

IN BRIEF

- The operator's dexterity has a real influence upon laser welding quality but this can be reduced when the choice of welding parameters has been optimized.
- It is possible to avoid the empiric choice of irradiation parameters (energy, pulse duration, power) to improve the welding procedure and get a full penetration depth of the laser beam in the dental alloy used.
- Adequate combination of energy and pulse duration using a power set around 1 KW has been performed on different diameters of FeNiCr orthodontic wires. A classification of welding parameters have been performed for that kind of material and for this type of pulsed Nd-Yag laser, so that the operators can optimize their laser welding procedure.
- Unfortunately, changing the composition of the alloys requires another systematic study.

Optimization of operator and physical parameters for laser welding of dental materials

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Objective Interactions between lasers and materials are very complex phenomena. The success of laser welding procedures in dental metals depends on the operator's control of many parameters. The aims of this study were to evaluate factors relating to the operator's dexterity and the choice of the welding parameters (power, pulse duration and therefore energy), which are recognized determinants of weld quality.

Design *In vitro* laboratory study.

Materials and methods FeNiCr dental drawn wires were chosen for these experiments because their properties are well known. Different diameters of wires were laser welded, then tested in tension and compared to the control material as extruded, in order to evaluate the quality of the welding. Scanning electron microscopy of the fractured zone and micrograph observations perpendicular and parallel to the wire axis were also conducted in order to analyse the depth penetration and the quality of the microstructure. Additionally, the micro-hardness (Vickers type) was measured both in the welded and the heat-affected zones and then compared to the non-welded alloy.

Results Adequate combination of energy and pulse duration with the power set in the range between 0.8 to 1 kW appears to improve penetration depth of the laser beam and success of the welding procedure. Operator skill is also an important variable.

Conclusion The variation in laser weld quality in dental FeNiCr wires attributable to operator skill can be minimized by optimization of the physical welding parameters.

laser welding causes changes to the microstructure of NiCrMo and CoCrMo cast alloys due to the rapid heating and solidification processes.⁹ Cracks appeared in the welded area due to thermal residual stresses during the welding stage and / or changes in microstructure that affect the quality of the welded parts. The influence of laser beam quality, power and other physical parameters on the penetration depth of metals has been researched primarily for industrial purposes. Specific data relating to the choice of laser parameters to weld dental alloys successfully, to enhance laser penetration and to avoid surface damage are lacking in the literature. In this paper we examine various parameters that influence success or failure of the laser welding procedure.

Parameters due to the operator are: dexterity (quality of alignment of the metal wires to be joined), eyesight (has an influence on the adjustment of the laser beam focusing) and knowledge (concerning the possible dysfunction of the machine).

Physical parameters are: power and pulse duration of the laser radiation to determine the best settings to improve the beam's penetration depth and ensure success in the welding procedure (function of the wire diameter and thermal conductivity of the alloy).

MATERIALS AND METHODS

The study was conducted in three parts:

Firstly, the influence of the operator upon the welding procedure was studied. Eight different operators were each asked to weld 10 stainless steel orthodontic wires manufactured by the company Nichrominox[®] (Lyon, France). All the wires had a diameter of 0.8 mm and were welded in the same experimental conditions and with the same irradiation parameters (P=0.8 kW, t=3.6 ms, E=2.8 J and focal lens =0.90 mm). These parameters were chosen as being optimal in a previous study for wire of this diameter and composition.⁹

Secondly, physical parameters were optimized to avoid the need for empirical choice of settings and in order to have a better understanding of the most appropriate irradiation parameters necessary to obtain the best welding possibilities. Various irradiation energy settings were determined, beginning with the lowest level of energy necessary to produce melting and the highest energy level that resulted in metal vapourisation. Variations of power and pulse duration were performed at the same energy level using the following formula:

$$E (J) = P (kw) \times t (ms)$$

INTRODUCTION

Numerous studies have been made on the use of the laser beam for welding dental metals, especially titanium alloys.¹⁻⁸ With laser welding, it is possible to join parts by self-welding of the metal components themselves. In a previous paper, we demonstrated that

