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Effect of Welding Parameters of the Nd:YAG Laser on the Penetration Depth of Cobalt Chromium Alloys

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Abstract - *The aim of the investigation was to study the effect of the laser welding parameters of energy and spot diameter on the penetration depth of the weld of cast Co-Cr alloy when a single weld was performed. Within the limitations of the study as voltage increased and the spot diameter decreased, penetration depth increased. However, SEM investigation showed more defects in the welded area under these circumstances. The clinical significance is that during selection of the welding parameters the thickness of the components to be welded should be considered to achieve an extended welded area without the induction of micro-structural defects.*

KEY WORDS: Cobalt chromium, Nd:YAG laser, welding parameters, focal spot size, energy.

INTRODUCTION

Comparatively little has been published on laser welding of cobalt-chromium alloys in dentistry and so optimum parameters have not been established. Previous studies[1-9] have chosen different parameters, often without justifying their choice, as well as using different units for energy measurements: amperes, volts and kilowatts. Welding conditions have often not been clearly described[2,3] and the welding protocol, either single or double or overlapping percentage have varied. In addition the presence or absence of argon shielding has differed.

The literature concerning laser welding of Co-Cr alloys is very limited. No studies have been reported that specify the range of parameters needed to obtain optimal depth, strength and avoidance of cracks and other defects in the microstructure of the welded area. Bertrand and Poulin-Quintin[10] in their review paper state that the interaction of the laser and the substrate being welded is complex and there are at least seven parameters on current commercially available machines that can be adjusted. They also state that, due to the alloy's less reflective nature and lower thermal conductivity than gold alloys, Co-CR alloys require a lower energy output on medium power settings together with a longer pulse duration. However, in conclusion, they state that guidelines to optimize the reliability of the weld are still required to reduce the empirical nature of the various welding parameters[10].

Studies that examined the effect of the energy on the penetration depth of the laser beam in Co-Cr alloys[5,7] showed that the increase of input energy increased the penetration of the weld. Baba and Watanabe[4] concluded that the penetration depth was increased when the spot diameter decreased.

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The purpose of this study was to examine the penetration depth of the laser beam into Co-Cr alloys under different conditions of voltage and spot diameter when a single weld was performed. The purpose of the SEM examination was to identify any possible differences in the microstructure of the welded and the non-welded area, as well as the presence of defects, such as cracks and pores, in the welded area. The working hypothesis of the study was that the penetration depth was increased when the voltage was increased and the spot diameter decreased.

MATERIALS AND METHODS

72 specimens with a rectangular cross-section 2x4x40mm were cast in Croform Excel alloy using a pressure casting machine. The chemical composition of the alloy as stated by the manufacturer was: 62%Co, 31%Cr, Mo5%, and 2% minor constituents. After divesting, specimens were sand-blasted with coarse silica-free blast grain (particle size: 60-80μm). Specimens were measured at the centre and at two other points 1cm from the centre with a Vernier Caliper. Variation up to ±0.1mm in diameter was considered acceptable. Specimens with a greater thickness variation or surface deficiencies were discarded. The specimens were sand-blasted on a second occasion to produce a dull matt uniform surface and were ultrasonically cleaned for 15 minutes in distilled water.

Specimens were sectioned in the centre, perpendicular to their longer surface with a cut off disk, while supported by a jig tightened with finger pressure. Contact between the two pieces was visually inspected and any slight burring of edges was removed to ensure optimal contact. The contact point that was established for the welding was the "I shape" as recommended for sections of 2mm in thickness[10]. An alignment jig was constructed to support and hold the two parts of the specimen during welding[16]. Laser welding was performed using a pulsed Nd:YAG laser. The conditions of laser welding tested were: voltage 220V, 240V and 260V and spot diameter 0.6mm, 0.8mm and 1mm. The decision for the range of voltage, spot diameter, pulse duration and frequency used was based on the study of

Baba and Watanabe[5] and manufacturer's recommendations. One single weld was performed at the centre of the joint.

Measurement of the penetration depth

Penetration depth was measured using a video based measuring system comprising an optical travelling microscope with a digital readout. Specimens where the weld was not judged to be at the centre of the join (6 in total) were discarded and replaced.

