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A New Approach to Quantitative Evaluation of a Design for Brazed Structures

A system of design criteria with assigned score values is proposed

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ABSTRACT. Brazement design is a critically important characteristic of a brazed joint structure. The design is responsible for reliability and proper service behavior of brazed products. According to the state of the art, a good design provides not only required properties of the brazed structure, but also a very high technological suitability. The latter is necessary in order to fabricate a product using the most economical manufacturing processes. Therefore, a rigorous approach to the assessment of the design beyond intuitive tools of the brazing art is necessary. However, many design variables should be considered during the development of a brazing task to reach the correct design solution. This variety of factors significantly complicates quantitatively assessing design. This paper offers such a rigorous methodology for achieving this goal.

A system of quantitative characteristics inherent to a good design is proposed. Subsequently, a figure of merit called "design effectiveness" is defined to facilitate the related assessment procedure. This is accomplished by evaluating the final design solution in terms of design effectiveness. Subsequently, a comparison between multiple designs (the proposed vs. all the other options for similar brazed structures available in practice) should be performed. Almost 100 design criteria levels and corresponding weighing coefficients are included in the analysis and their impact is evaluated. Ultimately, the design figure of merit is defined. The result of such an analysis leads to a single value of the design effectiveness magnitude. This value ranges between 0 (worst design) and 1 (ideal design), with an actual value between 0 and 1 as a carrier of a very complex assessment effort.

The application of this approach is illustrated by two examples extracted from the engineering practice. The design evaluations were made for a brazed aircraft structure and a computer hardware component.

Introduction

An analysis that precedes design consideration of a new brazed structure must resolve three problems: 1) provide a solution for required physical, chemical, and mechanical properties of the joint, 2) offer the procedure to manufacture the brazed structure at the lowest production costs, and 3) lead to the product and manufacturing process with minimal negative environmental impact (a sustainable product/process). An optimal solution capable of satisfying all factors rarely can be achieved. Most of the time, one has to accept a compromise among quality, expenses, and product/process sustainability. Market, application specifics, and/or governmental regulations dictate priority of one of these factors in any specific case. For instance, mechanical and/or corrosion reliability is more important than cost for the brazed structure of a submarine life-support system. However, low cost is more important in mass production, and the quality may be sacrificed, at least partially, with relatively recent environmental/societal impact considerations.

KEYWORDS

Brazement
Brazing
Design Criteria
Score Values
Weighted Coefficients

Traditionally, the base metal and the brazing filler metal are selected first, based upon the projected mechanical and service properties of the brazed structure. The selected combination of materials specifies a choice of the brazing method and possible manufacturing equipment.

Recently, a system of design criteria and their score values was proposed to optimize brazing design solutions and to compare several competitive designs (Ref. 1). According to this system, the sum of all criteria numbers multiplied by a weight coefficient provides the final score value of the brazed design. Despite the simplicity, this approach has a serious drawback: it does not offer to a designer a clear reference value for an ideal design solution. Furthermore, the quantitative values for equally good designs for different products may be quite different, hence leading to possible misleading interpretations. Finally, an absence of formal generalization and scaling necessary for any figure of merit leads to an approach that would be difficult to use for an analysis of individual contributions to design quality and for comparison purposes. To mitigate these problems, a more rigorous definition of the design quality figure of merit is proposed in this paper.

The main idea behind the definition of a figure of merit for design evaluation is straightforward and can be expressed by stating that it must satisfy three requirements: 1) a figure of merit must be defined using objectively quantified design criteria, 2) a figure of merit must be a dimen-

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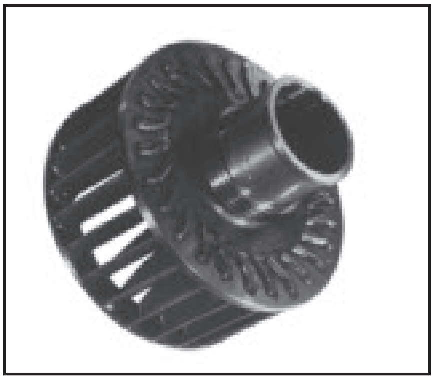

Fig. 1 — Titanium impeller brazed in vacuum at 890°C (1630°F) using Ti-24Zr-16Cu-16Ni (AWS BTi-4) filler metal (Design B).

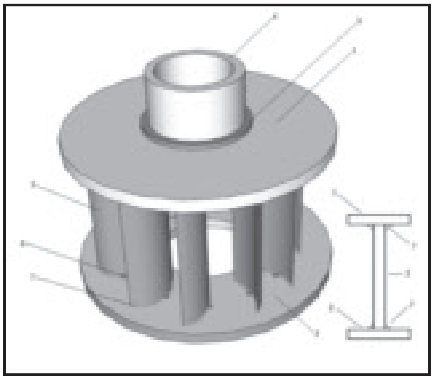

Fig. 2 — Titanium impeller assembled to be brazed: Design A. 1 and 2 – support plates, 3 – blades, 4 – tubing, 5 – braze preform, 6 – spot arc welding for fixing blades, 7 – brazing paste.

