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ORIGINAL ARTICLE

Effects of Conventional Welding and Laser Welding on the Tensile Strength, Ultimate Tensile Strength and Surface Characteristics of Two Cobalt–Chromium Alloys: A Comparative Study

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Abstract The purpose of this study was to evaluate the efficacy of laser welding and conventional welding on the tensile strength and ultimate tensile strength of the cobalt–chromium alloy. Samples were prepared with two commercially available cobalt–chromium alloys (Wironium plus and Diadur alloy). The samples were sectioned and the broken fragments were joined using Conventional and Laser welding techniques. The welded joints were subjected to tensile and ultimate tensile strength testing; and scanning electron microscope to evaluate the surface characteristics at the welded site. Both on laser welding as well as on conventional welding technique, Diadur alloy samples showed lesser values when tested for tensile and ultimate tensile strength when compared to Wironium alloy samples. Under the scanning electron microscope, the laser welded joints show uniform welding and continuous molt pool all over the surface with less porosity than the conventionally welded joints. Laser welding is an advantageous method of connecting or repairing cast metal prosthetic frameworks.

Keywords Welding · Cobalt–chromium alloys · Tensile strength

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Introduction

An accurately fitting removable partial denture framework is a prosthodontist's delight. For such a restoration to provide long-term service in patient's mouth without fracture, many factors play a role. These factors are modulus of elasticity of the alloy, thickness of the alloy framework, the material of the alloy used, presence or absence of bruxism and other oral habits, structural defects like subsurface porosities in casting, improper adjustment, careless handling by the patient etc.

It is observed and noted in clinical practice, that the fracture of the clasps of even cobalt–chromium alloy is not uncommon, and repair of the broken fragments would be an urgent necessity more often [1]. When a component of a removable partial denture framework fractures while in use, the options available for the clinician; is to repair the broken removable partial denture or redo the prosthesis. The option to redo the prosthesis involves more time and an additional cost to the patient. But, the process of repair overcomes these drawback and the advances in materials and technology has also ensured more longevity of such repaired prosthesis.

Welding is one of the methods to join metals and may be performed by different methods like arc welding, resistance welding, gas welding, gas metal arc welding, gas tungsten arc welding, sub-merged arc welding, energy beam welding and laser beam welding.

Gas welding, also known as oxyacetylene welding, is one of the oldest and most versatile welding processes. Laser beam welding is a technique in which two or more pieces of material (usually metal) are joined together using a laser beam. The laser beam is a coherent (single phase) light of a single wave length (monochromatic), low beam divergence and high energy content and will create heat when it strikes a surface. The more commonly utilized welding technique in dentistry are Neodymium:Yttrium Aluminum Garnet (ND:YAG) lasers.

A review of recent literature indicated a lack of consensus among researchers, regarding the best method of welding broken parts of cobalt–chromium alloy to produce a joint with high tensile strength. Although the efficacy of laser welding is reported, the effect on tensile strength and surface characteristics of the joint area have not been researched much. Some studies have indicated that the electric soldering heat source is better than gas torch for joining of cobalt–chromium alloy [2, 3]. Dawes [4] and Ream [5] suggested that laser welding is one of the best fusion welding techniques for dissimilar metals.

In view of contradictory opinions regarding efficacy of different welding techniques, the present study has been undertaken to evaluate the tensile strength, ultimate tensile strength and surface characteristics of the joint area in two commercially available cobalt–chromium alloys (Wironium plus, Bego, Germany and Diadur, DFS, Germany) after laser and conventional gas welding.