Scanning Electron Microscopy Investigation

One specimen from each group was viewed with SEM. The same section of the specimen that was viewed under the optical microscope was examined with SEM. The specimens were mounted on Hitachi stubs using Leit-C-Plast plastic conductive carbon cement. No coating was necessary since specimens exhibited satisfactory conductivity. The specimens were viewed using a Hitachi S35000N scanning electron microscope with a 15kV at x50, x250 and x1000 magnification.

Statistical analysis

Data was analyzed using STATA 8 statistical program. The data were also tested for normality and exhibited a normal distribution. Subsequently a two-way ANOVA was used to determine if the variable welding parameters of voltage and spot diameter produced statistically significant differences ($p<0.05$) between the groups. The data was further analyzed with post-ANOVA, contrasts adjusted for multiple comparisons.

RESULTS

Penetration depth of the laser beam

There were 9 groups of 8 specimens in each, with different welding conditions (voltage and spot diameter). The minimum and maximum of the penetration depth in each group of specimens along with the mean penetration depth and the standard variation are presented in Table 1 and graphically in Figure 1.

The two-way ANOVA showed that there were statistically significant differences between the groups when the spot size ($p=0.001$) and the voltage ($p=0.009$) were different. Further statistical analysis was performed to examine differences between pairs of groups (Tables 2 and 3).

Post-ANOVA tests indicated that there were statistically significant differences in penetration depth between 260V and both 220V and 240V levels when the spot diameter was set at 1mm. No differences were observed in penetration depth between voltage when the spot diameter was set at 0.6mm or 0.8mm. Statistically significant differences were observed in penetration depth between all spot diameters at voltages of 220V and 240V. At 260V there was a statistical significant difference in penetration depth between spot diameters of 0.6mm and 1mm.

Table 1. *Descriptive statistics of the penetration depth measurements*

Energy (v)	*Spot diameter (mm)*		
	0.6	0.8	1.0
220	1.61 (0.38) 1.06-2.14	1.12 (0.24) 0.85-1.54	0.67 (0.12) 0.4-0.8
240	1.86 (0.16) 1.60-2.03	1.45 (0.48) 0.48-1.91	0.62 (0.1) 0.44-0.74
260	1.86 (0.11) 1.79-2.04	1.30 (0.49) 0.75- 1.96	1.21 (0.62) 0.47-2.10

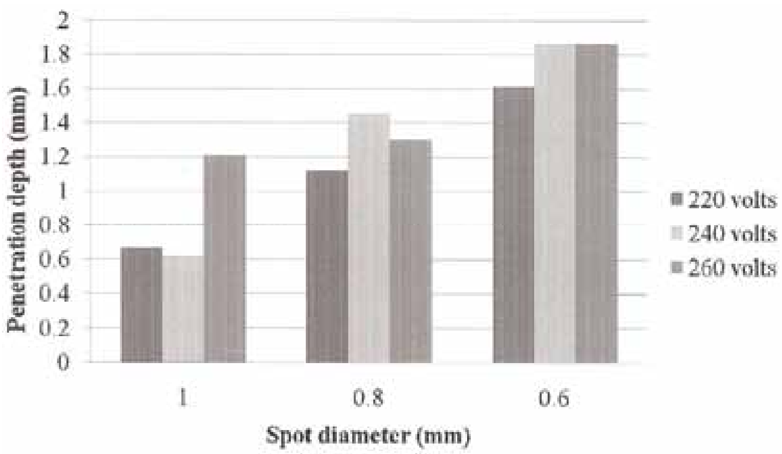

Figure 1. *Mean penetration depth(mm) by spot size and voltage*

Table 2. *Post-ANOVA comparison of energy levels for individual spot diameters*

Stable Parameter	*Compared pairs of energy level*	*P value for difference*
Spot diameter:0.6mm	220V-240V	(p=0.152)
	240V-260V	(p=0.999)
	220V-260V	(p=0.162)
Spot diameter:0.8mm	220V-240V	(p=0.134)
	240V-260V	(p=0.075)
	220V-260V	(p=0.702)
Spot diameter:1mm	220V-240V	(p=0.964)
	240V-260V	(p=0.015)*
	220V-260V	(p=0.026)*

* Indicates a statistically significant difference in penetration due to a change in energy level at the same spot diameter