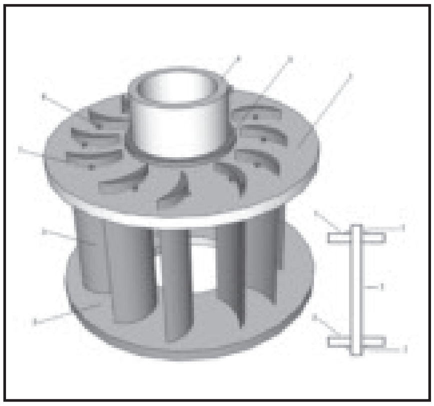

Fig. 3 — Titanium impeller assembled to be brazed: Design B. 1 and 2 – support plates, 3 – blades, 4 – tubing, 5 – braze preform, 6 – arc-spot welding for fixing blades, 7 – brazing paste.

sionless entity, and 3) a figure of merit has to have a fixed range of values — preferably between 0 (the worst scenario) and 1 (the best scenario). The first requirement reflects the need for having a figure of merit involving relevant quantifiers that reflect the trade-off between the influential factors and performance criteria. For

Table 1 — Brazing Design Criteria and Score Values

Symbol	Design Criteria Name	Scores	Weighing Coefficient
A	Brazeability of the base metal:		10
A_1	• good	10	
A_2	• satisfactory	4	
A_3	• limited	0	
A_4	• poor	–10	
B	Compatibility of the base and brazing filler metals:		10
B_1	• good	10	
B_2	• satisfactory	3	
B_3	• poor	–10	
C	Type of joint:		10
C_1	• lap joint or tubing joint	10	
C_2	• thread or seam joint	6	
C_3	• T-joint	4	
C_4	• butt joint or scarf joint	–4	
C_5	• stepped joint ($C_1 + C_4$)	2	
D	Joint clearance:		20
	• capillary clearance for this combination of the base and brazing filler metals:		
D_1	- uniform capillary clearance,	10	
D_2	- nonuniform capillary clearance.	8	
	• noncapillary clearance:		
D_3	- uniform noncapillary clearance,	–5	
D_4	- nonuniform noncapillary clearance.	–10	
E	Fixturing of parts and brazing filler metal during the brazing operation:		10
E_1	• self-fixturing or gravity location	10	
E_2	• knurling with pressing-fit	8	
E_3	• pressing-fit	8	
E_4	• tack welding	6	
E_5	• coiling of one part on the other part	5	
E_6	• one brazed part is expanded, riveted, swaged, crimped, stacked, etc.	6	
E_7	• use of compressing devices or fixtures	2	
E_8	• impossible fixturing of parts to be brazed	–5	
F	Thermal expansion coefficient (CTE) of base metals:		9
F_1	• equal (matched joint)	10	
	• different (unmatched joint)		
F_2	- compressive stresses appear in the joint during cooling after brazing	5	
F_3	- tensile stresses appear in the joint during cooling after brazing	–10	
F_4	• use of transition segments between dissimilar base materials to compensate the difference in CTE	2	
G	Forms of brazing filler metals:		9
G_1	• preform made of foil, wire, transfer tape, or compacted powder	10	
G_2	• coating	5	
G_3	• brazing paste	2	
G_4	• manual feeding of brazing filler metal in wire form	–5	
H	Design for preplacement of brazing filler metals:		9
H_1	• space for placement performs, paste, or powder is available	10	
H_2	• preplacement of the brazing filler metal is impossible (no space for brazing filler metal)	–5	
I	Ratio of thickness of brazed parts:		7
	• equal thicknesses		
I_1	- smooth transit from one part to another	10	
I_2	- sharp transit from one part to another (a step)	4	
	• unequal thicknesses		
I_3	- smooth transition from a thin part to a thick part	7	
I_4	- sharp transition (a step)	–5	
J	Stress concentration:		7
J_1	• design removes stress concentration in the joint	10	

Table 1 — Brazing Design Criteria and Score Values (continued)

Symbol	Design Criteria Name	Scores	Weighing Coefficient
J_2	• design distributes stress concentration in the point	2	
J_3	• brazed joint with stress concentration	–10	
J_4	• availability of flanges, doubles, or sleeves for joints subjected to alternating or dynamic loads	5	
J_5	• absence of flanges, doublers, or sleeves for joints subjected to alternating or dynamic loads	–5	
K	Possibility to use highly productive equipment for brazing:		9
K_1	• conveyor-belt furnace	10	
K_2	• multichamber automatic vacuum furnace	10	
K_3	• one-chamber vacuum or argon-atmosphere furnace	8	
K_4	• high-frequency induction coil	9	
K_5	• automatic multitorch system	8	
K_6	• electron beam or laser beam	9	
K7	• IR radiation	8	
K_8	• dipping in a flux bath	6	
K_9	• electric resistance heating	6	
K_{10}	• manual brazing	2	
L	Residual stresses in the joint after brazing:		8
L_1	• not possible	10	
L_2	• possible but can be eliminated by heat treatment	0	
L_3	• possible and cannot be eliminated by heat treatment	–10	
M	Effect of brazing thermal cycle on mechanical properties of the base metal:		8
M_1	• no effect	10	
M_2	• deterioration $\leq 20\%$	4	
M_3	• deterioration $\geq$ 20% but can be restored by heat treatment after the brazing	–2	
M_4	• deterioration $\geq$ 20%, which cannot be restored by heat treatment after the brazing	–10	
N	Mechanically secured design for joints served under high-stress, creep, fatigue, and impact loads:		8
N_1	• available	10	
N_2	• not available	–5	
O	Matching the joint design to the brazing process:		7
O_1	• possibility of uniform heating	10	
O_2	• possibility of uniform heating of all parts when brazing several parts simultaneously	10	
O_3	• access of electron beam or laser beam scanning, or IR radiation to brazing zone is available	10	
O_4	• design elements or places for using compressive fixtures are available	10	
O_5	• design does not match to the brazing process	–10	
P	Necessity of brazing fixtures:		6
P_1	• fixtures are not needed	10	
P_2	• universal fixtures are needed	4	
P_3	• specially made fixtures are needed	–5	
Q	Complexity of joint shape:		6
Q_1	• straight brazed seams	10	
Q_2	• simple, symmetric shape (e.g., circle, square, etc.)	10	
Q_3	• combination of $Q_1 + Q_2$	6	
Q4	• complex curvilinear shapes of joint	4	
R	Quality inspection of resulting brazed article:		6
R_1	• only observation is needed	10	
R2	• nondestructive testing is needed	4	
R_3	• selective distractive testing is needed	–5	
S	Possibility of brazing all joints of the article simultaneously:		5
S_1	• possible	10	
S_2	• impossible	3	