Materials and Methods

Sixty sprue waxes of 3.0 mm diameter and 5 cm length were used to prepare wax patterns (according to ANSI/ADA specification for a tensile specimen) and divided into two groups of 30 each. The first group was subjected to casting using Wironium plus alloy and the second group was casted using Diadur casting alloys. The castings (Fig. 1) thus obtained were cleaned with 50 µm Sio_2 (silicon dioxide) at 25 ψ. The 60 satisfactory samples of these two groups were randomized into three sub-groups of 10 samples in each group. Twenty samples in each sub group

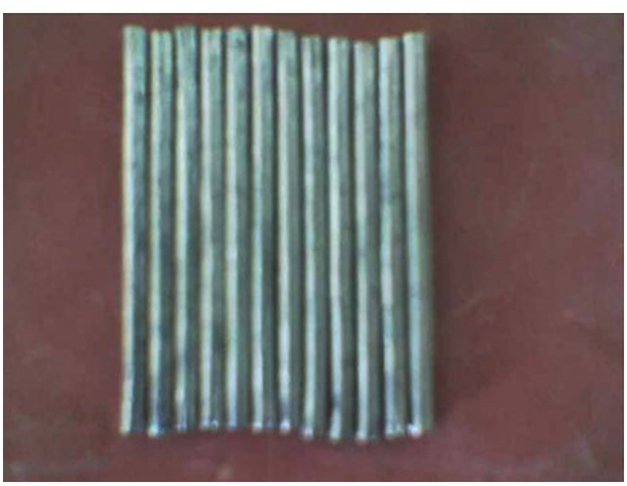

Fig. 1 Casted samples

Fig. 2 Sectioned samples

were numbered on either ends and sectioned in the midline with 7/8 in. diameter carborundum discs. The numbering will orient the cut segments for welding. This mark denoted the position where the joint would be formed (Fig. 2). The remaining ten samples in each group were left intact as control group. The sectioned 40 samples (ten in each group) were subjected to welding as given below.

- Laser welded Wironium plus alloy
- Laser welded Diadur alloy
- Conventionally welded Wironium plus alloy
- Conventionally welded Diadur alloy (Tables 1, 2).

Table 1 Composition of cobalt–chromium alloy for Wironium plus

Composition	Percentage amount
Cobalt	62.5
Chromium	29.53
Molybdenum	5
Carbon	0.1
Manganese, Iron, Nitrogen	Each 2

Table 2 Composition of cobalt–chromium alloy for Diadur

Composition	Percentage amount
Chromium	29.00–31.00
Molybdenum	4.50–6.00
Silicon	0.70–1.30
Manganese	0.50–1.00
Carbon	0.40–0.50
Cobalt	60.0–64.5
Iron, nickel, nitrogen	Traces

Procedure for Laser Welding

Ten sectioned samples from each group were subjected to laser welding. Each sectioned sample assembly was placed in the working chamber of the laser unit (GSI lumonics JK 401 model). The Neodymium:Yttrium Aluminium Garnet (Nd:YAG), a solid state laser was set at a output power level of 4 kW (peak) with 20 W coverage's, pulse duration of 1/12 ms, and weld overlap of 75 %. The focal point of the laser beam was approximately 1.5 mm from the surface of the sample [6]. After the samples were assembled, they were subjected to laser welding.

Procedure for Conventional Welding (Gas Welding)

The remaining ten sectioned samples in each group were subjected to conventional gas welding. Each sectioned sample was placed in an index made with Type V gypsum material, and assembled. The combustion of acetylene in oxygen to produce a welding flame temperature of more than 3,000 °C was employed. After weld completion, the specimens were left to bench cool at room temperature.

Method of Testing

The samples were subjected to a tensile loading rate of 0.5 cm/min, and the tensile fracture and the ultimate tensile strength were recorded using the Instron universal testing machine (Mechanical Department, CIPET, Chennai). Each fracture site was examined under a scanning electron microscope (Model FEI Quanta 200, CLRI, Chennai) and the surface characteristic of the joint area was evaluated.

Statistical Analysis

The statistical analysis was performed by Student's independent t test and Mann–Whitney U test, which was employed to identify the significant difference between the groups at $P < 0.001$ level.