Table 3. *Post-ANOVA comparison of spot diameter for the applied energy levels*

Stable Parameter	Compared pairs of groups	Statistical Difference
Energy level:220V	0.6mm-0.8mm	(p=0.006)*
	0.6mm-1mm	(p=0.000)*
	0.8mm-1mm-	(p=0.010)*
Energy level:240V	0.6mm-0.8mm	(p=0.038)*
	0.6mm-1mm	(p=0.000)*
	0.8mm-1mm	(p=0.000)*
Energy level:260V	0.6mm-0.8mm	(p=0.075)
	0.6mm-1mm	(p=0.035)*
	0.8mm-1mm	(p=0.927)

* Indicates a statistically significant difference in penetration due change in spot diameter at a fixed energy level

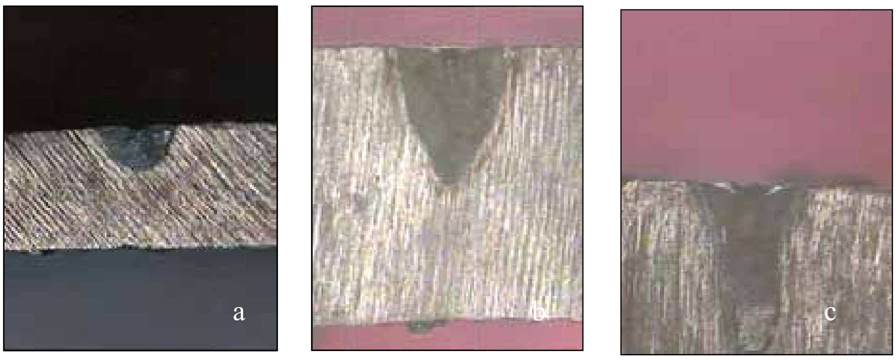

Figure 2. *(a,b,c): Specimens welded at 220V and spot diameter of (a) 1mm, (b) 0.8mm, (c) 0.6mm*

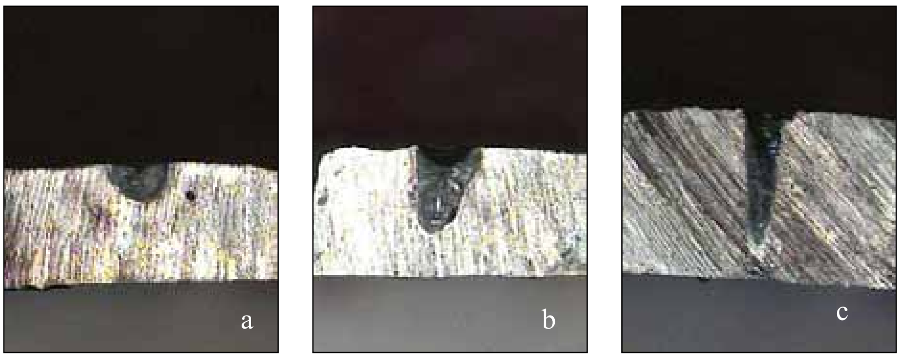

Figure 3. *(a,b,c): Specimens welded at 240V and spot diameter of (a) 1mm (b) 0.8mm, (c) 0.6mm*

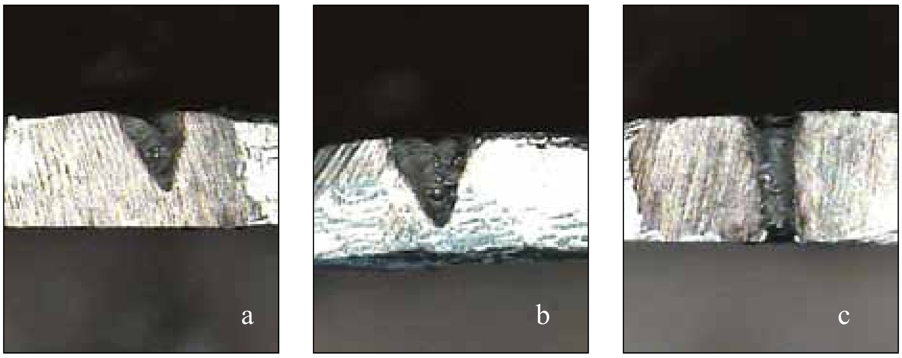

Figure 4. *(a,b,c): Specimens welded at 260V and spot diameter of (a) 1mm, (b) 0.8mm, (c) 0.6mm*

Microscopic examination

Examination with the optical microscope showed an increasing penetration depth with increased voltage and reduction in the spot diameter (Figures 2, 3, 4) . The welded area appears to become narrower, especially when the spot diameter decreased to 0.6mm and the voltage increases at 240V and 260V. Figure 3c showed that at 240V with a spot diameter of 0.6mm, a narrow weld is formed that nearly penetrates the whole specimen.