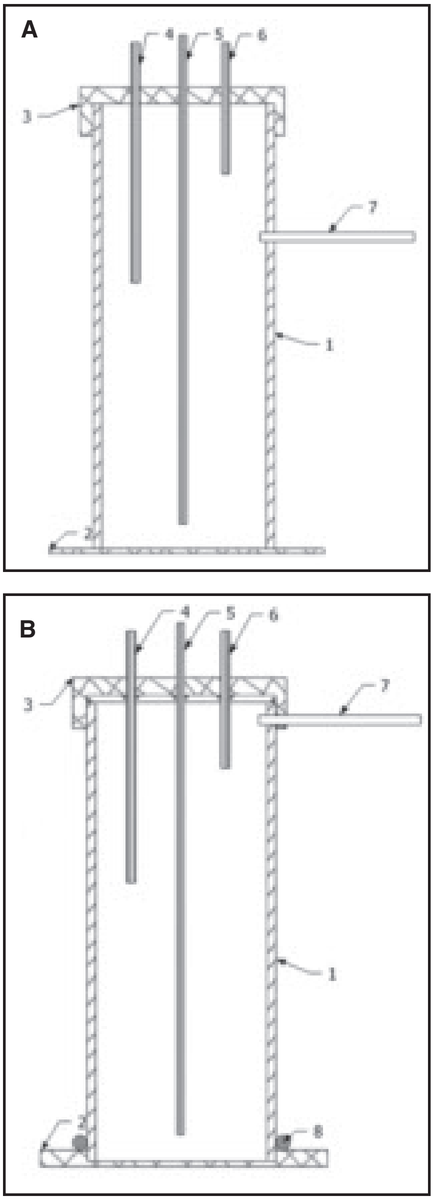

Fig. 4 — Competitive designs of a cryogenic copper evaporator. A — Design C; B — Design D. 1 – tube vessel of liquid nitrogen, 2 – contacting plate, 3 – lid, 4 and 6 – vapor outlet pipes, 5 – thermocouple pipe, 7 – nitrogen inlet pipe, 8 – preforms of brazing filler metal.

example, this requirement may be interpreted as signifying the departure of a given design from the one that would constitute the worst possible case or the departure of the ideal design from the worst case. The second requirement is a consequence of establishing relative value of the figure of merit by comparing the entities of the same physical character, while the third establishes the scale range easy to identify with limiting cases of design. Such figure of merit is defined later in this paper.

As an illustration of the application of the method, a demonstration of the use of

Table 1 — Brazing Design Criteria and Score Values (continued)

Symbol	Design Criteria Name	Scores	Weighing Coefficient
T	Necessity of using special brazing equipment that is not available in the industry or commercially on the market:		5
T_1	• unusual equipment is not needed	10	
T_2	• unusual equipment is needed	–10	
U	Accessibility of brazed seams:		4
U_1	• accessible	10	
U_2	• partially accessible	4	
U_3	• inaccessible	–5	
V	Unification of parts in the brazed article (n – total number of parts, n_1 – number of names of the parts):		4
V_1	• $n/n_1=1$	2	
V_2	• $n/n_1=2$	4	
V_3	• $n/n_1=3$	6	
V_4	• $n/n_1=4$	8	
V_5	• $n/n_1\geq 5$	10	
W	Possibility of rebrazing or repair:		4
W_1	• possible repeatedly	10	
W_2	• only one time	6	
W_3	• impossible	0	
Y	Other technological criteria of brazing design:		
	• free gas (air) exit from the joint clearance and any closed space:		6
Y_1	- possible	10	
Y_2	- impossible	–5	
	• formation of smooth fillets:		3
Y_3	- possible	10	
Y_4	- impossible	3	
	• removal of flux residues:		6
Y_5	- possible	10	
Y_6	- impossible	–10	
	• ratio of the overlap size to the thickness of the brazed part (thin part if different thicknesses):		5
Y_7	- from 2 to 5	10	
Y_8	- $\geq$ 5	4	
	• stress compensators in face or embracing joints of ceramics, glasses, or graphite:		5
Y_9	- available (compensated joint)	10	
Y_{10}	- unavailable (uncompensated joint)	2	
	• mechanical treatment after brazing (machining, filing, or grinding to remove sags, make fillets smooth, surface polishing, etc.):		6
Y_{11}	- mechanical treatment is not needed	10	
Y_{12}	- mechanical treatment is needed	–5	

this new figure of merit for design evaluations of two brazed structures will be presented. These structures represent two demanding brazing tasks related to aerospace and electronics applications: 1) a titanium impeller and 2) a copper cryogenic evaporator for electronics cooling.

List of Design Criteria

General Considerations

A thorough study of the influential factors that may hamper adequate brazed-joint formation during brazing and hence compromise the design solution of a brazed structure has uncovered that more than two dozen design criteria must be satisfied (Table 1). These criteria include at this stage only assessments of the joint technical aspects and implicitly manufacturing/cost considerations, without an inclusion of engineering sustainability issues. The authors approach to the latter are addressed elsewhere.