Results

Four comparisons were made from the data: (1) a comparison of tensile strength between the Wironium plus alloy and Diadur alloy samples after laser welding, (2) a comparison of tensile strength between the Wironium plus alloy and Diadur alloy samples after conventional welding, (3) a comparison of ultimate tensile strength between the Wironium plus alloy and Diadur alloy samples after laser welding, (4) a comparison of ultimate tensile strength between the Wironium plus alloy and Diadur alloy samples after conventional welding. Student's independent t test and Mann–Whitney U test were used to analyze differences in the means of the alloys within the laser welded and the conventional welded samples. Tables 3 and 4 show the tensile strength values for the two test groups and the means and standard deviations. Tables 5 and 6 show the ultimate tensile strength values for the two test groups and the means and standard deviations.

Scanning Electron Microscope Results

Examination of the samples under 1,200× magnification revealed different quality and quantity of porosities on the

Table 3 Comparison of tensile strength—Diadur alloy sample versus Wironium plus alloy sample for laser welding

Laser welding	Diadur alloy		Wironium plus alloy		Sig (two-tailed)
	Mean	SD	Mean	SD	
Tensile strength (MPa)	196.68330	23.8479	479.48970	78.98669	0.000

After laser welding, the mean values of tensile strength of Diadur alloy samples were 196.68330 MPa and Wironium plus alloy samples were 479.48970 MPa. The tensile strength of Wironium plus alloy samples was more than the tensile strength of Diadur alloy samples after laser welding. There was a significant difference between laser welding and conventional welding at $P < 0.000$

Sig significance, *SD* standard deviation

Table 4 Comparison of tensile strength: Diadur alloy sample versus Wironium plus alloy sample for conventional welding

Conventional welding	Diadur alloy		Wironium plus alloy		Sig (two-tailed)
	Mean	SD	Mean	SD	
Tensile strength (MPa)	369.14980	89.41450	488.82090	77.18789	0.005

After conventional welding, the mean values of tensile strength of Diadur alloy samples were 369.14980 MPa and Wironium plus alloy samples was 488.82090 MPa. The tensile strength of Diadur was more than Wironium plus alloy samples after conventional welding. There was a significant difference between laser welding and conventional welding at $P < 0.005$

Sig significance, *SD* standard deviation

Table 5 Comparison of Ultimate tensile strength: Diadur and Wironium plus for laser welding

Laser welding	Diadur alloy		Wironium plus alloy		Sig (two-tailed)
	Mean	SD	Mean	SD	
Ultimate tensile strength (N)	1400.6250	154.0987	3348.8430	571.9251	0.000

After laser welding, the mean values of ultimate tensile strength Diadur alloy samples was 1400.6250 N and Wironium plus alloy samples was 3348.8430 N. Ultimate tensile strength of the Wironium plus alloy samples was more after laser welding when compared to conventional welding. There was a significant difference between laser welding and conventional welding at $P < 0.000$

Sig significance, *SD* standard deviation

Table 6 Comparison of Ultimate tensile strength: Diadur alloy and Wironium plus alloy for conventional welding

Conventional welding	Diadur alloy		Wironium plus alloy		Sig (two-tailed)
	Mean	SD	Mean	SD	
Ultimate tensile strength (N)	3480.379	558.9973	2369.8080	779.3880	0.000

After conventional welding, the mean values of ultimate tensile strength of Diadur alloy samples were 3480.379 N, and Wironium plus alloy samples was 2369.8080 N. The Ultimate tensile strength of Diadur alloy samples was more after conventional welding when compared to laser welding. There was a significant difference between laser welding and conventional welding at $P < 0.000$

