CHAPTER ONE

INTRODUCTION AND OBJECTIVES

1.1. Introduction

Welding is the joining of two or more pieces of metal by applying heat, pressure or both with or without the addition of filler metal to produce a localized union through fusion or recrystallization across the interface. The heat source may be a gas torch or an electric soldering unit. A welded joint is a composite of three regions: the fusion zone, the heat affected zone (HAZ), and the unaffected parent metal (Uzun, 2004).

The fusion zone contains material that was melted during welding and usually has a chemical composition similar to that of the base metal. The heat-effected zone consists of material that is not subject to a high enough temperature for fusion but has undergone a thermal cycle that observably alters the microstructure of the parent materials. The choice of welding method will depend on whether the technique produces enough heat to join the materials without deformation and conserve their properties, whether the materials to be welded are similar or different metals/alloys, and the procedural costs (Brandi, 1992). There are various joining and welding techniques of which a few can be named as friction welding, fusion welding, electron beam welding, arc welding, etc. A technique that theoretically gives localized, controllable high heat input was laser welding. However, initially laser welding equipment was expensive and also significant tooling and setup time to obtain a satisfactory weld was required.

The use of laser welding has increased in the past few decades in dentistry (Sjogren et al., 1988; Roggensack et al., 1993; Yamagishi et al., 1993; Berg et al., 1995; Wang and Welsch, 1995; Chai and Chou, 1998). There are many advantages for laser welding. Firstly, there is very little heat generated outside the beam contact or weld area. This eradicated the need of any fluxes and leaves the piece bright and clean. As the material is not heated to a greater degree, the operator could hold the pieces he is joining with hands, eliminating the need for fixturing, clamping, etc. Also, there is no worry of melting of small pieces. Prefabricated parts can easily to be fixed by using the laser-welding-technology (Tiffany et al., 1999). However, looking at the available literature, since 1970 many experiments have been conducted into non precious and precious alloys and have shown contradictory results, probably because the experimental procedures used were different (Gordon and Smith, 1970).

For the joining of dissimilar metals, the common types of welding techniques available are fusion welds, low-dilution welds, non-fusion joining, etc. Using any of these methods, dissimilar joints can be made, but low-dilution and non-fusion joining processes are more often used for high production and special-application joining.

Retention of partial denture prosthesis depends on the amount of undercut engaged on an abutment tooth and the flexibility of the clasp. Flexibility is influenced by clasp length and material used. Cobalt-chromium is still the standard dental material for a removable partial denture framework. The major difference between titanium and cobalt-chromium alloys lies in their modulus of elasticity. Titanium has more resilience compared to cobalt-chromium. This property would allow for the retentive clasp arm of a removable partial denture to be constructed in a shorter arm length than it is possible with cobalt-chromium and to be placed in deeper undercut on abutment tooth. This characteristic is useful in clinical situations when the abutment tooth is not a molar or there are concerns with aesthetics or periodontal healthrequirement. Utilizing the low modulus of elasticity of titanium with rigid cobalt-chromium property as base material would appear to offer ideal solutions to some cases. Although some studies showed that welding cobalt-chromium and stainless steel alloys possess better joining properties. Clinical studies demonstrated that the chromium alloy/stainless-steel couple was unstable. Therefore Cobalt-chromium alloys should not be used in combination with stainless steel but may be used in combination with titanium alloy (Kummer and Rose, 1983).

1.2. Aim of the study

The aim of this study was to evaluate properties of the welded joints between cobalt-chromium and titanium.

1.3. Objective of the study

The objectives of the current study were as follows:

1. To determine the feasibility of laser welding cobalt-chromium and titanium.
2. To evaluate some properties (tensile strength, modulus elasticity and bending strength) in laser welded dissimilar alloys between cobalt-chromium and titanium.