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Refereed Paper

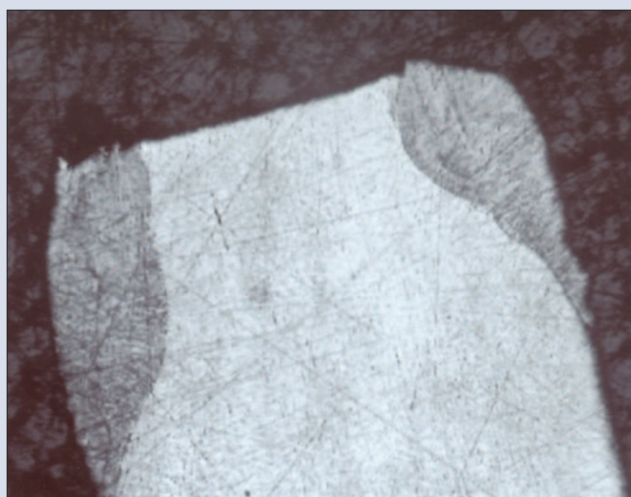
Received 07.01.02; Accepted 23.09.02

doi: 10.1038/sj.bdj.4811138

© British Dental Journal 2004; 196: 413-418

Table 1 Composition of the NICHROMINOX material (% by weights)

C	Si	Mn	Mi	Cr	s	P	Mo	Cu	Fe
0.018	0.41	0.56	11.22	18.26	0.001	0.023	0.32	0.34	bal.

**Fig. 1** Microstructure of the wire: Interface between the welded and non-welded area

Finally, two operators from the initial eight tested welded 20 stainless steel wires of 1.1 mm diameter, using the optimized power and pulse settings.

Properties of the wire

A drawn stainless steel wire, Nichrominox[®], was chosen because its properties are well controlled by the drawing process (Table 1). The FeNiCr wires exhibit a fine microstructure and a strengthening effect due to the drawing step of wire production (Figure 1).

Control of wire alignment for laser welding

A type III dental stone base support was fabricated to facilitate the joining process. To create a base support and prevent joint contamination before laser welding, each specimen was embedded to half depth in a heavy silicon material included in the stone. After the stone initially set, a U-shape was prepared in the stone at the joint location to promote joint visibility during the welding procedure. Finally, the support with the wire was put on an adjustable stage to provide the optimal adjustment of the laser focal point on the wire surface before each laser impact (Figure 2).

Laser parameters and welding conditions

Eight series of 10 stainless steel wires with diameter of 0.8 mm and five series of four stainless steel wires, with diameter of 1.1 mm were prepared. All the wires, 40 mm in length were sectioned at their midpoint, put in their support and butt joined. To prevent joint contamination, a soft brush was used to remove any impurities due to the silicon material or dust. Each wire was welded using a 50 Watts pulsed Nd Yag laser HASS[®] (TRUMPF company, Roissy Charles de Gaulle, France). The power and the pulse duration were set up on the laser machine, and the energy was directly derived from these settings. The wires were first assembled by the 4-cardinal points, then fully welded all over the circumference point per point, with 80% overlapped by the next point to avoid distortion.

Microstructure and mechanical properties

The wires were tested in tension using an INSTRON type machine with a crosshead speed of 0.5 mm min⁻¹. They were then compared to the non-welded material in order to evaluate the quality of the welding. Stress-strain curves were used to

**Fig. 2** Device used in order to control the alignment of the two pieces of wire

determine the ultimate tensile strength and the yielding elongation, in order to determine the change in physical properties at the welding zone. Scanning electron microscopy and optical microscopy of the fractured zone using polished sections in both perpendicular and parallel wire axes were conducted.

Additionally, the micro-hardness (Vickers type) was measured both in the welded and the heat-affected zone (HAZ) and then compared with the non-welded alloy.

RESULTS

Microstructure and hardness

After the melting, the alloy exhibits large grains (Fig. 1). Due to these modifications in the microstructure, the welded area is softer (HV 0.1=290) than the non-welded alloy (HV 0.1=410). The change in the hardness of the welded area is due to the re-crystallisation of the alloy.