Figures 5, 6, 7 show the same specimens by SEM. In these images the defects in the microstructure of the laser welded area such as cracks, porosity and metal vaporization are clearly visible along with increasing penetration depth and the narrower welded area. Metal vaporization, in particular, was observed in specimens welded at the higher energy levels of 240V and 260V. The surface damage and formation of "dig spots" due to ejection of molten metal caused by the laser beam was clearly identified in these images.

DISCUSION

The purpose of this study was to examine the penetration depth of the laser weld into a widely available commercial Co-Cr alloy under different conditions of voltage and spot diameter when a single weld was performed. The selection of the welding conditions was based on the study of Baba and Watanabe[5] and recommendation of the laser welder manufacturer. The voltage suggested by the manufacturer was the initial point for investigation and the higher voltage levels used were derived from the literature.

The choice for spot diameter was based on the report that when the spot diameter is less than a certain value the penetration depth significantly increased for all welded metals[5] . For Co-Cr alloy this threshold was less than 1mm, so this was the value chosen for the widest spot diameter. The pulse duration was standardized at 10ms and was based on studies of laser welding of Ti alloys that showed no notable differences among different pulse durations except for the lowest (1ms) pulse duration[13]. A previous study showed the depth or the mechanical properties[14] were not influenced, by the pulse duration.

Laser welding may result in several defects in the joint, and surface damage[6,15] changes in grain size of the metal[2,4-8,11,16], cracks in the weld area[2,4,6,7,9,] and pores in the area of the weld[1-3,6,7,9,17]. In this study, surface damage was observed as the voltage increased and especially as the spot diameter decreased. However, in specimens welded at 260V and spot diameters of 1mm and 0.8mm the surface damage was not as extensive as was expected, although the welded area exhibited a more irregular microstructure (cracks and metal vaporization). Cracks appeared in the welded area regardless of the welding conditions of voltage and spot diameter with the exception of specimens welded at 220V, 1mm spot diameter. Pores were also observed but less frequently than cracks.

In the literature, surface damage during welding has been attributed to the excess heat induced at the surface of the material. This heat cannot be transferred deeper into the material due to its given thermal conductivity and results in metal vaporization[15]. The porosity was also caused by metal vaporization; the metal vaporization appeared to be trapped during molten metal solidification due to the high viscosity of the Co-Cr alloy[6]. Cracks were linked to residual stress induced by rapid solidification[4,6]. The rapid solidification was associated with the relatively high thermal conductivity of Co-Cr alloys compared to Titanium alloys[4,5].

In clinical practice double welding with overlapping of the welds is performed for reduced distortion[2,18] a rough surface and avoidance of unwelded areas[4] with the intention to increase the welded area without inducing defects.[2-4,18] Therefore the penetration depth of the laser beam should be considered with regards to the thickness of the component to be welded and the need to avoid the creation of internal or external defects in the welded area. On the basis of this present study, the recommendation is that if a part of a cobalt chromium framework with average thickness of 0.6-1mm needs to be welded the parameters 220-240V, with a spot diameter of 1mm should be used. For thinner (0.6mm) components a lower voltage should be considered. In clinical practice welds will be undertaken around the circumference of a component, therefore a single weld needs to penetrate only to the midpoint of the component. If a component with thickness of 1.5 to 2mm needs to be welded then the settings of 220V 0.8mm could be applied. Lower voltage in combination with spot diameter less than 0.8mm could possibly be applied for the thinner section of 1.5mm of the metal framework. With higher settings of 260V at 1mm, or 260V, 0.8mm or 240V, 0.8mm, the penetration depth was slightly higher but more defects detected at the microstructure of the welded area.