CHAPTER TWO

LITERATURE REVIEW

2.1 Titanium

Titanium is presented on the periodic table as element 22 with an atomic weight of 47.88. It is the ninth most abundant element in the earth's crust, (Table 2.1). Titanium and its alloys were used as biomaterials with its property being relatively inert and corrosion resistance because of its thin surface oxide layer. Titanium has become one of the most important metals in prosthodontics because of its desirable physical and mechanical properties (William, 1984)

Table 2.1 Weight percentage of selected elements found in igneous rock

Element	Percent (wt %)
Oxygen	46
Silicon	28
Aluminium	8
Iron	5
Calcium	4
Sodium	3
Potassium	3
Magnesium	2
Titanium	0.6
Manganese	0.1
Zirconium	0.3
Nickel	0.02
Copper	0.01
Lead	0.002

(McCracken, 1999)

2.1.1 Types of titanium

Donachie (1984) stated that commercially pure titanium (CPTi) is also referred to as unalloyed titanium. It consists of 99.5% pure titanium and available in four different grades (ASTM grades I to IV). This is based on the incorporation of small amount of oxygen, nitrogen, hydrogen, iron, and carbon during purification procedures (Table 2.2). Titanium can be alloyed with a wide variety of elements to alter its properties, mainly for the purposes of improving strength, high temperature performance, creep resistance, weldability, response to ageing heat treatments and formability.

Table 2.2 Types of CPTi (American Society of Testing and Material (ASTM))

Unalloy grade(ASTM)	Tensile strength(MPa)	YieldStrength (0.2%)	N	C	H	O	Fe
Grade I	240	170	0.03	0.1	0.015	0.018	0.2
Grade II	340	280	0.03	0.1	0.015	0.25	0.3
Grade III	450	380	0.05	0.1	0.015	0.35	0.3
Grade IV	540	480	0.05	0.1	0.015	0.4	0.5

Source: http://www.scribd.com/doc/21800897/M-Materials-En

Table 2.3 Mechanical properties of alloys used in prosthodontics

Alloys	Ti (CPTi)	Ti-6A1-4V	Chromium cobalt cast	Stainless steelwrought
Modulus of elasticity	15×10^6 psi	113.8×10^2	218.7×10^3	200×10^3
Ultimate tensile strengthN/mm^2(MPa)	240 – 540	570	760	1800
Elongation	15 - 25	10	4	8
Hardness(VHN)	160	250 to 500	370	440

The most commonly used titanium alloy is Ti-6A1-4V because of its desirable proportion and predictable producibility.

Table 2.4 Mechanical properties of titanium according to the American Society of Testing and Material (ASTM)

Un alloy grade ASTM	elongation %	Tensile strength (MPa)	Yield strength
Grade I	25	240	170
Grade II	20	340	280
Grade III	18	450	380
Grade IV	15	540	480

Table 2.5 Physical properties of metals in prosthodontics

Alloy	Melting Range (ºC)	Casting Shrinkage (%)	Density (g/cm^3)
Type IV Gold	850 – 1000	1.5	15
Titanium (CPTi)	1668 - 1720	2	4.5
Titanium alloy	1940	2	**4.5**
Chromium Cobalt	1400 – 1500	2.3	7-8

Table 2.6 Physical properties of titanium

Material	Density (g/cm^3)	Melting Range(°C)	Str/Density x 10^{6}N.m.mg)
Ti Grade 1	4.51	1670	54
Ti Grade 2	4.51	1677	54
Ti Grade 3	4.51	1677	54
Ti Grade 4	4.54	1660	54

2.1.2 The use of titanium as dental materials

1. Implant material

Commercially pure titanium and titanium alloy is the metal of choice in endosseous implantology and prostheses superstructures. It has been used for the past more than three decades as successful implant material because of its biocompatibility (Lee, 1997). The biocompatibility of titanium is due to the favourable interaction between host tissue and the surface oxide layer of the metallic implant at the interface (Glantz, 1998).

2 Removable partial dentures (RPDs)

The standard material used for a removable partial denture framework is cobalt chromium alloy. With the development in titanium casting technology in the past decades there has been opportunities in utilizing titanium for the construction of denture framework. Titanium as removable partial denture (RPD) framework started in the late 90's when technologies of casting and welding for dental prostheses were relatively new. However, with improved casting technology and melting techniques like laser welding, this has greatly facilitated the casting of titanium-based metals. Titanium for prostheses is superior in terms of its excellent biocompatibility in that avoids metal allergic reaction. The allergenic and carcinogenic properties of base metal alloys used in dentistry especially Ni-Cad and beryllium-based alloys have fuelled controversies. For these reasons, titanium base plate was indicated as protection for cases with metal allergy (Ohkubo et al., 2008). Due to its lightweight, (low density) it is good in large size prosthesis. It has high strength to weight ratio fatigue and corrosion resistance (Hakan et al., 2005).