Operator influence on the procedure

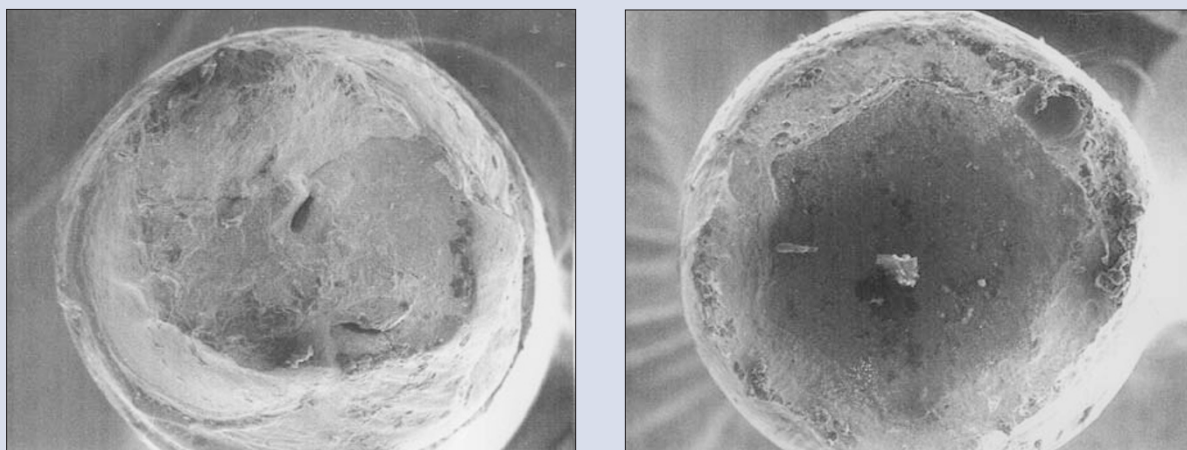
The quality of joining was checked by scanning electron microscopic observations on polished sections (Fig. 3) (Table 2). Analysis using optical microscopy showed that the proportion of the welded area compared with the non-welded area differed with the operator even if the same laser parameters were applied. The welding penetration was sometimes full and sometimes showed defects such as cavitations due to lack of energy in the laser beam, or lack of fusion due to the misalignment of the wires in their support (Fig. 3). These experiments were undertaken by non-specialist operators, who received only one day of training. The operator's dexterity appeared to have a significant influence on the results (Fig. 4).

Physical welding parameters

The findings relating to the determination of the most appropriate welding parameters that could achieve complete joining, without cracks or gas entrapments in the welding area are shown in Table 2 and Figure 5.

Selection of 2 Joules (J) for the energy parameter did not provide a satisfactory union (only 20–30% of the surfaces were welded). For E=3 J, the results were similar and the welding areas were never fully dense. From E=4–5.5 J, complete welding was achieved, but only when the power was set at 1 kW. Beyond E=9 J, the material underwent some evaporation by the impact of the laser beam. At E=6.2 J, an energy level was reached that provides complete welding, whatever the power or the pulse duration (Figs 5 and 6, Table 2).

Tensile strength is determined by welding defects and the modifications to the microstructure induced by the laser process. The elongation to rupture values (ϵ^B) give some indication of the ductility and properties of the wire. When welding is not



Figs 3a and 3b SEM fractographies after a tensile test of 0.8 mm wires. These were also used to determine by image analysis, the proportion of the welded and non-welded area

achieved over a whole section, elongation to rupture is poor (Fig. 1). This was observed when $E=2-3$ J. For 6.2 J, the welding was complete and the rupture of the wire was controlled by the properties of the welded zone itself. When the coarsening of the grains becomes significant, the wire exhibits a poor tensile strength to rupture. This was observed at long pulse duration settings, ie ~ 12.5 ms (Table 2). For this reason a compromise setting of pulse duration (7.8 ms), was used for the next part of the study, which also used a power of 0.8 kW. Under these conditions the wire had the optimal mechanical properties that could be obtained. However, these values represented approximately half of the 'as-drawn' control wire tested in the same conditions (GR=1300 MPa).

It was further observed that at the same level of energy, when the power settings were high and the pulse durations very short,

the laser impact was too strong and part of the material was ejected. In contrast, when the power was too low (0.5 to 0.7 kW) and the pulse duration too long, the laser light appeared to 'slide over' the surface of the material without achieving any melting. In addition, the tensile strength and elastic deformation decreased. Optimal parameters were chosen following all these observations (Table 2). Two operators then welded 10 wires each using these settings.

Under the above mentioned conditions, welding appeared complete. In tension, rupture in the welding zone then controlled the rupture of the wire. The welded section showed coarsening of the grains due to the melting and re-crystallisation steps. In these experiments, welding parameters had been adjusted for a 0.8 mm wire in diameter (Fig. 7).¹⁰

The histograms (Fig. 8b) show that the scattering can be reduced with a better selection of parameters even with wires of larger diameter. In one case however, the tensile strength was weak. The dexterity and concentration of the operator or the instability of the laser beam influenced the results. Nevertheless, under these experimental conditions, the optimum results for this alloy and this wire diameter were determined.