The most important criteria for the brazed structure design are the following:

- brazeability of the base metal,
- metallurgical compatibility of the base metal with the brazing filler metal,
- type of joints,
- the uniformity and size of joint clearance,
- fixturing of parts to be brazed,
- compatibility of thermal expansion if dissimilar base materials are joined, and
- a form of the brazing filler metal and its method of placement in the brazing zone.

Mistakes in the implementation of these criteria cause serious problems both on the manufacturing plant floor and in the quality of brazed products.

The design criteria presented in Table 1 determine the technological suitability and service properties of the resulting brazed assemblies. The best approach to the evaluation of these criteria is to consider all of them before and during the design process. This is particularly important for mass production and for complex and critical products such as compressor vanes, nuclear reactor coolers, and fuel heat exchangers. But, adequately addressing all design criteria is useful even in custom production of simple brazed parts. Such an approach will provide high-quality products, including the development of an adequate brazing design procedure important for other similar designs.

Traditionally, the base metal and the brazing filler metals are selected first, based on the projected mechanical and service properties of the brazed structure. The selected combination of materials specifies a choice of the brazing method and possible equipment. For example, if a ceramic is the base material, one has to go with vacuum furnace brazing rather than torch brazing.

Brazeability: Criterion A

Generally, we evaluate the brazeability as good if the base material can be brazed easily using 1) any of the suitable methods, such as furnace brazing, induction brazing, or torch brazing; 2) a number of brazing filler metals over a wide range of temperatures; and 3) a brazing operation that does not impair the structural or mechanical properties of the base material, or does not change those properties significantly. Carbon steels, austenitic stainless steels, and wrought copper alloys are examples of base metals with good brazeability.

The term *satisfactory brazeability* relates to base metals that also can be joined by many brazing methods and filler metals but require special attention or specific approach to brazing operations. An appropriate example of such base metals are titanium alloys. Brazing of titanium requires high-vacuum or high-purity inert gas and a temperature below or only slightly higher than the temperature of $\alpha \leftrightarrow \beta$ transus. Additionally, the brazing thermal cycle should be adjusted to minimize the growth of an intermetallic layer at the interface of the base and braze metals. Another example is martensitic stainless steels that require compatibility of the brazing thermal cycle with specific heat treatment.

Magnesium alloys and most refractory alloys are base metals with *limited brazeability*. These metals are characterized by difficult wetting and can be joined with a limited number of brazing filler metals. Surprisingly, some ordinary metals such as cast iron or cast bronzes also have limited brazeability.

Finally, base materials that have poor wettability and require additional operations to be brazed are described as having *poor brazeability*. Diamonds and ceramics such as silicon carbide and yttria-stabilized zirconia are typical examples of this class of base materials that require preliminary metallization or brazing using active filler metals in high vacuum.

Metallurgical Compatibility: Criterion B

Compatibility of brazing filler metal with the base metal is the first problem that the designer faces when he/she starts the project. This is not as simple a problem as it may appear at first glance. A number of factors should be evaluated and weighed such as 1) the effect of the brazing thermal cycle on possible changes in the microstructure and the properties of the base material, 2) metallurgical reactions between the base material and molten filler metal, 3) formation of intermetallics and phase composition of the joint metal, and 4) corrosion problems and cracking resistance.

We can speak about a *good compatibility* of the base and brazing filler metals if 1) easy wetting of the base metal and flow of the brazing filler metal (BFM) can be reached during brazing, 2) heating to the brazing temperature of the BFM will not result in phase or structural transformations that may impair physical and mechanical properties of the base metal, 3) microstructures of the joint, interface, diffusion zone, and base metal can be controlled by adjusting parameters of the brazing thermal cycle (or optionally, by additional heat treatment), and 4) the resulting brazed joint exhibits physical, chemical, and mechanical properties required by the blueprint (customer).

The *satisfactory compatibility* of the base materials and BFMs means that the easy satisfaction to at least one of the above-listed points (1–4) is difficult. However, these problems can be resolved technologically, for example, by metallization of the base material, adjusting the heating or cooling rates, multistep brazing with two different BFMs, deposition of protective coatings on the joint after brazing, etc.

An example of the compatibility of different brazing filler metals with titanium base metals is presented in Table 2. Titanium base metals with the temperature of $\alpha \leftrightarrow \beta$ transus above 900°C have good compatibility to the brazing filler metals of the Ti-Cu-Ni family, while base metals with the $\alpha \leftrightarrow \beta$ transus below 900°C have good compatibility with the brazing filler metals of the Ti-Zr-Cu-Ni system. Both silver-based or aluminum-based BFM have satisfactory compatibility to titanium alloys due to galvanic corrosion problems, low strength, and thick intermetallic layers at the interface. However, the growth of intermetallics can be partially suppressed by using a short brazing time and fast cooling, the strength of joints can be improved by using a mechanically secured joint design, and fillets of joints can be protected against corrosion by using polymer, phosphate, or other coatings.

Finally, *poor compatibility* means that the given combination of BFM and base material results in problems that cannot be ameliorated by any one of the following: wetting, structure transformation, reactive phase growing, corrosion, and loss of the strength. This case is very rare. A typical example of poor compatibility is the brazing of carbon steel by Cu-P filler metals that always is accompanied by uncontrolled growth of iron phosphide, which causes a brittleness of brazed joints.

