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SPRUE DESIGN AND ITS EFFECT ON THE CASTABILITY AND POROSITY OF TITANIUM REMOVABLE PARTIAL DENTURE FRAMEWORKS

A
THESIS

Presented to the Faculty of
The University of Texas Graduate School of Biomedical Sciences
at San Antonio
in Partial Fulfillment
of the Requirements
for the Degree
MASTER OF SCIENCE

By
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San Antonio, Texas
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SPRUE DESIGN AND ITS EFFECT ON THE CASTABILITY AND POROSITY OF TITANIUM REMOVABLE PARTIAL DENTURE FRAMEWORKS

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DEDICATION

I wish to dedicate this thesis to my loving wife, Meda. She provided invaluable motivational support, editorial assistance, mathematical talent, and never ending patience during this project.

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SPRUE DESIGN AND ITS EFFECTS ON THE CASTABILITY AND POROSITY OF TITANIUM REMOVABLE PARTIAL DENTURE FRAMEWORKS

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The use of titanium in dentistry has expanded steadily over the past thirty years. Many properties of titanium make it an ideal restorative material. Titanium has excellent corrosion resistance, fatigue resistance and biocompatibility. In addition, it has a low weight-to-volume ratio and a high strength-to-weight ratio. The primary dental application of this metal has been in the area of implantology. Recent advances in dental titanium casting machines allow for the use of titanium for crowns, fixed partial dentures, and removable partial denture frameworks.

Questionable biocompatibility of nickel-chromium-beryllium alloys has fueled the search for replacement metals for removable partial denture framework fabrication. Titanium and its alloys may be the answer to this search. The casting of titanium, however, is not without problems. Titanium's high reactivity requires casting in an inert environment. Its high melting temperature, low thermal conductivity, and rapid cooling can result in poor castability and high levels of porosity.

The purpose of this investigation was to evaluate the effects of five sprue designs on the castability and porosity of titanium removable partial denture frameworks. A review of the dental literature revealed no castability monitors to accurately replicate the size and intricacy of removable partial denture castings.

Castability is highly dependent on the spruing method and is defined by many investigators as the ability of a molten metal to completely fill a mold space.

The sprue designs used in this investigation included: 1) overhead-direct, 2) wedge, 3) gooseneck, 4) wedge with flared attachment and casting aids, and 5) overhead-indirect.

An aluminum master die was used in this investigation. The master die measured 50 mm x 60 mm, with 4 mm elevations, and 12 mm x 12 mm land areas. The die was duplicated with an addition-reaction silicone to produce a master mold. From the master mold, fifty refractory casts were made with a phosphate-bonded investment. A simulated Kennedy Class III removable partial denture pattern was waxed on the refractory cast and used as the castability monitor. The wax pattern consisted of a major connector (30 mm x 35 mm x 0.87 mm); four minor connectors (1.4 mm x 3 mm x 7 mm); and four 10 mm x 10 mm, 1000 μm polyester sieve areas. The sieve areas represent the removable partial denture clasp assemblies.

Following the fabrication of standardized wax patterns, individual sprues were attached. Each pattern was invested using phosphate-bonded investment, creating a ringless mold. Commercially pure titanium, DIN 3.7065 Grade 4, was cast into the mold using was a two-chamber argon-arc, vacuum-pressure type casting machine.

Standardized pre-casting and post-casting photographs were made. A reference wire, 20 mm x 1 mm, was placed adjacent to each wax pattern or casting. The wire allowed image calibration of photographs and radiographs on the same scale during digital image analysis. Radiographs of the castings were made with standardized settings of 60 kVp, 15 mA, and 12 impulses.

Digital image analysis was performed on all photographs and all radiographs. For analysis, the wax patterns and castings were divided into three areas: sieve, mesh, and connector. The castability values were calculated as the percent of the total area cast. The radiographic images were analyzed for total area of the casting and total area of porosity to obtain porosity values.

The experimental factor was sprue design. The response variables were castability and porosity. A One-Way ANOVA test, with a level of significance of

0.05, was performed. The results showed no significant differences in mean porosity values (p=0.54). Furthermore, no significant differences in mean castability values were found for the connector (p=0.08) and mesh areas (p=0.20). However, a statistically significant difference was found for the castability of the sieve areas (p<0.00001). A post hoc Tukey-B test, with a level of significance of 0.05, identified the wedge and overhead-direct sprue designs as significantly different from the other sprue design groups.

In conclusion, the results of this investigation indicated that sprue design significantly affects the castability of fine peripheral areas of a titanium removable partial denture framework. The wedge and overhead-direct sprue designs significantly improved the castability when compared to the other designs. Differences in sprue design did not significantly affect porosity values.

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I. Introduction

Although titanium occurred discovered of more than 200 years ago, the metal was not introduced into the United States until the 1930s. The US aerospace industry became interested in this element in the late 1940s (Lippert, 1970). From 1948 through 1957, one of the most extensive metallurgical investigations of all time was accomplished on titanium and its alloys. Titanium's attractive physical properties then became the focus of potential medical applications (Lynd, 1985). The metal's corrosion resistance in the biological environment and its excellent biocompatibility sanctioned the use of titanium for medical implant prostheses (McKinney and Lemons, 1985; Williams, 1981). By the end of the 1960s, titanium found a niche in dental implantology (Branemark, 1985).