Table 2 Different parameters applied on a 1.1 mm diameter wire and their effects on the properties of the welded specimens

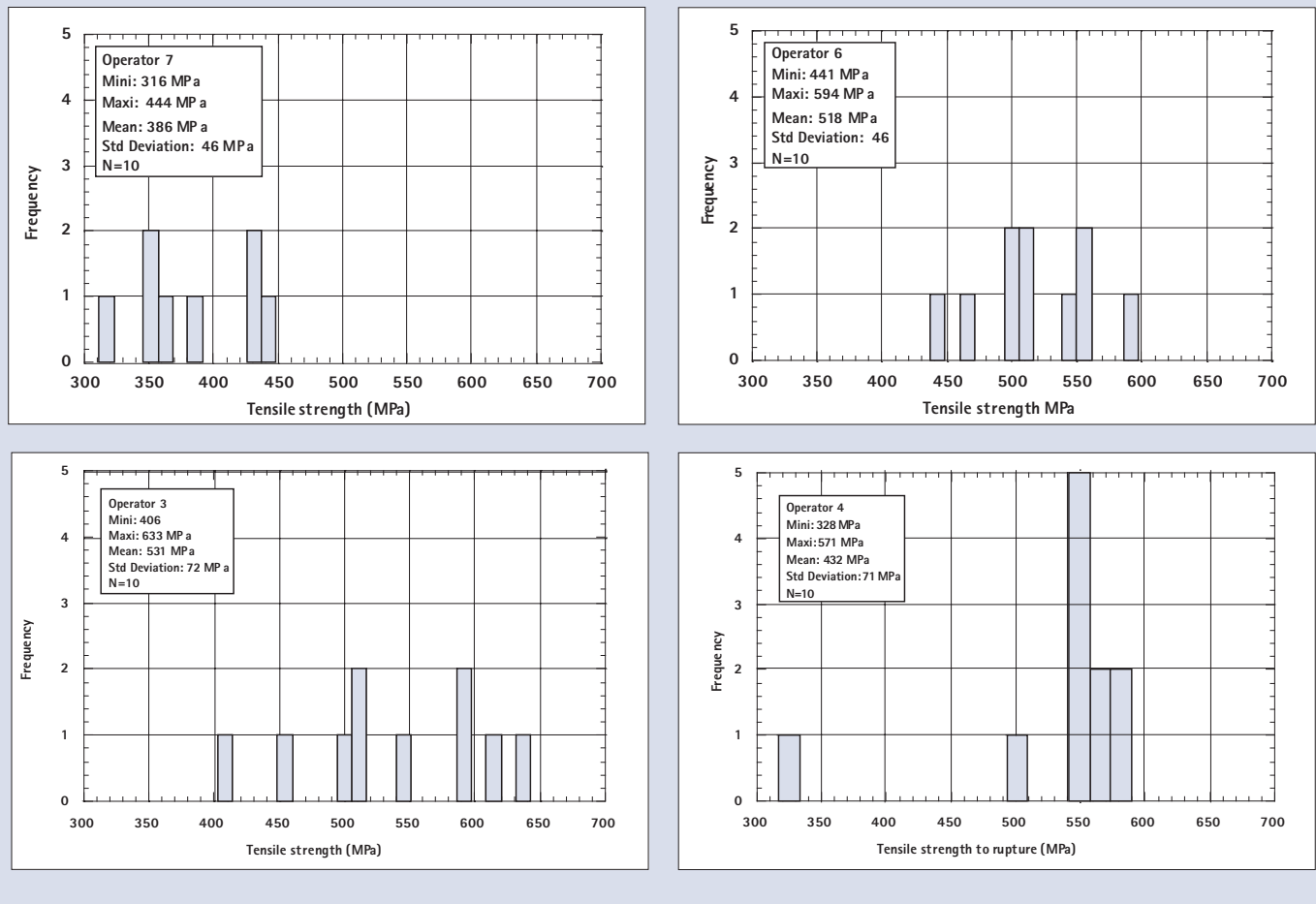
Experimental conditions		Properties of the welded wires			Unwelded area (%)
		σ^R (MPa)	HV _{0,100}	ϵ^R (%)	
E=2 J					
t=4 ms	P=0.5 kW	329	204.7	1.25	68
t=3.4 ms	P=0.6 kW	372	283.7	1.4	83
t=1 ms	P=2 kW	348	289.7	1.05	87
t=2 ms	P=1 kW	380	209.7	1.35	79
E=3 J					
t=2 ms	P=1.5 kW	545	324	2.22	28
t=3.4 ms	P=0.9 kW	567	321.7	2.25	36
t=4.4 ms	P=0.7	558	320.7	1.95	32
t=1 ms	P=3 kW	587	318.3	2.75	11
E=4 J					
t=8 ms	P=0.5 kW	537	324	2.04	25
t=4 ms	P=1 kW	636	327.3	3.30	0
t=5.8 ms	P=0.5 kW	540	332	3.25	17
t=5 ms	P=0.5 kW	548	338	2.21	0
E=5.5 J					
t=9.2 ms	P=0.6 kW	588	226	2.59	15
t=5 ms	P=1.1 kW	648	267	4.45	6
t=6.2 ms	P=0.9 kW	648	255	4.20	0
t=11 ms	P=0.5 kW	492	247	2.06	25
E=6.2 J					
t=12.5 ms	P=0.5 kW	505	319	2.35	0
t=7.8 ms	P=0.8 kW	640	299	3.35	0
t=6.2 ms	P=1 kW	623	309	5.32	0
t=5.2 ms	P=1.2 kW	523	310	3.75	0

