and orientation.

7.2 Limitations of Composites The following is a list of limitations of the use of composites. This list may not be all inclusive.

- a. Stress concentrations.
- b. Fastener holes.
- c. Part rigidity.
- d. Customized tooling.
- e. Design expertise required.
- f. The support infrastructure/support tooling required is directly proportional to the size of the fabrication required.
- g. In order to fabricate dimensionally accurate structures an understanding of material specific shrinkage properties is critical.

7.3 Material System and Selection

7.3.1 Thermoset Resins During the curing process thermoset materials form three-dimensional molecular connections. These molecular connections are often called cross-links. The properties of thermoset materials will not allow it to be re-melted or reformed once it's cured.

Types of Thermoset Resins:

- a. Epoxy.
- b. Phenolic.
- c. Polyester.

7.3.2 Thermoplastic Resins Thermoplastic materials have properties of being more ductile than thermoset materials. Since the thermoplastic materials do not have the cross-linking properties of thermoset materials, the thermoplastic resins can typically be reprocessed or recycled.

The disadvantage of thermoplastics over thermosets is they have a lower stiffness and less strength than a thermoset material.

Types of Thermoplastic Resins:

- a. Acetal.
- b. Nylon.
- c. PEEK.
- d. Polycarbonate.
- e. Polyester.
- f. Polyethylene.
- g. Teflon.
- h. Fiberglass reinforced composites.
- i. Graphite reinforced composites.

7.3.3 Constituent Materials

7.3.3.1 Fibers

7.3.3.1.1 Carbon and Graphite Fibers Carbon and graphite have substantial capability as reinforcing fibers, with great flexibility in the properties that can be provided. Primary characteristics for reinforcing fibers in polymer matrix composites are high stiffness and strength. The fibers should maintain these characteristics in hostile environments such as elevated temperatures, exposure to common solvents and fluids and environmental moisture. To be used as part of a primary structure material it should also be available as continuous fiber. These characteristics have substantial implications for the physical, chemical and mechanical properties of the fiber which in turn implies processing and acceptance parameters.

7.4 Design Parameters The design of a composite structure is complicated by the fact that every ply should be defined. Drawings or design packages should describe the ply orientation, its position within the stack and its boundaries.

This is straightforward for a simple, constant thickness laminate. For complex parts with tapered thicknesses and ply build-ups around joints and cutouts, this can become extremely complex. The need to maintain relative balance and symmetry throughout the structure increases the difficulty.

Composites should not be designed without concurrence. Design details depend on tooling and processing as does assembly and inspection. Parts and processes are interdependent.

Another factor approached differently in composite design is the accommodation of thickness tolerances at interfaces. If a composite part should fit into a space between two other parts or between a substructure and an outer mold line, the thickness requires special tolerances. The composite part thickness is controlled by the number of plies and the per-ply-thickness. Each ply has a range of possible thicknesses.

When these are laid up to form the laminate they may not match the space available for assembly within other constraints. This discrepancy can be handled by using shims or by adding “sacrificial” plies to the laminate (for subsequent machining to a closer tolerance than is possible with nominal per-ply-thickness variations). The use of shims has design implications regarding load eccentricities.

Another approach is to use closed die molding at the fit-up edges to mold to exact thickness needed. The anisotropy of special laminates, while more complicated, enables a designer to tailor a structure for desired deflection characteristics. This has been applied to some extent for aeroelastic tailoring of wing skins.

Composites are most efficient when used in large, relatively uninterrupted structures. The cost is also related to the number of detail parts and the number of fasteners required. These two factors drive designs towards integration of features into large co-cured structures. The nature of composites enables this possibility. Well designed, high quality tooling will reduce manufacturing and inspection cost and rejection rate and result in high quality parts.