The low modulus of elasticity of titanium compared to Co-Cr alloy promises a good quality for clasp unit; however titanium is not rigid enough for connectors (Niinomi, 1998). Thomas et al. (1997) reported that occlusal rests and clasps fracture in cobalt-chromium within 2 year period of RPD use with the survival rate of 91%. Their report revealed general favourable acceptance of titanium RPDs.

The main drawback of titanium is its difficulty in casting. This is attributed to the high melting temperature, inferior castability, reaction layer formed on the cast surface, difficulty of polishing and high initial cost (Koike et al., 2003; Ohkubo et al., 2003).

2.2 Cobalt-chromium alloys

The use of base alloys for the fabrication of removable partial dentures (RPDs) is widely accepted. In the beginning of the 20^{th} century, Elwood Haynes first introduced this alloy which has high strength (Angelini and. Zucchi, 1991). Since the early 1930s, these alloys have been widely used in dentistry. Their main use is as a framework in removable partial dentures and base-plates in complete dentures.

Removable partial dentures (RPD) are usually used for partially edentulous patients. There is a thin cast alloy framework in the prostheses on which replacement teeth are attached with dental acrylic resin. Mostly all of these casts are from cobalt-chromium alloys. These were first used for this purpose in 1932 and are being used extensively to date. Advantages for their preference are good castability, high rigidity, very good corrosion resistance and they are much cheaper than gold alloys (Behr et al, 2000).

2.2.1 Physical and Mechanical properties

Cobalt and chromium are the chief constituents of cobalt-chromium alloys. The base element is cobalt and is has about a solid solution of 70% cobalt and 30% chromium. Chromium content, with an upper limit of 30% for mechanical reasons, gives passivity on the alloy, and is the major reason of high resistance against corrosion (Arvidson et al., 1987). Metals like molybdenum, iron, copper, tungsten and beryllium may also present in minute quantities in cobalt-chromium alloy system (Phillips, 1991). Table 2.7 shows the selected physical and mechanical properties of cobalt-chromium alloys.

Table 2.7 Selected physical and mechanical properties of cobalt-chromium alloys

Property	**Value**
Ultimate strength (MPa)	931
Modulus of elasticity (GPa)	232.8
0.2% ductile yield (MPa)	414
Elongation limit (%)	70
Shear modulus (GPa)	83.36
Melting point °C	1315-1440
Thermal conductivity at316°C	17.0 W / m-k

2.2.2 Cobalt-chromium framework for RPD

The outstanding properties of Co-Cr together with its proven biocompatibility have been documented by its use for over 60 years in the dental literature. cobalt-chromium alloys have a very good history of biocompatibility, even though there are some reports of tissue hypersensitivity in a very limited population (Geurtsen, 2001).

Compared to acrylic resin, RPDs with rigid cobalt-chromium frameworks have shown to be better in terms of preserving the health of oral tissues (Bissada, 1974; Lechner, 1987; Wilding and Reddy, 1987). A number of studies have shown that cobalt-chromium alloys are more resistant to corrosion than Ni-Cr alloys and therefore, it is believed to be an appropriate alternative for use in dental prostheses (Viennot et al., 2005; Eliasson et al., 2007). Because of their high physical strength, resistance to corrosion, and cost performance cobalt-chromium (Co-Cr) casting alloys are widely used in removable partial denture frameworks (Mezger, 1988; Pratt et al., 1989; Lawson, 1991; Philips and Skinner 1996).

2.2.3 Advantages of cobalt-chromium alloys as RPD base:

Besides cost other positive aspects for these alloys as:

1. Higher wearing comfort for the patient (Strietzel, 2001).
2. As this non precious metal alloys have remarkably reduced heat conductivity, the hot-cold sensation is more pleasant for the patient.
3. Higher modulus of elasticity, it can be worked with more ease and in the case of space restrictions a reduction in cross sectional radius without compromising on the stiffness can be achieved.
4. The same strengths can be achieved with smaller thickness when compared with other precious metal alloys.
5. Low density, lightweight compared to the precious metal alloys. These properties are significant in maxillary prostheses with complete palatal coverage and distal extension frameworks. (Galloza et al., 2004)

Colour stability: No discoloration of the alloy occurs in the mouth of the patient. Discoloration may happen occasionally with other precious metal alloys which have silver or copper as they react with oxygen or sulphur containing groups; forming black or dark coatings.