DISCUSSION

Optimization of welding parameters has been carried out for FeNiCr wires of differing diameters (Fig. 9). Appropriate combinations of energy and pulse duration with a power setting around 0.8 or 1 kW appear to improve the penetration depth of the laser beam and achieve success in the welding procedure. The empirical equation derived from Fig. 9, may be used for FeNiCr alloys only to select the most appropriate pulse duration over a range of wire diameters. With the laser equipment used, the minimum energy which can be adjusted is 0.5 J (0.5 ms for the pulse duration) and the maximum energy 20 J (20 ms for the pulse duration). It can be deduced that the minimum thickness that can be welded is around 0.25 mm (0.5 mm in diameter) and the extrapolation to larger thickness gives a value of around 1.3 mm (2.6 mm in diameter).

Factors known to influence penetration depth are absorption and reflection of the laser beam upon the surface of the metal, and thermal conductivity of the alloy ($1.5 \text{ W cm}^{-1} (\text{C}^\circ)^{-1}$ for this FeNiCr). To improve the laser beam absorption, all the wires had been sand-blasted with alumina powders before laser welding. Togaya and Shinosaki¹² reported that the penetration depth is greater into titanium as compared with gold alloys. Togaya and Shinosaki¹¹ and Watanabe¹³ considered that this difference in laser penetration occurs because the rates of laser beam absorption and thermal con-

Fig. 4 The influence of the operators on the quality of the laser welding, eight different operators, from the lowest tensile strength mean value to the highest one



ductivity are different in those metals: titanium has a lower thermal conductivity ($0.17 \text{ W cm}^{-1} (\text{C}^\circ)^{-1}$) than gold alloys ($2.97 \text{ W cm}^{-1} (\text{C}^\circ)^{-1}$) but a better rate of laser beam absorption (0.4%) than the gold alloys (0.03%). It is likely therefore that optimal laser welding settings will vary considerably between different alloys.

It is concluded that the following factors influence laser weld quality:

It is clear that operator skill has a major effect on the success of welding procedures. Knowledge of the laser machine and the problems that may occur during the welding procedure, dexterity to control the joint preparation and the alignment of the metal wires to be joined, all influence the results. This is demonstrated by the way in which one operator obtained better results compared with the others.

The variation of distribution of the energy in the laser beam (transverse mode) is the parameter relative to the laser machine, which will have a very negative influence on the reproducibility of the welding procedure. Laser light is electromagnetic energy that is coherent, monochromatic and collimated. With a powerful source of light, the energy concentrated in the light beam is fully homogeneous when the tube and the two mirrors in the laser cavity are in a perfect alignment. Because thermal effects in intra-cavity space affect the beam, a misalignment of its two mirrors can occur resulting in a decrease of energy in the laser beam. The effect on the material is characterized by an inhomogeneous melting that causes lack of fusion and defects in the melting area (for example cavitations and gas entrapment) and could explain the weak value