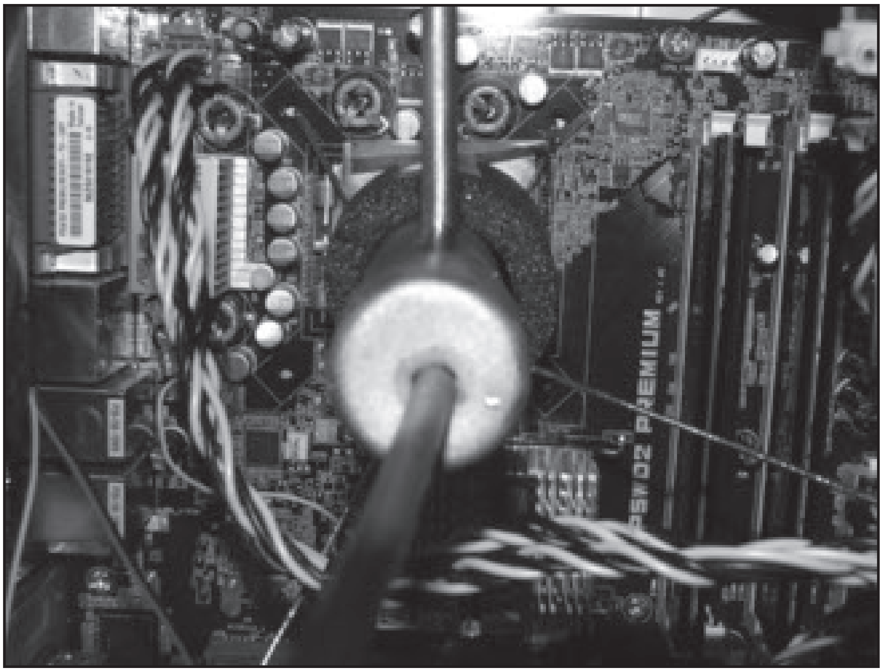

Fig. 5 — Copper evaporator (brazed with the silver-free filler metal P81) mounted in the working position to cool a CPU.

Table 2 — Compatibility of Titanium Base Metals with Brazing Filler Metals

Brazing filler metals			
Ag-based	Al-based	Ti-Cu-Ni system	Ti-Zr-Cu-Ni system
Good wetting of base metals			
Brazing temperature is $<\beta$-transus		Brazing temperature is $>\beta$-transus	Brazing temperature is near or $<\beta$-transus
Formation of intermetallics in the brazed joint			
Working temperature <300°C	Working temperature <150°C	Working temperature ≤500°C	Working temperature ≤600°C
Tempering is possible	Heat treatment is not recommended Brazing time is critical	Aging, solution treatment, or tempering are possible after the brazing	
Middle strength Corrosion problems	Low strength Corrosion problems	High strength of brazed joints High corrosion resistance	

Fig. 6 — Microstructure of copper joint made by torch brazing at 750°C (1380°F) with the silver-free filler metal P81 (Cu-Zn-6P-6Ni).

Score Values

Classification of design brazing criteria and their score values are presented in Table 1.

One of the most important issues related to a proper assessment of suggested brazing criteria is a clear definition of each criterion and a precise quantification of its levels. For example, the first two criteria, brazeability of the base metal and compatibility of the base and filler metals, must both have precise definitions to be quantified within a range that spans from poor to good. The level of subjectivity in such an evaluation ideally would not exist. However, there is no consensus on what such terms may mean for each particular case. What is important is that an assessment of each individual criterion must be a subject of a rigorous study. Each level of the assessment of a criterion has two quantitative values: 1) the score value, $A \in (-10,10)$, and 2) the weighing factor $g \in (3,20)$. The weighing factor assigns the relative value of the score value for a given criterion vs. the remaining set of criteria. So, the criteria listed as the most important would have the highest weighing coefficients.

Negative score values were used as well to make an adequate difference between superior and inferior designs, i.e., the negative scores are assigned to criteria that strongly disadvantageously affect a brazing process and/or the quality of the final product.

The adverse effect of a noncapillary joint clearance is defined as one of the most important factors. This criterion's importance was emphasized by a weighing coefficient value of 20 instead of 10 as assigned to most other criteria as the maximum. Indeed, it is practically impossible to get a stable brazing process and a decent quality of the brazed article if the

Table 3 — Brazing Design Criteria and Their Scores for Examples A and B

Symbol	Design Criteria Name	Scores		Weighing Coefficient
		Design A	Design B	
A	Brazeability of the base metal:			**10**
A_1	• good	**10**	**10**	
B	Compatibility of the base and brazing filler metals:			**10**
B_1	• good	10	**10**	
B_2	• satisfactory	**3**	3	
C	Type of joint:			**10**
C_1	• lap joint or tubing joint	10	**10**	
C_2	• threaded or seam joint	**4**	4	
D	Joint clearance:			**20**
	• capillary clearance for this combination of the base and brazing filler metals:			
D_1	-nonuniform capillary clearance	**8**	**8**	
E	Fixturing of parts and brazing filler metal during the brazing operation:			**10**
E_1	• self-fixturing or gravity location	10	**10**	
E_7	• use of compressing fixtures	**2**	2	
F	Thermal expansion coefficient (CTE) of base metals:			**9**
F_1	• equal (matched joint)	**10**	**10**	
G	Forms of brazing filler metals:			**9**
G_3	• brazing paste	**2**	**2**	
H	Design for preplacement of brazing filler metals:			**9**
H_1	• space for placement performs, paste, or powder is available	**10**	**10**	
I	Ratio of thicknesses of brazed parts:			**7**
	• equal thicknesses			
I_1	- smooth transition from one part to another	10	**10**	
I_2	- sharp transition from one part to another (a step)	**4**	4	
J	Stress concentration:			**7**
J_2	• design distributes stress concentration in the joint	2	**2**	
J_3	• brazed joint with stress concentration	**–10**	–10	
K	Possibility to use highly productive equipment for brazing:			**9**
K_3	• in one-chamber vacuum or argon furnace	**8**	**8**	
L	Residual stresses in the joint after brazing:			**8**
L_1	• not possible	**10**	**10**	
M	Effect of brazing thermal cycle on mechanical properties of the base metal:			**8**
M_1	• no effect	10	**10**	
M_2	• deterioration ≤20%	**4**	4	
N	Mechanically secured design for joints served under high-stress, creep, fatigue, and impact loads:			**8**
N_1	• available	10	**10**	
N_2	• not available	**–5**	–5	
O	Matching joint design to brazing process:			**7**
O_2	• possibility of uniform heating of all parts when brazing several parts simultaneously	**10**	**10**	
P	Necessity of brazing fixtures:			**6**
P_1	• fixtures are not needed	10	**10**	
P_3	• specially made fixtures are needed	**–5**	–5	
Q	Complexity of joint shape:			**6**
Q_1	• straight brazed seams	**10**	10	
Q_4	• complex curvilinear shapes of joint	4	**4**	