2.3 Joining of metals

Welding is the joining of two or more pieces of metal by applying heat or pressure, or both with or without the addition of filler metal, to produce a localized union through fusion or recrystallization across the interface (American Society for Metals, 1988).

A welded joint is a composite of three regions: the fusion zone, the heat affected zone (HAZ), and the unaffected parent metal. The fusion zone contains material that was melted during welding and usually has a chemical composition similar to that of the base metal. The heat affected zone consists of material that is not subject to a high enough temperature for fusion but has undergone a thermal cycle that observably alters the microstructure of the parent materials (American Society For Metals, 1988).

In dentistry, soldering and brazing are the most common procedures for joining metals. According to the American Welding Society, if the joining process is below 425ºC, the operation is called soldering. A process of joining metallic parts by the fusion of an intermediary alloy with a melting temperature above approximately 450ºC, but below the melting temperature of the parent metal alloy, is called brazing (ISO (DIN/ISO 8505).

Soldering in RPD work authorization requests are often related to fractures in framework, additions of clasps and retention for resin. The method used to provide heat for soldering could affect the microstructure of the component. Soldering at a high temperature could subject the alloy to one form of heat treatment. Heat treatment of cobalt-chromium alloys has been reported to influence the microstructure and mechanical properties of the alloys. It also reduces their ductility of strength (Strandman 1976; Staffanou et al., 1980).

A material which has a lower melting point is usually selected as the filler material for this purpose, either cobalt-chromium alloy or other noble alloys or gold alloys. Dental soldering, brazing and welding can be accomplished with a variety of heat sources.

2.3.1 Electrosoldering

Electro soldering (resistance brazing) is used for joints that have a relatively simple configuration. The high heat generated in brazing could cause brittle joints. Although it had been suggested that it can be minimized with a rapid soldering at low soldering temperature it is also expensive (Brudviket al 1983).

2.3.2 Torch soldering (conventional torch technique)

In conventional dental soldering, the parent metals are joined with different types of metal, which has a lower melting point than the parent metal. Recurrent fractures because of stress concentration (eg, clasps in RPD) with most of the failures occurred within the soldering area which is the weakest portion of RPD (Angeliniet al., 1991). Technical skill is needed. Heating may burn the denture resin base. Inevitable gas inclusion in the solder joint creates porosities that compromise strength. Uncontrolled temperatures can overheat the soldered alloy and cause excessive oxidation with ion diffusion from the parent alloy to the solder vice versa.

A low tensile strength was also reported due to a wide area of the melted filler metal, the heat affected zone in which there is an alteration in grain size of the parent alloy. Discoloration caused by electric and chemical erosion may occur. The use of fire and gas may be hazardous (Suzuki et al., 2004). Researchers tried to overcome these undesirable effects by modifying the heat source. In the last two decades numerous works reported on the newly developed heat sources that include infrared and lasers.

2.3.3 Infrared heat source

This technique was introduced as an alternative to torch soldering. The infrared heat source provide more precise temperature control (Honigsberg et al., 1967; Wictorin and

Fredriksson, 1976; Cheng et al., 1994; Louly et al., 1991) investigated the used of infrared heating for soldering various dental alloys. They claimed that the infrared source, have no gas inclusions, limitation of heating area and reduces working time and produced satisfactory union of the parts.

2.3.4 Plasma welding

This method can be characterized as a special type of shielded-metal arc welding. The electric arc is generated from a tungsten electrode. The arc is shielded by argon gas and carries titanium plasma originating from a second rod placed into the gap ((Roggensach et al., 1993).

2.3.5 Laser welding

In recent years, there has been a progressive development in laser technology. Heat generation from laser beam has been used in joining of metal component. Lasers are devices that amplify light by simulated emission of radiation. It is a device that transform various frequencies into an intense, coherent, small and nearly nondivergent beam of monochromatic radiation within the visible range (Glossary of Prosthodontics Terms) To weld dental alloys, crystals of yttrium, aluminium and garnet (YAG) doped with neodymium (Nd) are mainly used to emit laser beam (Nd:YAG laser).