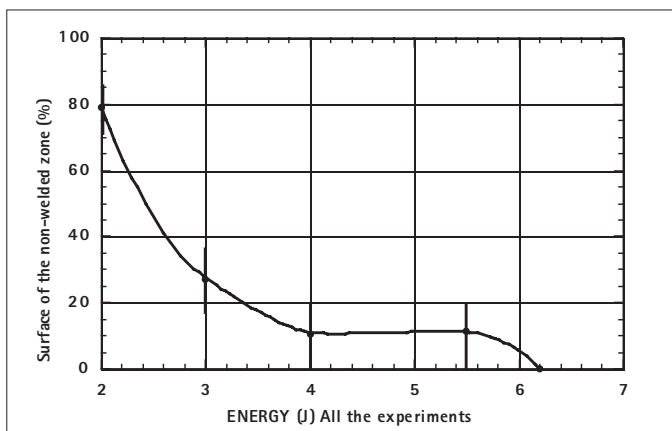


Fig. 5 Influence of the energy on the percentage of the welded area

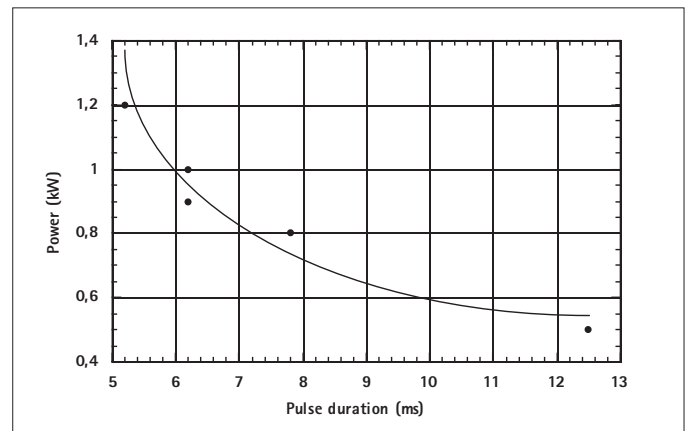
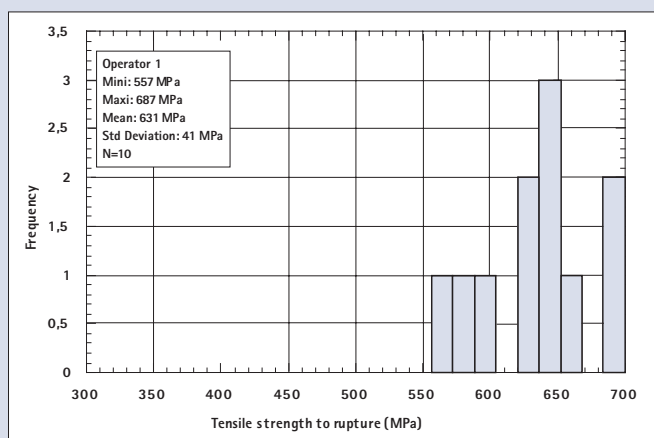
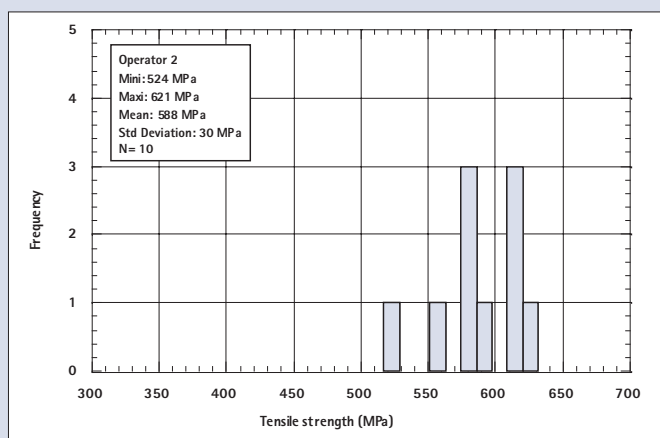
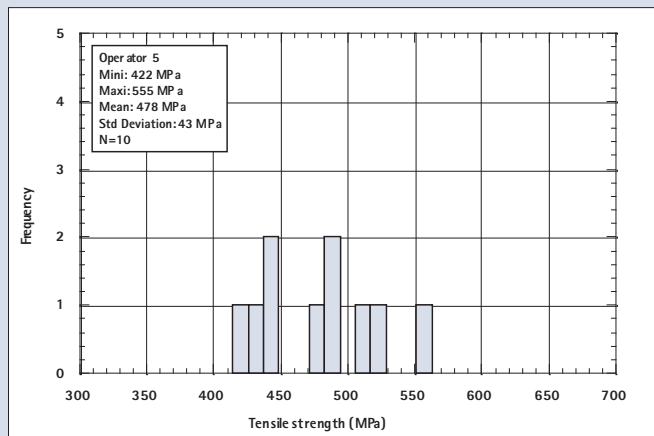
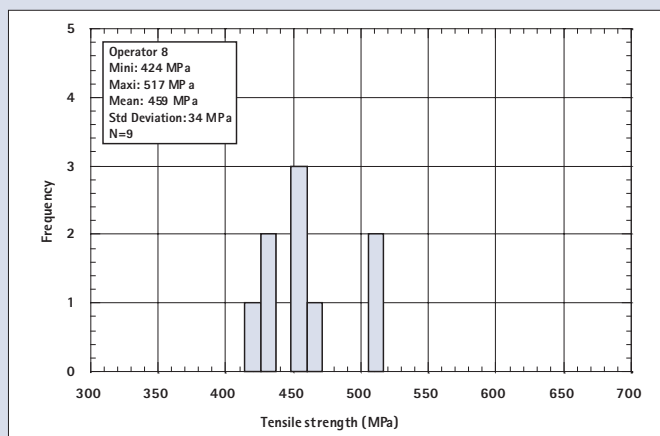