Designers should use CAD or Finite Element Analysis (FEA) to determine the required material properties and requirements. Additional composite design criteria, such as the use of mechanical inserts and machining criteria should be included in the design of the composite. The designer should also consider prototype testing to verify the composite meets the structural design input requirements. The following are important design considerations:

- a. Weight requirement.
- b. Environment (temperature limits, humidity, vibration, shock, drop, UV, etc.).
- c. Service life.
- d. Moisture permeability.
- e. EMI.
- f. Electrical ground.
- g. Feed-throughs.
- h. Mating/attachment interface(s).
- i. Fastener requirements.
- j. Dielectric withstanding voltage.

Structural Considerations (thermoplastic vs thermoset):

- a. Ply orientation.
- b. Joints (fastener, bonded).

- c. General design Guidelines.
- d. Corrosion.

7.5 Fabrication Considerations

- a. Shape – composite constructions lends itself to unusual shapes and loading requirements very well.
- b. Layup method.
- c. Ply orientation.
- d. Cure.

7.5.1 Cure and Consolidation Processes Resin consolidation and cure processes should ensure that the individual sections or layers of a composite part are properly bonded and that the matrix is intact and capable of maintaining the placement of the fibrous reinforcement which will carry the loads applied to the part. These processes are among the most sensitive in the materials processing pipeline. As a thermosetting composite part is formed during cure, the material is undergoing extensive chemical and morphological change. As a result, there are many actions occurring simultaneously. Some of these actions can be controlled directly, others only indirectly and some of them interact. Such actions as evolution of voids or shifting of reinforcing fibers during matrix flow may result in large changes in properties of the cured composite.

In the case of a thermoplastic matrix composite, the matrix is not intended to undergo chemical change, during consolidation, but changes such as chain scissions resulting in production of volatiles may occur inadvertently. In addition, resin flow is required for consolidation, and semi-crystalline thermoplastics may undergo morphological changes such as changes in the degree of crystallinity upon melting, flow and recrystallization, particularly in the fiber/matrix interphase. These changes can cause significant changes in mechanical and physical properties of the consolidated composite. In amorphous thermoplastics, segregation of varying molecular weight materials in the interphase may also result in changes in composite properties.

7.5.2 Vacuum Bag Molding Vacuum bag molding is a process in which the lay-up is cured under pressure generated by drawing a vacuum in the space between the lay-up and a flexible sheet placed over it and sealed at the edges. In the vacuum bag molding process, the reinforcement is generally placed in the mold by hand lay-up using prepreg or wet resin. High flow resins are preferred for vacuum bag molding. The following steps are used in vacuum bag molding:

- a. Place composite material for part into mold.
- b. Install bleeder and breather material.
- c. Place vacuum bag over part.
- d. Seal bag and check for leaks.
- e. Place tool and part in oven and cure as required at elevated temperature.
- f. Remove part from mold.

Parts fabricated using vacuum bag oven cure have lower fiber volumes and higher void contents. Vacuum bag molding is a low-cost method of fabrication and uses low-cost tooling for short production runs.

7.5.3 Oven Cure Composite material can be cured in ovens using various pressure application methods. Vacuum bagging, as described in the above section, can be used to remove volatiles and trapped air and utilize atmospheric pressure for consolidation. Another method of pressure application for oven cures is the use of shrink wrapping or shrink tape. This method is commonly used with parts that have been filament wound, because some of the same rules for application apply. The tape is wrapped around the completed lay-up, usually with only a layer of release material between the tape and the lay-up. Heat is applied to the tape, usually using a heat gun, to make the tape shrink, and can apply a tremendous amount of pressure to the lay-up. After shrinking the part is placed in the oven for cure. High quality parts can be made inexpensively using shrink tape, with a couple of caveats. First, the part should be of a configuration where the tape can apply pressure at all points. Second, flow of the resin during cure should be limited, because the tape will not continue to shrink in the oven. If the resin flows excessively, the pressure applied by the shrink tape will be reduced substantially.