Sig significance, *SD* standard deviation

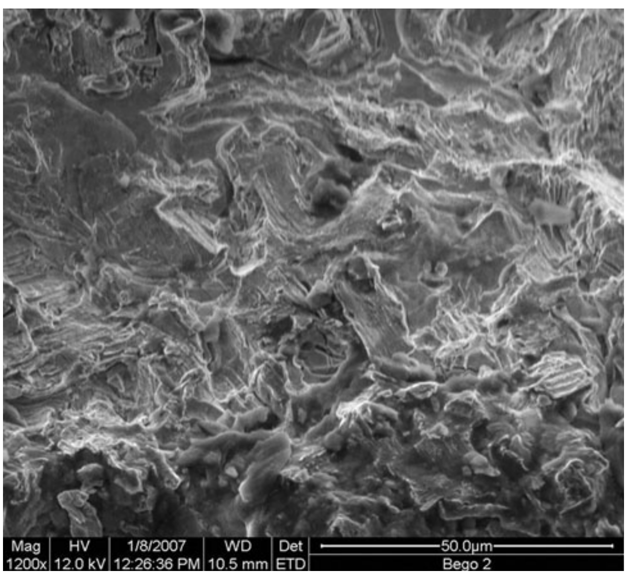

Fig. 3 Scanning electron microscope image of laser welded Wironium plus alloy

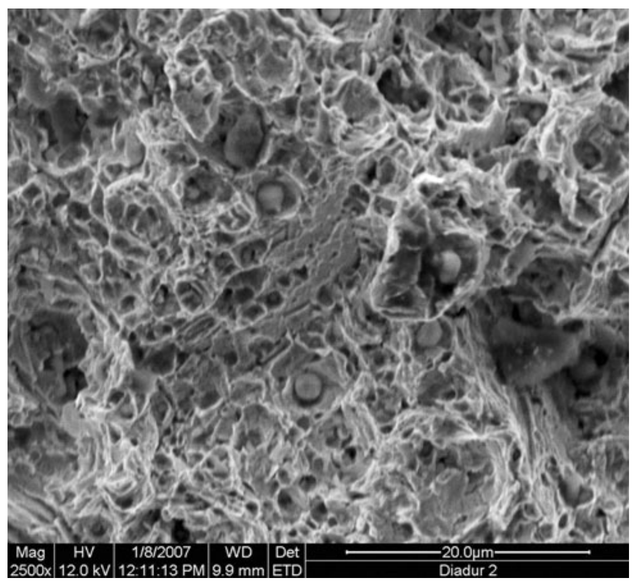

Fig. 4 Scanning electron microscope image of laser welded Diadur alloy

welded surfaces. Both Wironium plus alloy samples (Fig. 3) and Diadur alloy samples (Fig. 4), after laser welding revealed uniform flow of the molt pool, suggesting uniform welding. Porosities were seen but much smaller in diameter. Whereas, after conventional welding large porosities and flakes were seen in both types of alloys (Figs. 5, 6). Uniform flow of the molt pool was not seen. Diadur alloy samples showed more porosity when compared to Wironium plus alloy samples in both conventionally and laser welded samples.

Discussion

Long-term success of removable and fixed prosthesis depends upon fundamental biomechanical approaches to prevent additional stress on the prosthesis. In removable partial denture castings, certain components such as retainer arms are required to deform elastically during function. Elastic stress developed in the metal during such movement may be concentrated sufficiently at certain locations, resulting in fracture. This is particularly so in alloys with

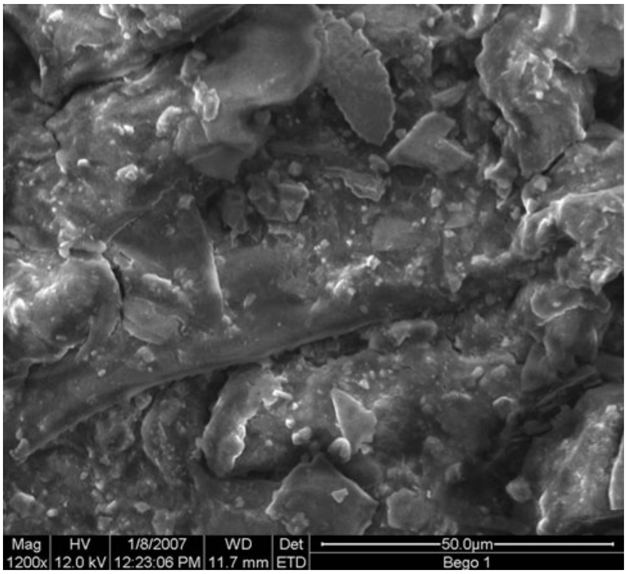

Fig. 5 Scanning electron microscope image of conventionally welded Wironium plus alloy