Table 3 — Brazing Design Criteria and Their Scores for Examples A and B

Symbol	Design Criteria Name	Scores Design A	Design B	Weighing Coefficient
R	Quality inspection of resulting brazed article:			**6**
R_1	• only observation is needed	**10**	**10**	
S	Possibility of brazing all joints of the article simultaneously:			**5**
S_1	• possible	**10**	**10**	
T	Necessity of using special brazing equipment that is not available in the industry or commercially on the market:			5
T_1	• unusual equipment is not needed	**10**	**10**	**4**
U	Accessibility of brazed seams:			
U_1	• accessible	**10**	**10**	
V	Unification of parts in the brazed article (n – total number of parts, n_1 – number of names of the parts):			**4**
V_1	• $n/n_1=1$	**10**	**10**	
W	Possibility of rebrazing or repair:			**4**
W_1	• possible repeatedly	10	**10**	
W_3	• impossible	**0**	0	
Y	Other technological criteria of brazing design:			**6**
	• free gas (air) exit from the joint clearance and any closed space:			
Y_1	- possible	**10**	**10**	
	• formation of smooth fillets:			**3**
Y_3	- possible	10	**10**	
Y_4	- impossible	**3**	3	
	• mechanical treatment after brazing (machining, filing, or grinding to remove sags, make fillets smooth, surface polishing, etc.):			**6**
Y_{11}	- mechanical treatment is not needed	10	**10**	
Y_{12}	- mechanical treatment is needed	**–5**	–5	

joint clearance is noncapillary. In this case, additional efforts and special materials are always needed to fill or close the gap during brazing.

If one limits design considerations to a selection of materials and brazing method only, many technological and quality problems will appear in production. So, the correct design provides not only required mechanical and service properties of the brazed structure, but also leads to a high technological suitability. In such a case fabrication of the brazed assembly becomes highly productive, and is assisted by optimal methods of cleaning, heating, heat treatment, inspection, and testing.

So, many design variables should be considered during the development of brazing technology to reach the correct design solution. This realization is clearly reflected in the richness of the design criteria listed in Table 1.

Definition of the Design Figure of Merit

Let us define the brazing design figure of merit as follows:

$$\varepsilon = \frac{\sum_{i=1}^{n} A_i g_i - \sum_{i=1}^{n} A_{i,\min} g_i}{\sum_{i=1}^{n} A_{i,\max} g_i - \sum_{i=1}^{n} A_{i,\min} g_i} \qquad (1)$$

In Equation 1, the terms $\sum_{i=1}^{n} A_i g_i$ represent the compounded value of the products of score values and weighing coefficients for selected, relevant design criteria for 1) an actual design, $\sum_{i=1}^{n} A_i g_i$, 2) the fictitious, worst case scenario design determined assigning the lowest score values for the selected design criteria, $\sum_{i=1}^{n} A_{i,\min} g_i$, and 3) the idealized, best case scenario design determined assigning the highest score values for the same selected design criteria, $\sum_{i=1}^{n} A_{i,\max} g_i$, respectively. Note that, by definition, Equation 1 in any considered case always offers the value of the design figure of merit within the prescribed value range $\varepsilon \in (0,1)$. The result is dimensionless, and represents the measure of the actual design departure from the best possible design scenario case. Hence, the figure of merit satisfies all the requirements imposed previously.

Examples of Competitive Designs

It is best to demonstrate effectiveness of the proposed evaluation system by evaluating selected competitive designs of real brazed products. Two examples were selected: 1) a titanium impeller (Fig. 1, Table 3) and a copper cryogenic evaporator used in high-speed computers (Fig. 5,Table 4). For each example, two design solutions were presented.

The first design of the titanium impeller is presented in Fig. 2. Base metal is the Alloy Ti-3Al-2.5V. The filler metal is AWS BTi-1 (Ti-15Cu-15Ni), having the liquidus temperature of 950°C (1742°F) and brazing temperature range between 980°–1050°C (1800°–1920°F). This means that brazing should be performed at the temperature above the β– transus temperature of the base metal, which is 935°C (1715°F). In order to cut production costs, the designer made a decision not to make the shaped holes for blades in the top and bottom titanium plates, and this resulted in an appearance of T-joints of blades with plates. A need for delicate assembling of all blades with the plates requires an application of a special fixturing device; consequently, all blades must be fixed to plates by arc spot welding — Fig. 2.