7.5.4 Autoclave Curing Processing

7.5.4.1 General Description Autoclave curing is the process of curing materials using relatively high heat and high pressure in an autoclave. An autoclave is a heated pressure vessel typically capable of 2 MPa [300 psi] in temperature and pressure.

temperatures up to 370 °C [700 °F]. Thermoset composite materials are generally processed at less than 0.69 MPa [100 psi] and at temperatures ranging from 120 to 200 °C [250 to 400 °F]. Thermoplastic composites may require higher temperatures and pressures. Due to the high temperatures in the autoclave during processing, the atmosphere within the vessel is generally purged of oxygen using an inert gas, such as nitrogen, to displace the oxygen thereby preventing thermal combustion or charring of the materials being cured.

Materials that are cured in an autoclave are located onto tooling providing the eventual shape of the cured material. The tooling, frequently referred to as the mold, may be comprised of an assembly of mandrels or tool details to accommodate complex geometry. The mold may also include features such as locating devices, tooling tabs or net-molding details to enhance the subsequent processing of the final product or material. Typically, an impervious layer of bagging film or a reusable elastic bladder is located over the material being cured and sealed against the mold. Vacuum is applied between the bagging material and the material being cured such that the plies of material are compressed through the thickness against the mold. In some instances, an autoclave or oven is used to apply heat and pressure to only a portion of the material being cured as an interim de-bulk step to enhance the quality of the finished product through improved consolidation. As the temperature in the autoclave is raised, the viscosity of the curing material is generally lowered to a fluid state and the gasses within and between the layers escape as the material consolidates. A porous “bleeder” layer and/or a “breather” in the form of sheet, strips or strands may be utilized under the bagging material to help enable the evacuation of gasses. Surface films or in mold coatings may also be included against the tool surface to improve the surface finish of the cured material. Rigid caul plates or intensifiers may also be incorporated under the bagging material to locally control the thickness and quality of the finished product. In some cases, pre-cured or stage-cured components may be co-cured or co-bonded with the material being cured in the autoclave.

7.5.5 Press Molding Press curing uses heated platens to apply both pressure and heat to the part. Presses, in general, operate at 140 - 7000 kPa [20 - 1000 psi] and up to 320 °C [600 °F]. Press curing is very economical for flat parts and high production rates. Tooling includes matched die molds for contoured parts. The following steps are used in press molding:

- a. Composite material is placed in the mold cavity.
- b. Cure monitoring devices are installed.
- c. Parts are placed into press and cured. Pressure, temperature and time are monitored during the cure cycle to ensure curing parameters are met.

Press curing produces high quality parts with low void content.

7.5.6 Integrally Heated Tooling With integrally heated tooling the heat required for cure is provided through the tool itself, rather than through the use of external heating in an oven or autoclave. This can be used to make high quality parts without using an autoclave if matched mold tools are used. The heat is usually provided by imbedding electrical resistance elements or hot oil circulation channels within the tool. This can result in hot and cold spots within the tool. Heat surveys should be performed to ensure that all parts of the tool perform with a heat profile that allows the part to be cured completely and with high quality.

7.5.7 Pultrusion Die Cure and Consolidation Pultrusion is an automated process for the continuous manufacture of composites with a constant cross-sectional area. A continuous reinforcing fiber is integral to the process and the finished product.

Pultrusion can be dry, employing prepreg thermosets or thermoplastics, or wet, where the continuous fiber bundle is resin-impregnated in a resin bath. The wet resin process was developed around the rapid addition reaction chemistry exhibited by thermoset polyester resins, although advances in resin and catalyst systems have made the use of epoxy systems commonplace.

In pultrusion the material is cured in a continuous process that can provide large quantities of high quality cured shapes. The material is drawn through a heated die that is specially designed for the shape being made. The tool is designed such that the volume of the cavity for cure causes the resin pressure to build, allowing consolidation of the material to occur. This cure cavity pressure is built up against the cured material that is downstream of it, and induced by the new material upstream which is continuously being drawn into the cavity. As a result this process can be very sensitive to variation in the tow and rate used for pultrusion.

7.5.8 Resin Transfer Molding (RTM) RTM is a process which combines a dry fibrous reinforcement material or mixture of materials, generally referred to as a “preform,” with liquid resin during the molding process, whereby the combined materials are cured to produce a 3-dimensional component. RTM is a term which is broadly applied to describe