The use of titanium as a dental restorative material has evolved slowly. The majority of investigators have concentrated on the use of wrought forms of titanium. Mechanical milling and electric discharge machining (EDM) can be used to fabricate dental prostheses with wrought titanium (Andersson *et al.,* 1989; Bergman *et al.,* 1990; Karlsson, 1993; King *et al.*, 1994). Nevertheless, these methods tend to be laborious. Prior to the process, multiple machine graphite electrodes must be created. Subsequently, a lengthy spark erosion process must be undertaken. This process yields extensive amounts of titanium waste.

The "lost wax" casting technique is a simple and low cost alternative to complex machining processes. The aerospace industry has shown that casting titanium can produce very intricate and precise components, with little loss in strength and minimal waste (Donachie, 1988).

Restorative dentists have avoided using titanium for prostheses because of problems associated with casting. Titanium's high affinity for oxygen, nitrogen, carbon, and hydrogen necessitate casting in an inert environment. Its high melting temperature and chemical reactivity cause adverse reactions with mold investments. In addition, titanium's flow characteristics, low specific gravity, and poor thermal conductivity tend to frustrate investigators with poor castability and high amounts of porosity (Donachie, 1982).

With recent advancements in dental casting technology, titanium is now being used for fabrication of crowns, fixed partial dentures, and removable partial denture (RPD) frameworks (Bessing and Bergman, 1992; Blackman *et al.,* 1991; Ida *et al.,* 1982; Lautenschlager and Monaghan, 1993). Technological advances have included improvements in dental titanium casting machines and investments. Several studies have emphasize titanium's reactivity to investments, porosity or castability as evaluated by various casting monitors (Ida *et al.,* 1982; Takahashi *et al.,* 1993a-c). However, very few investigations address one of the most basic requirements of the investment casting technique, namely sprue design (Eylon *et al.*, 1990; Jaffee and Promisel, 1970; Mason, 1961).

The gating or spruing system is of utmost importance for casting dental prostheses with the "lost wax" method. The sprue is the pathway through the investment, delivering the molten metal to the mold cavity. The sprue system provides a reservoir of metal to continuously feed the mold, compensating for metal solidification shrinkage upon cooling (Coleman, 1928; Ryge *et al.*, 1957). Castability is directly related to the ability of the molten metal to completely fill the mold following elimination of the wax pattern and is highly dependent on the spruing method (Baran, 1983; Presswood, 1983; Hinman *et al.*, 1985; Hirano, 1987; Verrett and Duke, 1989). Improper design of the sprue system can result in excessive voids, porosity, inclusions, or incomplete castings (Compagni *et al.,* 1984; Matin and Manderson, 1984; Ryge *et al.,* 1957; Suschil and Plutshack, 1988; Verrett and Duke, 1989).

The concept of sprue design for titanium castings is similar to other dental casting metals. An ideal sprue design should:

1. Supply a continuous source of molten metal to the solidifying casting (Coleman, 1928; Mason, 1961; Ryge *et al.*, 1957).
2. Minimize turbulent flow, decreasing the surface of the liquid exposed to gas within the mold cavity (Suschil and Plutshack, 1988).
3. Prevent mold erosion and displacement of investment particles into the solidifying casting (Stewart *et al.*, 1983; Suschil and Plutshack, 1988; Terkla and Laney, 1963).
4. Minimize internal porosity and surface porosity (Brockhurst *et al.*, 1983; Matin, 1984; Nielsen, 1976; Ryge *et al.*, 1957).
5. Provide for rapid mold filling to ensure delivery of molten metal to all areas of the mold space (Compagni *et al.*, 1984; Suschil and Plutshack, 1988; Wagner, 1980).

6. Minimize or eliminate casting distortion due to improper connection, especially with large, thin castings (Augthun *et al.*, 1994; Suschil and Plutshak, 1988).
7. Ensure that the geometry is properly matched to the wax pattern, specific gravity of the metal and the metal's flow characteristics (Nielsen and Shalita, 1983; Stewart *et al.*, 1983; Suschil and Plutshak, 1988; Terkla and Laney, 1963).

Manufacturers of dental titanium casting machines recommend different sprue designs for casting titanium removable denture frameworks. The five designs used in this investigation were:

1. Overhead-direct design (OD), central sprue connected directly to the pattern by four six-gauge sprues.
2. Overhead-indirect design (OI), central sprue connected to the pattern by five eight-gauge, flared-end sprues, with an interfacing element.
3. Gooseneck design (G), central sprue connected to the pattern by an overhead gooseneck shaped sprue, five millimeters in diameter, attached to the posterior margin of the major connector.
4. Wedge design (W), wedge-shaped central sprue with opposing flat sides , attached to the posterior margin of the major connector.
5. Wedge with flared attachment and casting aids design (WA), round-ended central sprue with a wedge interface attached to the posterior margin of the

major connector, and casting aids (reservoirs) placed at various areas of the wax pattern.

The overhead-direct (OD), overhead-indirect (OI), gooseneck (G), and wedge with flared attachment and casting aids (WA) sprue designs were recommended by manufacturers of dental titanium casting machines. The wedge (W) design was an adaptation of a sprue geometry recommended for casting nickel-chromium-beryllium dental alloys.

This investigation evaluated five sprue designs using a two-chamber, electric-arc casting machine to cast an RPD framework. Review of the literature showed no castability monitors equating to the conditions encountered when casting an RPD framework. A pilot investigation was accomplished and resulted in the development of a simulated RPD castability monitor used to assess titanium casting parameters. The castability test monitor developed simulates Kennedy's Class III RPD.