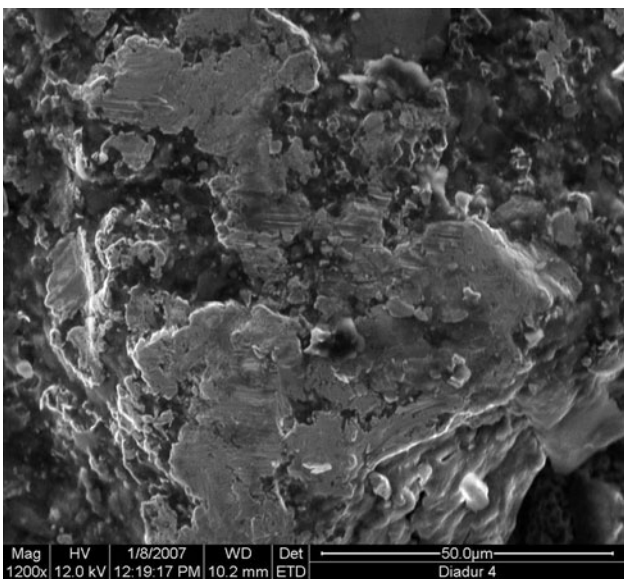

Fig. 6 Scanning electron microscope image of conventionally welded Diadur alloy

high moduli of elasticity and may lead to biological complications of the surrounding tissues and mechanical complications such as inadequate and improper distribution of the occlusal load and ultimately cause failure of the prosthesis.

Fatigue is an important factor in casting failure [7–9]. Clasps and connectors made of cobalt–chromium often fatigue and fracture from repeated insertion–withdrawal movements and masticatory loading [10–12].

Heat treatment and defective casting can also lead to fracture of casting. Asgar et al. [13] in 1982 stated that the strength of the RPD Co–Cr alloys decreases after heat treatment. Elarbi et al. [14] and Dharmar et al. [15] reported after evaluating the radiographs of the fractured site, that pre-existing internal porosities induced by the casting procedure can also cause metal frameworks to break.

The base metal alloys offer high values of modulus of elasticity and strength, excellent corrosion resistance, and very low metal cost when compared with the alternative Type IV gold casting alloys [16]. However, some base metal removable partial denture alloys have very high hardness, low ductility and a rapid rate of work hardening. These combinations of properties may result in clasp fracture when the clinician is performing adjustments on the framework.

Repair of fractured prosthesis is best established by welding. Oxyfuel welding (conventional gas welding) is one of the oldest and versatile welding processes. The welding equipment is relatively inexpensive and simple, generally employing the combustion of acetylene in oxygen to produce a welding flame temperature of more than 3,000 °C. But one of the main disadvantages is that the flame causes slower weld cooling.

Laser light is electromagnetic energy that is coherent, monochromatic and collimated with a powerful source of light. The beam of energy can be concentrated onto a small focal spot to result in laser welding [17]. Laser welding is especially useful on base metal alloys such as Co–Cr, since they have lower thermal conductivity and higher rates of laser beam absorption [18, 19].

The laser welding involves "key-hole welding" which is a high power continuous-wave laser that is focused on the metal to be welded, forming a capillary channel (key hole) filled with a partially ionized metallic gas. This vapour interacts with the laser beam and the melt pool, causing different effects. As the beam moves across the workpiece, the molten material flows around the key hole and solidifies to form a continuous weld.

Ten Diadur alloy and Wironium plus alloy samples were subjected to laser welding and ten Diadur alloy and Wironium plus alloy samples were subjected to conventional oxyfuel welding. After welding the samples were subjected to tensile strength and ultimate tensile strength testing. The surface characteristic of the joint area was analyzed with the scanning electron microscope.