Fig. 6 Influence of the pulse duration for the conditions leading to a 100% weld



shown in Figure 8b. Unfortunately, this is intrinsic to the laser machine and cannot be avoided with all commercialized multi-mode lasers at present.

This study shows that it is possible to achieve the appropriate welding parameters that could result in complete joining. The choice of the power can be fixed at around 1 kw. It is then possible to choose an energy level $E (J) = t (ms)$, to successfully weld different diameters of wires by using the empirical equation given in Figure 9, only for FeNiCr wires. For wires of different composition, a further systematic study would be required to determine optimum settings.

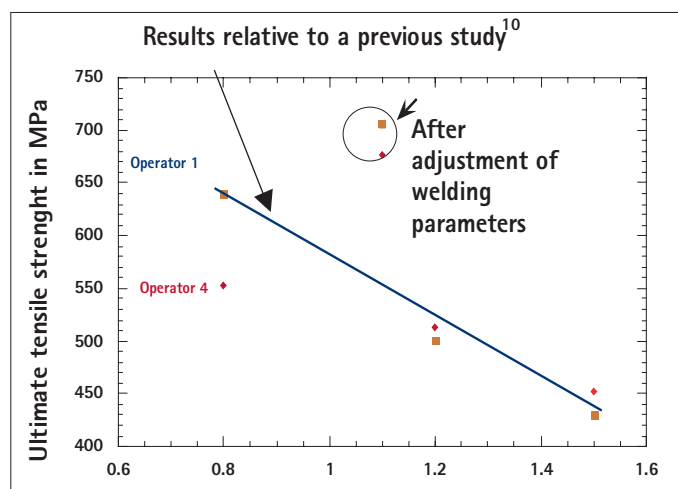


Fig. 7 Optimization of welding parameters for two operators welding each 10 wires per diameter tested