Digital image analysis was used to evaluate castability and porosity for each spruing method. The use of digital image analysis in the evaluation of casting photographs has been shown to result in highly accurate castability values (Cohen *et al.,* 1992). The low density of titanium also permitted nondestructive assessment of internal porosity using radiographic techniques (ASTM Designation E1320, 1991). Digital image analysis was also applied to analyze radiographic images of the castings.

The purpose of this investigation was to evaluate the effects of five different sprue designs on the castability and porosity of simulated titanium removable partial denture frameworks.

Research Hypothesis

1) Sprue design influences the castability of titanium removable partial denture frameworks.

2) Sprue design influences the amount of porosity produced in titanium removable partial denture frameworks.

Null Hypotheses

1) Sprue design does not influence the castability of titanium removable partial denture frameworks.

2) Sprue design does not influence the amount of porosity produced in titanium removable partial denture frameworks.

II. Literature Review

A. Discovery of Titanium

The discovery of titanium (Ti) was attributed to Wilheim Gregor, an English clergyman and amateur mineralogist, who investigated a black magnetic sand at Menachan in Cornwall in 1791. He called the sand menachanite, and the metal oxide contained in the sand, Menachin. In 1794, Klaproth found the same metal oxide in the mineral, rutile, which he named *Titanium,* after the mythological Titans (Williams, 1981). In 1925, van Arkel and de Boer of the Netherlands developed a refining process to obtain pure titanium (Jaffee and Promisel, 1970).

B. Sources of Titanium

Titanium is the ninth most abundant element and the fourth most abundant structural metallic element. It comprises 0.6 percent of the earth's crust (Donachie, 1982; Donachie, 1988; Lynd, 1985; Parr *et al.*, 1985; Polmear, 1981; Van Noort, 1978). The most common oxides of titanium take the form of various crystalline structures: rutile (TiO_2 -- reddish), anatase (TiO_2 -- white), brookite (TiO_2 -- black), and ilmenite (FeO TiO_2-black) (Voitik, 1991; Polmear, 1981). Titanium is found everywhere, from sand on the beach, to dirt, food, and water (WHO, 1982; Van Noort, 1978). The most convenient source of titanium is the mineral rutile. Although, the major source for the future will be the more plentiful ilmenite (Polmear, 1981).

The current industrial process used for titanium extraction today is based upon a technique developed by Kroll in the 1930s. The element is extracted from rutile and converted to titanium tetrachloride. Subsequently, titanium tetrachloride is reduced to pure titanium by interaction with magnesium (the Kroll process), or sodium (the Hunter process). The product of these processes is a porous material known as titanium sponge. Titanium sponge converts to titanium metal products by a sequence of consumable melting operations and appropriate casting or deformation processes (Donachie, 1982).

C. Properties of Titanium

Titanium has an atomic number of 22, molecular weight of 47.90, density of 4.507g/cm^3, and melting point of 1660 °C (Dean, 1979). Titanium's characteristics include: low weight-to-volume ratio, high strength-to-weight ratio, low modulus of elasticity, good fatigue strength, and excellent corrosion resistance (Donachie, 1982).

Titanium displays unique chemical characteristics. It is resistant to oxidation up to 593 °C (1100 °F). Above this temperature, titanium becomes highly reactive to oxygen, nitrogen, and hydrogen. Minute amounts of these elements incorporated interstitially can dramatically change titanium's physical properties. Excessive contamination can result in increased brittleness, decreased elongation, and poor ductility (Donachie, 1982; Jaffee and Promisel, 1970; Schutz and Thomas, 1987).

Titanium has a very high melting temperature and is allotropic, transforming from a hexagonal close-packed alpha phase, to a body-centered cubic beta phase, at 882°C. The transformation temperature is a function of alloy content and is strongly influenced by slight changes in oxygen, nitrogen, and carbon (Donachie, 1988).

Physical property differences among commercially pure grades of titanium are based upon the amount of oxygen and iron within the titanium structure. The oxygen content in ASTM Grade 1 is 0.18 wt %, while ASTM Grade 4 contains 0.40 wt % oxygen (ASM, 1983). Minor changes in the oxygen content increase the tensile strength from 240 MPa for Grade 1 to 550 MPa for Grade 4. Titanium's modulus of elasticity of 103 GPa (15.0 x 10^6 psi) is similar to that of Type IV gold (Donachie, 1982; Donachie, 1988; Jaffee and Promisel, 1970). Dental Type IV gold alloy has a modulus of elasticity of 105 GPa (14.4 x 10^6 psi) (Craig, 1993).

The hardness of titanium also varies with changes in the amounts of interstitial elements. Brinell Hardness Number (BHN) values range from 120 for Grade 1, to 265 for Grade 4 titanium (Donachie, 1988; Jaffee and Promisel, 1970; Polmear, 1981). These values compare favorably to dental Type III and IV gold alloys which range from 120 to 220 BHN, respectively (Craig, 1993).

Titanium gained popularity in medical applications due to its corrosion resistance in the biological environment. Titanium is virtually inert in near neutral solutions, especially those containing chloride ions which will normally attack metals and many alloys (Taira *et al.,* 1989; Williams, 1981).