The paste of the powdered brazing filler metal is deposited in all joint areas. First, the paste containing a polymer binder is deposited on the top plate. After this portion of paste is polymerized, another portion is deposited on the other side of the article and around the shaft. After brazing, all the welds and excessive braze metal should be removed mechanically to get smooth fillets of brazed joints. This operation can be done only manually, which increases the labor cost. Additional drawbacks of this design are 1) the necessity of using fixtures to compress the plates to blades during the assembling and brazing, 2) a stress concentration in the brazed T-joints due to sharp transition from blades to plates, and 3) problems with repair should it be needed.

The compatibility of different brazing filler metals with the titanium Alloy Ti-3Al-2.5V is presented in Table 2.

This table shows that the Ti-Zr-Cu-Ni system is preferred for the previously mentioned design of the titanium impeller because brazing can be done at a temperature below the β–transus temperature of the base metal, and its mechanical properties will not be reduced by the brazing thermal cycle.

Therefore, the brazing filler metal AWS BTi-4 (Ti-24Zr-16Cu-16Ni) should

Table 4 — Brazing Design Criteria and Their Scores for Examples C and D

	Design Criteria	Scores		Weighing
Symbol	Name	Design C	Design D	Coefficient
A	Brazeability of the base metal:			**10**
A_1	• good	**10**	**10**	
B	Compatibility of the base and brazing filler metals:			**10**
B_1	• good	**10**	**10**	
C	Type of joint:			**10**
C_1	• lap joint or tubing joint	10	**10**	
C_3	• T-joint	**4**	4	
D	Joint clearance:			**20**
	• capillary clearance for this combination of the base and brazing filler metals:			
D_1	- uniform capillary clearance,	10	**10**	
D_2	- nonuniform capillary clearance	**8**	8	
E	Fixturing of parts and brazing filler metal during the brazing operation:			**10**
E_1	• self-fixturing or gravity location	10	**10**	
E_8	• impossible fixturing of parts to be brazed	**–5**	–5	
F	Thermal expansion coefficient (CTE) of base metals:			**9**
F_1	• equal (matched joint)	**10**	**10**	
G	Forms of brazing filler metals:			**9**
G_1	• preform made of foil, wire, transfer tape, or compacted powder	10	**10**	
G_4	• manual feeding of brazing filler metal in wire form	**–5**	–5	
H	Design for preplacement of brazing filler metals:			**9**
H_1	• space for placement performs, paste, or powder is available	10	**10**	
H_2	• preplacement of the brazing filler metal is impossible (no space for brazing filler metal)	**–5**	–5	
I	Ratio of thicknesses of brazed parts:			
	• equal thicknesses			**7**
I_1	- smooth transition from one part to another	**10**	**10**	
J	Stress concentration:			**7**
J_2	• design distributes stress concentration in the joint	2	**2**	
J_3	• brazed joint with stress concentration	**–10**	–10	
K	Possibility to use highly productive equipment for brazing:			**9**
K_3	• one-chamber vacuum or argon furnace	8	**8**	
K_{10}	• manual brazing	**2**	2	
L	Residual stresses in the joint after brazing:			**8**
L_1	• not available	**10**	**10**	
M	Effect of brazing thermal cycle on mechanical properties of the base metal:			**8**
M_2	• deterioration ≤20%	**4**	**4**	
N	Mechanically secured design for joints served under high-stress, creep, fatigue, and impact loads:			**8**
N_1	• available	10	**10**	
N_2	• not available	**–5**	–5	
O	Matching joint design to brazing process:			**7**
O_2	• possibility of uniform heating of all parts when brazing several parts simultaneously	**10**	**10**	
P	Necessity of brazing fixtures:			**6**
P_1	• fixtures are not needed	10	**10**	
P_3	• specially made fixtures are needed	**–5**	–5	

be selected for the preferred design — Figs. 1 and 3. Several other important changes would also be made in the joint design. Incorporating shaped holes for the blades in the titanium plates that resulted in an easier assembly procedure without using a compressive fixture. Spot welding should also be used to fix the blades and they can be made outside of the flow passages of the working channels. Also, there is no necessity to remove them after the brazing. In addition, brazing paste is deposited outside of the working channels too. This guarantees the formation of smooth fillets at the inner side of the blade-to-plate joints. Stress concentration is insignificant in this design because the brazed joints are mechanically secured, and any impact or fatigue stresses would be transferred to the base metal, while in the first design the braze metal had to resist these stresses itself. The only drawback of this design is the complexity of the joint shape. The assessments of the design criteria score values and weighing factors from Table 1 are given in Table 3. Each design criterion taken into account is associated with the corresponding score level and weighing coefficient. Each design criterion score value is listed in bold and the not scored options are omitted for the sake of clarity.

Another example of the evaluation of competitive designs is presented in Figs. 4 and 5. The assembly to be brazed is a cryogenic evaporator for cooling electronics. All parts of the evaporator are made of copper. The selected brazing filler metal is BAg-24 in Design C, and the silver-free P14 (Cu-6Sn-6P-0.1Zr) or P81 (Cu-26Zn-6P-6Ni) filler metals in Design D.

The first design version (Fig. 4A, Design C) was made for manual torch brazing. According to Table 1, this design has a number of drawbacks that are characterized by the following criteria: C_3, D_2, E_8, G_4, H_2, K_{10}, N_2, P_2, S_2, Y_6, Y_8, and Y_{12} (Table 4).