Laser welding in dentistry is not a new technique in fact it has progressively increased during the past decade and is known as rapid, economic and accurate way for joining / fusing metal (Gordon and Smith, 1970). Although not widely used, the use of laser energy for fusing dental casting alloys has been around for the past three decades. These were described in an initial report by Gordon and Smith (1970). Nabadalung and Nicholls (1998) described the unique characteristic of the modern laser, is the single frequency light beam that can be focused to a fine focal point. This beam imparts energy into a metal causing it to heat up locally to a temperature above the liquids. The metal evaporates and a cavity or keyhole is formed immediately under the heat source and a reservoir of molten metal from the reservoir and this solidifies to form the weld bead. The laser beam must be focused to a small spot size to produce a high-power density. This controlled density melts and with deep penetration welds, vaporizes the metal. When solidification occurs, a fusion zone or weld joint is formed (American Society For Metals, 1988).

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In dental practice, the application of laser welding was used in connecting and repairing metal prosthetic frameworks. Watanabe et al. (2001) and Ohkubo et al. (2003) reported on the increase application of laser welding in fabrication of metal frameworks of prostheses. The convenience of using concentrated laser energy is an advantage in metal prosthetic frameworks (Roggensack et al., 1993; Watanabe et al., 2001; Liu et al., 2002; Baba and Watanabe, 2005). Other uses in restorative work included recovering of metal ridge and cusp, blocking holes on the occlusal surfaces after excess occlusal adjustments, thickening the metal framework or adding contacts points after excess grinding and adjusting of crown margins.

2.3.5.1 Advantages of laser welding

1. Simple way to connect dental alloys

   All metals can be joined by this technique, particularly titanium alloys (Dobberstein et al., 1990 and Hoffman, 1992). The laser devise saves time in commercial laboratory without the need for investment and soldering alloy and easy to operate (Roggensack et al., 1993).

2. Low distortion-lower thermal alteration of the workpiece.

Thermal changes are crucial when welding is carried out close to resin veneers, acrylic resins and ect. (Roggensack, 1993)

3. Nd:YAG laser is commonly utilized in dental laser welding machines. All welding is done directly on the master cast. This reduces inaccuracies and heat distortions caused by transfer from the master cast along with investment materials (Berg et al., 1995,). Working time is reduced.
4. A smaller heat affected zone

   Because the energy of laser welding can be concentrated on a small area, there are fewer effects of heating and oxidation on the wider area surrounding the spot to be welded (Baba et al., 2004). The possibility enables a weld very close to acrylic resin or ceramic parts with no physical cracking or other damage (Bertrand, 1995).

5. High power density with low energy input

   Less effect of heating and oxidation (performed in argon atmosphere). The laser welding technique has demonstrated less heat affected zone and more accuracy. With the laser welding, it is possible to joint parts by the self-welding of metal parts themselves without the effect of the oxidizing layer which usually affect the mechanical properties of joint metal in other soldering techniques (Yamagishi, 1993). Laser welding joints have high reproducible strength for all metals, consistent with that of the substrate alloy (Dobberstein et al, 1990).

6. Rapid heating and cooling.
7. Aesthetics: Maximum aesthetics in the anterior section of the mouth can be afforded by the laser welding technique, because individual erosions and veneering of abutments can be accomplished without the restrictions enforced by solder joint design (Gordon and Smith, 1970).

8. The magnetic fields do not cause a detrimental effect on the laser beam (Wang and Welsch, 1995).

2.4 Laser welding of commercially pure titanium (CPTi)

The most common welding methods for CPTi are:

1. The laser welding technique.
2. The plasma welding technique
3. Electric air welding technique

Due to its chemical properties, titanium has to be processed differently from conventional alloys. Its high melting point and its strong affinity with gases such as oxygen, hydrogen and nitrogen which made it difficult to cast and solder (Watanabe &Topham, 2006; Okabe et al 1998). Titanium would give a rapid reaction (high reactivity to oxygen) at high temperature. Conventional dental soldering methods that use oxygen flame or air torch are likely to introduce significant concentrations of oxygen into the titanium surface layer and cause brittleness. Suitable fusing techniques for joining dental prostheses made of titanium are necessary. (Roggensack et al., 1993; Baba et al., 2004) suggested that laser welding as suitable methods over plasma welding to fuse unalloyed titanium in prosthetic dentistry. Laser welding is suitable to weld titanium and its alloys because they have higher rates of laser beam absorption and lower thermal conductivity than dental casting alloys like gold alloy (Liu et al., 2002).The laser welded joints achieved superior mechanical properties compared to unsectioned parent metal of CPTi when optimal laser setting is used.