One of the strengths of this highly reactive metal is that the oxide formed on the surface is extremely stable, tightly adherent and passive. (Albrektsson, 1985; Schutz and Thomas, 1987; Van Noort R, 1978). Breakdown of titanium's oxide layer under physiologic conditions is a very slow process (Kasemo, 1983; Parr *et al.*, 1985). The oxide layer of titanium is considered "self-healing", with the ability to form in a wet or dry environment (Polmear, 1981; Schutz and Thomas, 1987). Surface oxides include TiO, TiO_2, and Ti_2O_3, with TiO_2 being the most common (Kasemo, 1983; Schutz and

Thomas, 1987). Stress corrosion seldom occurs and titanium is not susceptible to crevice or pitting corrosion (Van Noort, 1978). Titanium can be safely coupled with other metals intraorally without causing increased corrosion (Brune *et al.*, 1982; Nakayama and Ando; 1993; ReClaru, 1995; Schutz and Thomas, 1987). These properties enhance titanium's biocompatibility.

D. Dental Titanium Biocompatibility

Evaluation of the biocompatibility of an alloy must include an examination of the alloy's constituents. If an alloy corrodes and breakdown of the protective oxide film on the alloy's surface occurs, substantial quantities of metallic ions could be released to the adjacent tissues or body fluids. The corrosion products must be non-toxic, otherwise the alloy should not be used as an implant or restorative material. In the field of dental implantology, evidence suggests that metal corrosion and allergenicity may be important factors in biocompatibility (Phillips, 1991; Williams, 1981).

Questionable biocompatibility of base metal alloys has promoted the use of titanium as a possible replacement metal for fabrication of dental prostheses (Kononen *et al.,* 1995; Latta *et al.,* 1993). *In vitro* studies demonstrated that nickel-chromium-beryllium alloys display a high surface concentrations of beryllium (Covington *et al.*, 1985b). The potential for chemical dissolution creates a hazard to the laboratory technician, dentist and patient (ANSI/ADA Specification No. 41, 1982; Anusavice, 1985; Blanco-Dalmau, 1982; Com. Med. Biol. Effects, 1975; Covington *et al.*, 1985b; Tai *et al.,* 1992). Specific handling requirements when utilizing beryllium-containing base metal alloys have been recommended, although no instances of beryllium toxicity in dentistry have been reported (Brune and Beltesbrekke, 1980; Hinman *et al.*, 1975; Moffa *et al.*, 1973; Moffa and Jenkins, 1974; Moffa, 1983).

In dental implantology, evidence suggests metal sensitivity may be an important factor in biocompatibility. Many of the metals commonly used in dentistry are known to be allergenic, with nickel being the most allergenic (Com Med Biol Effects, 1975; Blanco-Dalmau, 1982). The incidence of nickel allergy is estimated to be ten percent in women and less than one percent in men (Moffa, 1983; NIDR, 1984). Cobalt, nickel, and some chromium compounds have been shown to cause dermatitis and could conceivably provoke an allergic response upon implantation (Bowman, 1982; Christensen, 1990; Com Med Biol Effects, 1975; NIDR, 1984).

The dental literature describes many clinical cases of adverse reactions to base metal RPD frameworks. Brendlinger and Tarsitano (1970) and Bezzon (1993) published case reports of patients with reactions to base metal removable partial denture frameworks. Brendlinger and Tarsitano noted complete healing of skin lesions when the patient's cobalt-chromium framework was replaced with an acrylic RPD. Bezzon suggested adverse reactions may be due to impurities in the metals. Hubler and Hubler in 1983, observed rapid healing of a patient with dermatitis, persistent erythema and desquamation areas following the removal of a chrome base metal denture. Numerous other reports have suggested the potential occurrence of hypersensitivity to base metal removable partial dentures (Kalkwarf, 1984; Lamster *et al.*, 1987; Wood, 1974; Woody *et al.*, 1977). Indeed, some reports suggest that nickel-chromium and cobalt-chromium base metals, and to a lesser extent, stainless steel are the cause of all the reported cases of hypersensitivity to implanted metals (Albrektsson *et al.*, 1981; Bowman, 1982; Blanco-Dalmau, 1982; Environ. Health Crit. No. 24, 1982; Magnusson *et al.*, 1982; Williams, 1981).

There are few reports of possible hypersensitivity to titanium alloys (Lalor *et al.*, 1991; Peters *et al.*, 1984; Redline *et al.*, 1986). Furthermore, the identification of titanium as the causative agent in these studies is questionable. Titanium has been shown to be well tolerated by osseous and soft tissues. Its toxicology appears to be very benign (Lautenschlager and Monaghan, 1993; Williams, 1981). Case reports of adverse reactions to nickel-chromium removable partial dentures showed resolution when the removable partial dentures were replaced with titanium frameworks. Kononen *et al.* (1995) successfully treated a male patient with a known allergy to cobalt by placing a titanium removable partial denture. Latta *et al.* in 1993, published a case report showing rapid resolution of cutaneous lesions following the replacement of a nickel-chromium RPD with a titanium alloy frame.

Titanium's corrosion resistance and biocompatibility make it attractive for dental applications (Branemark *et al.*, 1985; Kasemo, 1983).

E. Casting Dental Titanium

Difficulty in casting titanium led to the fabrication of titanium crowns and other prostheses by using machine duplication and electric discharge machining (EDM) (Andersson *et al.*, 1989; Bergman *et al.,* 1990; Karlsson, 1993; King *et al.*, 1994; Schmitt and Chance, 1995; Van Roekel, 1992). However, the machinery is expensive and the methods tend to be time consuming. The process also produces extensive amounts of titanium waste.