The second design version (Fig. 4B, Design D) is intended for furnace brazing or brazing using an automatic multitorch system. According to Table 4, this design does not have the drawbacks mentioned previously (except Y_6 — a problem with removing flux residues from the inner space of the article after brazing). Further, the problem of flux residue removal can be resolved, for example, by using self-fluxing brazing filler metals such as BCuP-6, BCuP-7, or silver-free P14 (Cu-6P-4Sn-0.1Zr). After testing, they can operate at cryogenic temperatures.

A brazed evaporator in the working position as a CPU cooler is shown in Fig. 5. The microstructure presented in Fig. 6 demonstrates the high quality of brazed joints provided by Design D. The brazed joint is fully dense, with developed diffu-

Table 4 — Brazing Design Criteria and Their Scores for Examples C and D (continued)

Symbol	Design Criteria Name	Scores		Weighing Coefficient
		Design C	Design D	
Q	Complexity of joint shape:			**6**
Q_2	• simple, symmetric shape (e.g., circle, square, etc.)	**10**	**10**	
R	Quality inspection of resulting brazed article:			**6**
R_1	• only observation is needed	**10**	**10**	
S	Possibility of brazing all joints of the article simultaneously:			**5**
S_1	• possible	10	**10**	
S_2	• impossible	**3**	3	
T	Necessity of using special brazing equipment that is not available in the industry or on market:			**5**
T_1	• unusual equipment is not needed	**10**	**10**	
T_2	• unusual euquipment is needed	–10	–10	
U	Accessibility of brazed seams:			**4**
U_1	• accessible	**10**	**10**	
V	Unification of parts in the brazed article (n – total number of parts, n_1 – number of names of the parts):			**4**
V_2	• $n/n_1=2$	**4**	**4**	
W	Possibility of rebrazing or repair:			
W_1	• possible repeatedly	**10**	**10**	**4**
Y	Other technological criteria of brazing design:			
	• free gas (air) exit from the joint clearance and any closed space:			**6**
Y_1	- possible	**10**	**10**	
	• formation of smooth fillets:			**3**
Y_3	- possible	10	**10**	
Y_4	- impossible	**3**	3	
	• removal of flux residue:			**6**
Y_6	- impossible	**–10**	**–10**	
	• ratio of the overlap size to thickness of the brazed part (thin part if different thicknesses):			**5**
Y_7	- from 2 to 5	**10**	**10**	
	• mechanical treatment after the brazing (machining, filing, or grinding to remove sags, make fillets smooth, surface polishing, etc.):			**6**
Y_{11}	- mechanical treatment is not needed	10	**10**	
Y_{12}	- mechanical treatment is needed	**–5**	–5	

sion zone and uniformly distributed eutectic. No intermetallics or cracks were found in the joint.

Quantitative Evaluation of Brazement Design

Determination of the design figures of merit for two competing designs, for each considered case, i.e., A vs. B, and C vs. D, can be performed using the numerical values from Table 3 and Equation 1. For example, for designs A and B, one obtains the following result.

$$\varepsilon^A = \frac{\sum_{i=1}^{n} A_i g_i - \sum A_{i,\min} g_i}{\sum_{i=1}^{n} A_{i,\max} g_i - \sum_{i=1}^{n} A_{i,\min} g_i} = 0.70$$

$$< \varepsilon^B = \frac{\sum_{i=1}^{n} A_i g_i - \sum A_{i,\min} g_i}{\sum_{i=1}^{n} A_{i,\max} g_i - \sum_{i=1}^{n} A_{i,\min} g_i} = 0.93 \qquad (2)$$

From the comparison given by Equation 2, it is easy to establish the superiority of Design B.

Analogous to the previous example, the determination of the design figures of merit for two competing designs of the second example, C and D, can be performed using the numerical values from Table 4 and Equation 1, i.e.,

$$\varepsilon^C = \frac{\sum_{i=1}^{n} A_i g_i - \sum A_{i,\min} g_i}{\sum_{i=1}^{n} A_{i,\max} g_i - \sum_{i=1}^{n} A_{i,\min} g_i} = 0.61$$

$$< \varepsilon^D = \frac{\sum_{i=1}^{n} A_i g_i - \sum A_{i,\min} g_i}{\sum_{i=1}^{n} A_{i,\max} g_i - \sum_{i=1}^{n} A_{i,\min} g_i} = 0.92 \qquad (3)$$

Again, the comparison illustrated by Equation 3 clearly establishes superiority of Design D over Design C.

Most principal design recommendations are based on a large body of art and science information accumulated over the years, for example, Chapter 2 of the AWS *Brazing Handbook* (Ref. 2), as well as Refs. 3–7. A designer can estimate a design solution using these recommendations in conjunction with the criteria system formulated in Table 1.

The score numbers and criteria priorities in Table 1 reflect, in particular, experience in brazing design in the aerospace and automotive industries. The evaluation system may be further adjusted and customized by adding specific criteria, or excluding some criteria or changing the values of the scores depending on the specifics and needs of production. An example of such need can easily be identified in an effort to consider more concisely the sustainability issues involving manufacturing disciplines. Such an approach requires an additional system of criteria. In addition to formulating overall design efficiency, one may consider defining specific figures of merit that are focused on a specific objective such as environmental impact and recycling.

Conclusions

A new figure of merit for quantifying the design of a brazed joint or assembly has been devised. The figure of merit is based on a rigorous set of requirements and involves a cumulative assessment of design criteria values based on the art and science of brazing. The system of design criteria with their quantitative values is proposed to facilitate the designing procedure, to evaluate the final design solution, and to compare it with the design of other brazed structures available in the practice of brazing.

About 100 design criteria are dedicated not only for providing reliability and service properties of the resulting brazed structures, but also for manufacturing them by the most economical and ecological way.

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