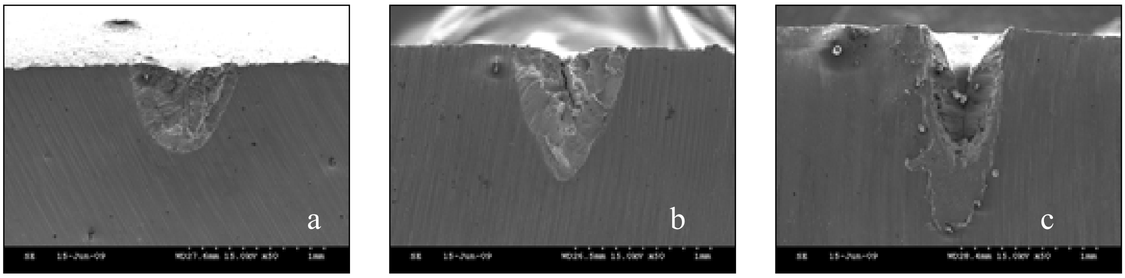

Figure 5. *(a,b,c): SEM images (50x) of specimens welded at 220V (a) 1mm, (b) 0.8mm, (c) 0.6mm*

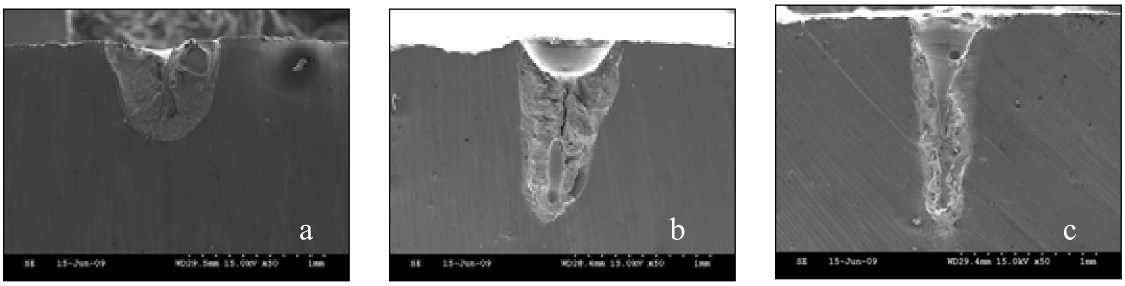

Figure 6. *(a,b,c): SEM (50x) images of specimens welded at 240V (a) 1mm, (b) 0.8mm, (c) 0.6mm*

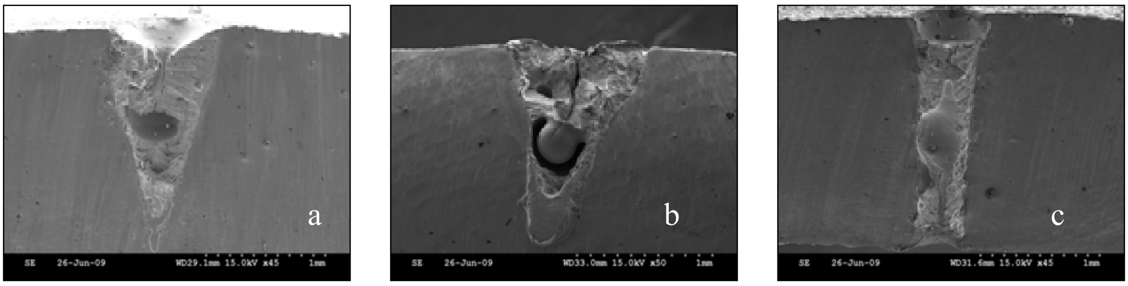

Figure 7. *(a,b,c): SEM (50x) images of specimens welded at 260V (a) 1mm, (b) 0.8mm, (c) 0.6mm*

CONCLUSION

Within the limitations of this study, the penetration depth showed a tendency to increase as the voltage increased and the spot diameter decreased in line with the working hypothesis. The SEM investigation showed that surface damage, cracks, pores and metal vaporization areas were increased as the voltage increased to 240V and 260V and the spot diameter decreased from 0.8 to 0.6mm.

MANUFACTURERS DETAILS

- (Davis Schottlander, Davis Ltd., Letchworth, UK)
- (Heracast IQ, Heraus Kulzer Gmbh & Co, Hanau, Germany).
- (Type 5921 Measy2000, Max Magerle, Switzerland)
- (Bracon Chrome Disks 1mm thick, Bracon, Etchingham, UK).
- (Neolaser ALC30/35, Alphalser, Puchheim, Germany).
- (Galileo EZ Video Measuring System, Starrett, Athol, USA).
- (Quadra Check 300, Metronics Incorporated, Bedford, USA).
- (Carbon Emitech Ltd, Ashford, UK).
- (Hitachi High Technologies Corporation, Wokingham, UK).

ADDRESS FOR CORRESPONDENCE

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