A simple and low cost alternative to machining is investment casting of titanium. Titanium castings are unlike those of other metals in that they are equal or nearly equal in strength to their wrought counterparts (Donachie, 1988). Koch *et al.* (1977) suggested that investment casting of titanium is the method of choice for the production of very complex shapes with close dimensional accuracy and smooth surfaces. The aerospace industry has demonstrated that investment casting of titanium produces very intricate and precise components, with minimal waste and little loss in strength (Donachie, 1988).

The casting of commercially pure titanium using conventional dental casting methods and materials presents four major problems or difficulties (Hamanaka *et al.*, 1989; Sunnerkrantz *et al.*, 1990; Waterstrat *et al.*, 1978). First, titanium cannot be melted using conventional methods because of its high affinity for atmospheric oxygen, nitrogen and hydrogen (Polmear, 1981; Sunnerkrantz *et al.*, 1990; Waterstrat and Giuseppetti, 1985). Second, molten titanium reacts adversely to many of the current investment materials (Bergman *et al.*, 1990; Ida *et al.*, 1982; Oda and Sumii, 1995; Hero *et al.*, 1993; Takahashi *et al.*, 1993a,b). Third, titanium has unusual flow characteristics when in a molten state (Takahashi *et al.*, 1993c; Watanabe *et al.*, 1991). Titanium's poor thermal conductivity contributes to its poor flow characteristics and rapid solidification (Donachie, 1982; Jaffee and Promisel, 1970). Finally, the temperature difference between the molten titanium and the mold creates a high potential for miscasts (Chung *et al.*, 1994; Hero *et al.*, 1993; Takahashi *et al.*, 1993c; Watanabe *et al.*, 1991).

When heated to its melting temperature, titanium easily reacts with oxygen, nitrogen and hydrogen (Donachie, 1982; Polmear, 1981; Sunnerkrantz *et al.*, 1990). Current melting techniques use electric-arc pressure/vacuum or centrifugal casting machines (Bergman and Bessing, 1992). These machines melt the titanium in an inert environment created by the infusion of argon or helium gas into the melting chamber. The inert atmosphere prevents molten titanium from becoming contaminated during melting (Ida *et al.*, 1982; Sunnerkrantz *et al.*, 1990; Waterstrat and Giuseppetti, 1985; Waterstrat *et al.,* 1978).

Once melted, titanium can react with investment materials (Bergman and Bessing, 1992). The reaction may cause investment decomposition. Calvert (1981) found interaction with the investment resulted in porosity and void formation. Investment breakaway which can produce inclusions also occurs. Taira *et al.* (1989) stated that the release of interstitial oxygen is due to molten titanium's reduction of the mold oxides. Takahashi *et al.* (1990), found surface hardening of titanium castings from the incorporation of interstitial elements contained in phosphate-bonded SiO_2 investments. Evidence of the interaction between the mold material and molten titanium is the moderately heavy scale formed on the external surface of the castings. Miyakawa *et al.* (1993) described the scale, or reaction zone, as having a typical structure consisting of a reacted products layer, an alpha case layer, a silicone oxide layer, and a layer of acicular (needlelike) crystals. To minimize the reactivity of molten titanium with the mold, dental titanium casting procedures use specially-formulated, high-temperature-resistant materials. These materials generally are phosphate-bonded investments, containing increased amounts of various refractory oxides, such as ZrO_2, MgO, Al_2O_3, and CaO (Hamanaka *et al.*, 1989; Ida *et al.,* 1982; Takahashi *et al.*, 1990; Takahashi *et al.*, 1993b; Waterstrat and Giuseppetti, 1985). More recently developed Al_2O_3/MgO-based (non-phosphate) investments also are being used (Mori *et al.*, 1994; Syverud and Hero, 1995).

Titanium displays unusual flow characteristics when in its molten state (Takahashi *et al.*, 1993c; Watanabe *et al.*, 1991). Takahashi *et al.* (1993c) suggested the low density of titanium causes rapid flow along the mold walls. Once the molten metal contacts the mold walls its flow decreases rapidly (Hero *et al.,* 1993; Watanabe *et al.*, 1991) resulting in pipe-like defects (Takahashi *et al.,* 1993c). Watanabe *et al.* (1991) compared casting titanium using pressure casting methods with centrifugal casting methods. The flow of titanium was found to be laminar and steady with pressure casting. However, with centrifugal methods the flow was turbulent and random. Their study noted a sudden drop in flow when the molten titanium entered a fine cavity and that the drop was greater for the centrifugal method. They suggested turbulence and random flow caused the molten titanium to solidify rapidly and led to poorer castability. Superheating methods can be employed to improve the fluidity of many alloys (Hero and Waarli, 1991). However, because of titanium's poor thermal conductivity, it does not respond to superheating (Donachie, 1982; Jaffee and Promisel, 1970).