The results revealed that the tensile strength of the two groups of control cobalt–chromium alloys in as-cast condition were similar. The tensile strength and ultimate tensile strength of Wironium plus alloys were more after laser welding than the values after conventional welding. The tensile strength and ultimate tensile strength of Diadur alloys were more after conventional welding and lesser after laser welding.

The comparative greater tensile strength of the Wironium plus alloy samples, after laser welding could be due to a probable increased depth of the key hole on the surface of the alloy. It was observed that the Wironium plus alloy samples could be finished to a smoother finish when compared to Diadur alloy samples during finishing and polishing of the samples. Perhaps the uneven surfaces of the broken fragments of Diadur alloy samples could have contributed to a shallower keyhole effect, resulting in comparatively lesser tensile strength and ultimate tensile strength values after laser welding.

The tensile strength of Diadur alloy samples after conventional welding was more than their tensile strength after laser welding. This is in contrast to the behavior of the Wironium plus alloy. The carbon content in Diadur and Wironium plus alloys are 0.4–0.5 and 0.1 % respectively. The higher content of carbon in Diadur alloy could perhaps be responsible for lesser bonding when subjected to laser welding. This is in agreement with Barakat and Asgar [20], where they reported that the strength of the alloy decreases after heat treatment due to dissolution of carbide precipitates.

Scanning electron microscope revealed that both the alloys exhibited micro porosities after laser welding and macro porosities after conventional welding of the broken fragments. Uniform flow was not seen in conventionally welded alloys. The results of the present study are in agreement with the study done by NaBadalung and Nicholls [6].

All features of Nd:YAG laser indicated that the amount of thermal energy required per unit length to produce laser beam weld was relatively low and also the dissipation of heat occurred rapidly.

The study proved that Nd:YAG laser was more effective in welding fractured Co–Cr framework. The small sized heat source in laser welding also protected the adjacent material with a lower melting point, e.g. Acrylic resin tooth or denture base resin. More importantly, the improved physical properties and joint toughness would reduce the possibility of joint failure from fatigue as frequently observed in clinical situations when the conventionally welded joints are used [6]. However the following factors that affect the cobalt–chromium joining should be considered: (1) joint area, (2) adequate and method of energy delivery to the areas to be joined, (3) cooling rate, and (4) amount of contamination during joining procedure [21].

Summary

This study was done to evaluate the efficacy of laser welding and conventional welding on the tensile strength and ultimate tensile strength of cobalt–chromium alloy. Samples were prepared with two different commercially available cobalt–chromium alloys (Wironium plus and Diadur alloy), which were casted and cut in the midpoint to perform fusion of the samples using conventional and laser welding. The welded joints were subjected to tensile and ultimate tensile strength testing. The welded area was subjected to scanning electron microscope to evaluate the surface. The results were tabulated and statistically analyzed. From the results of this study, it was found that laser welding is an advantageous method of connecting or repairing cast metal prosthetic frameworks and it was also possible to repair the frameworks with combustible acrylic denture base resins and artificial teeth, which would be burned by conventional welding.

Conclusion

The tensile strength and the ultimate tensile strength of the conventional welded and the laser welded joints of cobalt–chromium alloys were compared and the following conclusions were drawn.

- There were no statistically significant difference in the tensile strength and, ultimate tensile strength values between the two selected brands of cobalt–chromium alloys (Wironium plus and Diadur alloy) in their as-cast conditions.
- After conventional welding, the tensile strength and ultimate tensile strength of Diadur alloy samples were more than the values of laser welded samples.
- After laser welding, the tensile strength and ultimate tensile strength of Wironium plus alloy samples were more than the values after conventional welded samples.
- As regards the surface characteristics of the welded joints, porosities were observed in both conventional welded and laser welded samples.
- While conventional welding created macroporosities, laser welding created microporosities in the joint surfaces.
- Laser welding was proved as a better method for joining broken fragments of removable partial denture.

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