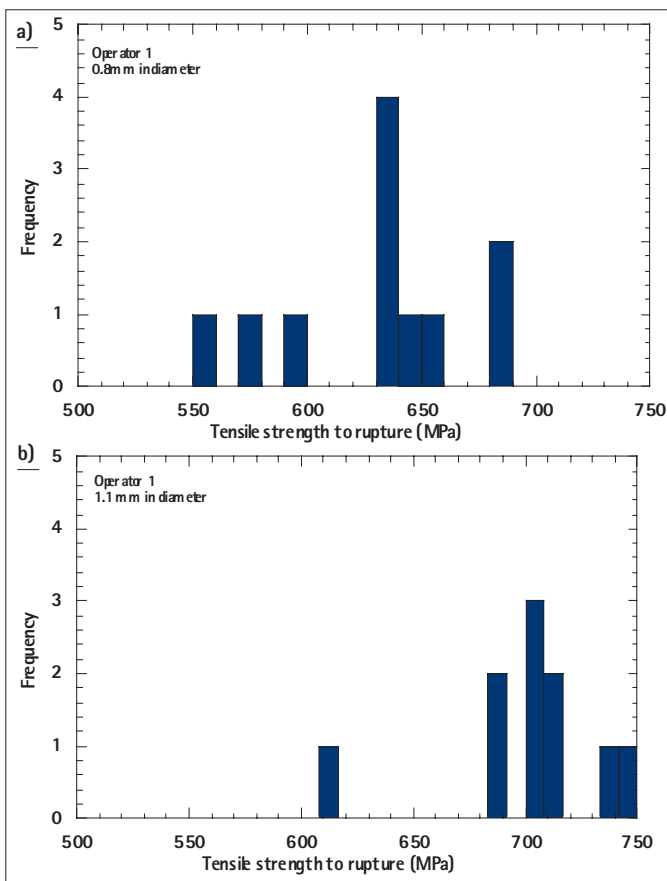


Fig. 8 Optimization of welding parameters with one operator and two wires in diameters as indicated

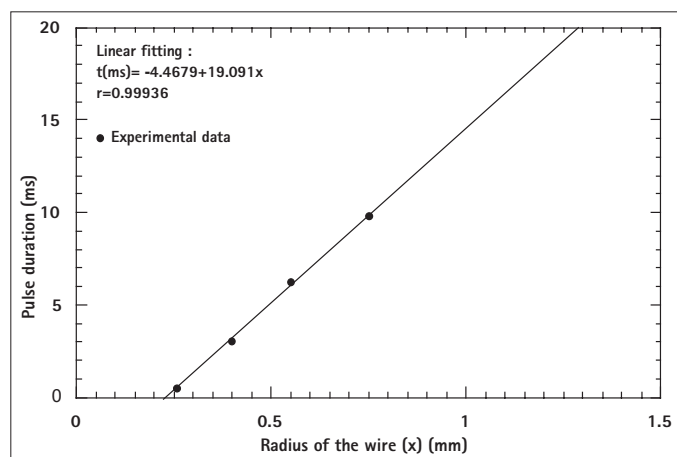


Fig. 9 Optimization of the welding parameters for different diameters of FeNiCr wires when P=1kW

1. Berg E, Wagnere W C, Davik G, Dootz E R. Mechanical properties of laser welded cast and wrought titanium. *J Prosthet Dent* 1995; **74**: 250-257.
2. Shinoda T, Matsunaga, Shinara M. Laser welding of titanium. *Welding Int* 1991; **5**: 346-351.
3. Borgstedt T. New technology for preparation of titanium crowns and bridges. *Dent Labor* 1991; **39**: 1205-1210.
4. Frolov V A, et al. Light beam welding thin sheets of titanium alloy. *Welding Int* 1994; **8**: 41-42.
5. Sjogren G, Anderson M, Bergman M. Laser welding of titanium in dentistry. *Acta Odontol Scand* 1988; **46**: 247-253.
6. Wang R R, Chang C T. Thermal modeling of laser welding for titanium dental restorations. *J Prosthet Dent* 1998; **79** : 335 - 341.
7. Oggensach M, Walter M H, Böning K W. Studies on laser-plasma-welded titanium. *Dent Mater* 1993; **9**: 104 - 107.
8. Chai T, Chou C K. Mechanical properties of laser welded cast titanium joints under different conditions. *J Prosthet Dent* 1998; **79**: 477-483.
9. Bertrand C, le Petitcorps Y, Albingre L, Dupuis V. The laser welding technique applied to the non precious dental alloys: procedure and results. *Br Dent J* 2001; **190**: 255- 257.
10. Bertrand C, le Petitcorps Y, Albingre L, Housty P, Dupuis V. Approche statistique de la qualité d'une soudure effectuée par impact laser sur alliage non précieux." Cahiers de l'I.E.B.M. Nancy, Oct. 2001. (to be published)
11. Togaya T, Shinosaki T. Introduction to laser welding in dentistry (1). *Quint Dent Tech* 1999a **24**: 740-749.
12. Togaya T, Shinosaki T. Introduction to laser welding in dentistry (3). *Quint Dent Tech* 1999b **24**: 1471-1479.
13. Watanabe I, Liu J., Atsuta M. Effects of heat treatments on mechanical strength of laser welding equi-atomic AuCu-6at%Ga Alloy. *J Dent Res* 2001, **80**: 1813-1817.