Watanabe *et al.* (1991) indicated that for successful casting, molten titanium must enter and spread through the mold cavity rapidly. A major obstacle to successful casting is that molten titanium solidifies rapidly due to the temperature difference between the melt and the mold (Donachie, 1982; Jaffee and Promisel, 1970). Recommended mold temperatures for casting titanium vary from 600°C to room temperature depending on the manufacturer (Chung *et al.*, 1994; Hero *et al.*, 1993; Takahashi *et al.*, 1993c; Watanabe *et al.*, 1991). The cooler mold temperature causes solidification on the mold walls first, resulting in an impermeable mold. The impermeable mold then prevents gas diffusion through the investment and proper filling of the mold space, thereby increasing porosity and decreasing castability (Hero *et al.*, 1993; Miyakawa *et al.,* 1993; Takahashi *et al.*, 1993c). The cold mold also causes a considerable loss in the fluidity of the titanium (Blackman *et al.*, 1992) and a reduction in the ability of the molten metal to wet the mold (Leong *et al.*, 1994). Therefore, to prevent adverse casting results, it is highly recommended that the path of the molten metal to the mold be as short as possible (Jaffee and Promisel, 1970).

F. Castability of Dental Titanium

Castability has been described by many investigators. Baran (1983) described castability as the "ability of an alloy to faithfully reproduce sharp detail and fine margins of a wax pattern." Presswood (1983) defined castability as the "ability of a molten metal to completely occupy the mold created by the elimination of a pattern." Hinman *et al.* (1985) said castability is "a measurement of capability of an alloy to fill a mold." Hirano *et al.* (1987) determined castability "is a measure of the ability to fill a mold of that pattern under the casting conditions employed." Finally, Verrett and Duke (1989) suggested castability is "the ability of a molten alloy to completely fill a mold space." Whatever the definition, the major objective of casting is for the metal to completely occupy the mold space produced as a result of wax elimination.

Factors affecting castability include:

1) sprue system design (Compagni *et al.,* 1984; Matin and Manderson, 1984; Myers and Pfeiffer, 1940; Verrett and Duke, 1989),

2) type of metal or alloy (Asgar and Arfaei, 1985; Covington et al., 1985a; Howard and Sheldon, 1980; Reiger *et al.,* 1986; Young *et al.,* 1987),

3) casting temperature of the metal (Brockhurst *et al.,* 1983; Hirano *et al.*, 1987),

4) mold temperature (Agarwal and Ingersoll, 1982; Hero and Waarli, 1991),

5) mold size and space (Ida *et al.,* 1969; Kuroiwa and Igarashi, 1995),

6) chemical composition of mold material (Calvert, 1981; Ida *et al.,* 1982; Miyakawa *et al.,* 1993; Takahashi et al., 1990),

7) permeability of the investment (Ida *et al.,* 1982; Shanley *et al.,* 1981)

8) type of casting machine (Bessing and Bergman, 1992; Takahashi *et al.,* 1993c; Watanabe *et al.,* 1991),

9) specific gravity of the metal or alloy (Phillips, 1947; Takahashi *et al.,* 1993c; Vincent et al., 1977),

10) casting force (Ida *et al.,* 1970; Jaffee and Promisel, 1970; Myers, 1941), and

11) position of the pattern in the mold (McLean, 1980; Naylor, 1992).

Hinman *et al.* (1985) suggested guidelines to evaluate the castability of certain metals or alloys. The test procedure should provide a quantifiable measurement of the capability to fill a mold space. The test should make use of generally available dental equipment and materials, duplication of the experiment should be possible in dental laboratories. The pattern and mold should be reproducible, evaluation of the casting should be objective and accomplished with currently available measuring instruments. Finally, the test procedure should be sensitive to the variables affecting castability.

Many test patterns and castability monitors have been developed. Generally, there are three types of castability tests: Abstract Tests, which use non-dental patterns; Simulation Tests, which use machined metal dies simulating preparations; and Replica Tests, which use reproductions of restorations constructed on dies of actual preparations made on humans or typodont teeth (Naylor *et al.*, 1990).

The dental literature describes many castability tests monitors such as: Whitlock grid (Whitlock *et al.*, 1981), Nielsen casting monitor (Nielsen, 1977), segmented disk (Asgar and Arfaei, 1985), spoked wheel with nylon line (Howard and Sheldon, 1980), spiral (Preston and Berger, 1977), and a cylinder with nylon line (Vincent *et al.*, 1977). The two tests receiving considerable support for evaluation of dental alloys, are the Nielsen casting monitor (Nielsen 1977) and the Whitlock grid (Whitlock *et al.*, 1981). Classically these patterns have been used to determine castability of gold alloys. Vaidyanathan and Penugunda (1985) noted that the sieve test monitor, the Whitlock grid, is very sensitive to changes in sprue designs. Recently, the same patterns have been employed to test base metal alloys of the nickel- and cobalt- chromium variety

(Agarwal and Ingersoll, 1982; Cohen *et al.,* 1992; Hero and Waarli, 1991; Naylor *et al.,* 1990; Presswood, 1983; Wight *et al.,* 1980; Young *et al.,* 1987).