Due to the high energy density of the laser welding (10 to 10 w/cm) comparatively to the conventional process of electric arc welding (10 w/cm), it is possible to operate with greater welding speeds and/ or greater power, resulting in lower heat input on the welding materials and consequently, more narrow welding cords and smaller heat affected zones (Goncalves & Salema, 2003).

2.5 Welding of dissimilar materials

The ability to manufacture a product using a number of different metals and alloys greatly increases flexibility in design and production (Sun & Ion, 1995). Joints between dissimilar metals are particularly common in components used in the power generation, chemical, petrochemical, nuclear and electronics industries. However the primary concern in welding of dissimilar metals:

1. Large difference in physical and chemical properties.
2. Large differences in melting temperature of one component to the other precision over location and magnitude control.
3. The mixing behaviour in the fusion zone.

2.5.1 Laser welding

The laser welding is most suitable production method in these industries. Laser welding has increasingly been applied in dentistry (Ishikawa et al., 2002; Ohkubo et al., 2003), because of the convenience of using concentrated laser energy to fix broken metal frameworks with combustible acrylic resin (Roggensack et al., 1993; Baba et al., 2004). Preston and Riesbick(1975) found laser fusion is as good as or better than unions created by conventional dental joining methods. This was also supported by other workers,

(Dawes, 1992); suggested that laser welding is one of the best fusion welding techniques for dissimilar metals.

2.5.2 Joining / welding of dissimilar materials in dentistry

(Goncalves & Salema, 2003) demonstrated laser welding of several set of dissimilar materials like electrolytic copper/ austenitic stainless steel, austenitic stainless steel/ brass and brass/ galvanized steel. They concluded that in the welding of dissimilar materials, several aspects are to be taken into account: such as the use of pulse mode and pulse time in a big heterogenecity (different thickness or different thermal diffusability). The heat input and the energy density of the laser welding process should be increased with the thickness of the specimen used.

2.5.3 Operating parameters

The operating parameters of welding machines are: pulse duration, maximum output, irradiation energy, output energy, irradiation frequency and laser spot diameter.

(Iwasaki et al., 2004) reported that operating parameters in welding of dissimilar metals varied with physical properties of individual metal. The complexity arises when 2 dissimilar metal with physical properties of different beam absorption ratio, thermal conductivity and melting temperature. Metals with high beam absorption ratio and low thermal conductivity are melted at low output energy levels. After laser welding they fuses together with each penetration depth and energy output. Welding conditions such as output currents and spot diameters affected the penetration depth as reported by (Huang et al., 2010). In dentistry, there has been limited work done experimenting on laser welding of dissimilar metals.

(Wu et al., 2008) studied micro morphology and element mixing distribution of different alloys welded by laser and analysed the feasibility to laser weld different alloys. They concluded that hybridization between pure titanium and any of other alloys were not good. The effects of laser welding different alloys are ideal except with pure titanium.

2.6 Mechanical Properties

In a study done by Mazumder and Steen, (1982) welds made in titanium alloy using a laser with inert gas shielding above and below the workpiece showed little variation in mechanical properties from the parent material. No significant oxygen pick-up was detected either chemically or in the resulting mechanical properties. Porosity appeared to be lower than would be expected with EBW. The microstructure was principally ∞ in the fusion zone and primary a with∞' in the HAZ. Both in properties and structure the welds reveal a high quality which makes laser welding an attractive method of welding titanium. In 2010, Huang et al. evaluated mechanical properties and microstructure of laser welded titanium and other alloys. The selected alloys were common alloys used in the dentistry i.e pure titanium, cobalt, pure titanium and Ni-Cr alloy. Their results demonstrated that titanium could not be directly melted together.

2.6.1 Hardness

In 2004, Iwasaki et al., investigated the performance of laser welding in joining titanium metals and dental precious alloys. eg: Ag-Pd-Au alloy and Au-Pt-Ag. They reported that hardness increased in the weld zone compared with the base metals.

Klages et al. (2003) studies fusion of brass and stainless steel they found that welded joint have a higher strength than the basic material.