Evaluations using similar castability test monitors are being performed with titanium and its alloys. Ida *et al.* (1980) used a recently developed dental titanium casting machine and found the castability of titanium comparable to current base metals. Greener *et al.* (1986) used mesh sieves of 1000 µm and 500 µm to test the castability of titanium and a titanium alloy, Ti-6Al-4V. They reported castability values of ten to twenty percent using a two chamber casting machine and a 1000 µm mesh test pattern. They also reported castability values of 100% using a centrifugal casting machine. Takahashi *et al.* (1990) also used a sieve cloth, as well as a simulated MOD inlay pattern, to study the casting characteristics of pure titanium. Their study indicated that the castability of pure titanium was less than twenty percent, when using an argon-arc pressure casting machine and five different investments. In the same year, Mueller *et al.* (1990) recorded castability of titanium as 85%. Both the Mueller and Takahashi studies emphasized the importance of using specially formulated investments to improve the castability of pure titanium. Watanabe *et al.* (1991) attempted to describe the flow characteristics of titanium by using a mesh pattern. Although this study did not report castability values, they did suggest that high pressure and laminar flow improved castability when using a pressure casting machine. Bessing and Bergman (1992) investigated castability of titanium using three different casting machines. The test pattern used in that investigation was a simulated crown with five degree tapered axial walls. They indicated the best castability of the crown edge was obtained with a vacuum/pressure casting machine. Finally, in a recent study, Chung *et al.* (1994) found that the castability of a 36 mm x 29 mm x 0.9 mm wax grid ranged from 69% to 100% using cold molds and vacuum/pressure casting methods.

The range of castability results indicates that there is a great need for further investigations. It is significant that the dental literature describes very few castability monitors equating to the size and complexity of a removable partial denture framework. Blackman *et al.* (1991) cast twenty simulated titanium removable partial denture frameworks using a centrifugal casting machine. Although not a titanium casting study, Augthun *et al.* (1994) also studied casting characteristics of removable partial denture frameworks using a simulated test pattern. These investigations studied the deformation or distortion of casting removable partial denture frameworks. To date there is no study of castability for titanium removable partial denture frameworks found in the dental literature.

G. Porosity

When solidification shrinkage of an alloy or metal is not compensated by the feeding of more metal into the mold, porosities can occur (Terkla and Laney, 1963; Stewart *et al.*, 1983). The presence of casting porosities can cause a prosthesis to fail in one of two ways. A large discrete void will reduce the cross-sectional thickness of metal. This can lead to tensile failure. Smaller intrametallic defects, frequently consisting of microporosity, may cause failure by acting as sites for the initiation of cracks (Lewis, 1978; Lewis, 1979). Lewis (1978) suggested that detection of microporosity on fracture surfaces is arduous and the cause of prosthesis failure is often difficult to determine. Titanium casting defects tend to be limited to shrinkage porosity that may be surface or subsurface. The extent of porosity may not affect the tensile strength, but fatigue strength and creep-rupture resistance are usually diminished (Donachie, 1981).

The types of porosity occurring in titanium castings are comparable to those described in the classic gold casting studies (ASTM Designation B367-93, 1993; Eridon, 1988). Coleman (1928), Ryge *et al.* (1957) and Strickland and Sturdevant (1959) provide explanations of the porosities that occur within dental castings.

1) Porosity occurring near the sprue attachment is called *localized shrinkage porosity*.

2) When the mold temperature is low or the alloy temperature is close to the melting range, the solidification may occur so fast that shrinkage develops throughout the casting. Such shrinkage porosity is termed *microporosity*.

3) When the metal is overheated or held in a molten stage for a long time, large amounts of gas may be dissolved or absorbed in the metal. On solidification, part of this gas may come out of solution, causing *pin hole porosity*, or globular pockets of gas distributed throughout the casting.

4) *Gas inclusions* occur when mechanically trapped gas is carried into the mold by the alloy. This type of porosity resembles pin hole porosity but usually is larger.

5) *Subsurface porosity* is characterized by formation in the interstices of the dendritic structure.

Three main factors contribute to the development of porosity within dental castings. These are: 1) shrinkage of the metal; 2) gas evolution and; 3) composition of the alloy. Other factors that can also contribute include: heating methods, type of casting machine, temperature of the mold, temperature of the molten metal, mold materials, reactivity of the molten metal, uniformity of the casting pattern, and sprue configuration (Bessing and Bergman, 1992; Compagni *et al.,* 1984; Ida *et al.,* 1982; Linefelder, *et al.,* 1963; Matin and Manderson, 1984).

H. Dental Titanium Porosity

Blackman *et al.* (1994) stated "there is a high propensity for internal voids in titanium castings." Voitik (1991) said that "surface porosity could be seen at only 13x magnification and that internal porosities measured approximately 30% of the cross-sectional thickness." Hero *et al.* (1993) expressed that "internal porosities appeared to be a more significant problem than mold filling." Other investigators have stated similar concerns with porosity and dental titanium casting (Hamanaka *et al.,* 1989; Takahashi *et al.,* 1993c; Wang and Boyle, 1993).

The literature indicated that titanium casting porosity may be due to a combination of many variables. These variables include: reaction with the mold material, casting methods, temperature difference between the mold and molten titanium, and the argon gas pressure. In 1981, Calvert observed that molten titanium reacted with mold materials causing dissociation and decomposition, resulting in the formation of mold gases. These gases may be dissolved into the liquid titanium and could cause embrittlement, reaction zones, blow holes, and porosity. Takahashi *et al.*

(1993b) found that molten titanium reacted adversely with investment containing cristobalite and quartz. The quartz investment reacted to the molten titanium at lower temperatures than the cristobalite. Artificial conversion of quartz to cristobalite with various reactants results in many impurities that react adversely with the titanium melt. These reactions could cause gas inclusions. Miyakawa *et al.* (1993) also found "skin hole-like" defects and stated that the cause was the interaction between molten titanium and the mold. New and improved investments with magnesium-oxide, zirconium-oxide, and calcium-oxide materials have reduced the interaction of titanium with the surrounding mold (Hamanaka *et al.*, 1989).

Koch *et al.* (1977) reported that casting titanium by the skull-casting method could result in pinholes, internal gas porosity and surface porosity. Watanabe *et al.* (1991) found that centrifugal casting of titanium promotes turbulent flow of the molten metal, whereas pressure-vacuum casting was shown to be laminar and symmetrical. The turbulent flow resulted in random areas of solidification and the possible formation of internal porosities. Contrary to the results of that investigation, Takahashi *et al.* (1993c) found that the centrifugal casting method produced superior results to those produced by two types of pressure casting machines. The investigators cast 20 mm x 20 mm plates using the centrifugal method. They found porosities of 150 μm in diameter, smaller than the porosity found in the plates produced with vacuum casting machines.

When casting titanium, molten titanium is cast into a much cooler mold. The vast differences between mold and melting temperatures result in rapid cooling and solidification, shortening the time provided for gases to escape and resulting in an increased risk of gas retention porosity. Hero *et al.* (1993) found that the mean densities of castings were less than the known density of titanium. Their results indicated porosity ranged from 1.5% to 15%. Titanium also has a reported solidification shrinkage of 1% to 2.6% which may also complicate casting of this metal with resultant shrinkage and/or surface porosity (Blackman *et al.*, 1991).

Argon gas used to create an inert environment when casting titanium has been implicated as a cause of porosity. Miyazaki and Tamaki (1992) found porosity ranged from 0.05% to 15.73%, depending on the argon gas pressure. Their study indicated that a decreased argon gas pressure and no vacuum suction reduced the formation of porosities. Hero *et al.* (1993) found similar results. The authors reported substantial porosity with an argon pressure of 400 torr, and minimal porosity when lowering the pressure to 50 torr. Hero *et al.* (1993) endorsed a highly permeable mold or adequate mold evacuation to decrease back pressure and decrease the amount of trapped argon gas. Sunnerkrantz *et al.* (1990) also emphasized the importance of adequate vacuum during mold evacuation, thereby eliminating argon gas entrapment and decreasing porosity.

I. Sprue Design

In the late 1800s, the “lost-wax” method to create dental castings was devised (Asgar, 1988). In 1907, Taggart popularized the investment casting method with his improved casting machine. Since that time, a multitude of investigators have studied the elements of sprue design.

A sprue is a metal or wax form used to create a passageway or gateway allowing molten metal to flow into a mold. The determination and design of the sprue is one of the most important variables in casting. Improper spruing of a wax pattern may lead to casting failures (Mason, 1961; Terkla and Laney, 1963). Shell (1925) suggested that for a perfect casting, the metal must flow to the extreme margins before solidifying and must be sufficiently heated to withstand the cooling influence of the mold until the margins have been filled with metal. Care must be taken to provide sprues of sufficient number and size. The sprues must remain molten and supply metal to the shrinkage areas during solidification (Coleman, 1928; Terkla and Laney, 1963). Furthermore, the sprue geometry should be such that the molten metal will be directed effectively to all parts of the mold and a central region of liquid is avoided (Nielsen and Shalita, 1983).

Compagni *et al.* (1984) suggested that "sprue design is more critical by far than either the type of casting machine or the source of heat." Brockhurst *et al.* (1983) concluded that porosity can be eliminated in most cases by proper spruing and melting. Augthun *et al.* (1994) stated that "distortions of cast removable partial denture frameworks result more from the method of sprue connection than from other variables in the investment and mold preparation."

There are two principal methods for spruing partial denture frameworks of Type IV gold or base metal. These methods are multiple or single spruing. Multiple spruing may be further divided into top spruing and inverted spruing. Top spruing methods consist of attaching large major sprues from a main, central sprue to each corner of the wax pattern. Usually four sprues are sufficient, but additional sprues may be added, depending upon the requirements of the case and type of metal used. With inverted spruing, the central sprue goes through the base of the refractory cast. The major and minor sprues connect to the cone-shaped central sprue on the lingual or palatal surface (Terkla and Laney, 1963; Stewart *et al.*, 1983).

The second common method, single spruing, which generally is used for lighter metals. Single spruing is accomplished by attaching a wedge-shaped major sprue to the central portion of the pattern. This method is used often for cases with complete palate major connectors. Attachment of the sprue occurs at the posterior border of the major connector. The inverted spruing technique also can be accomplished by using a single sprue (Terkla and Laney, 1963; Stewart *et al.*, 1983).

Generally, the central sprue must conform to the alloy system and be large enough to ensure that the molten metal will enter the sprue smoothly and not cause turbulence within the mold. Auxiliary sprues or secondary sprues can be used for any area of a framework separated from the central sprue by a relatively long span. Auxiliary sprues ensure sufficient amounts of molten metal reach the distant areas. (Terkla and Laney, 1963; Stewart *et al.*, 1983).

Gauges of the wax used for sprue leads are critical. Constrictions in the sprue can cause the molten metal to flow from a thick to a thin area and then back to a thick area. This also can cause turbulence, resulting in internal mold deformation and porosity (Stewart *et al.*, 1983).

J. Titanium Sprue Design

The dental literature contains few references concerning sprue design for titanium prostheses (Almquist *et al.,* 1991). As previously described, flow characteristics of molten titanium make it necessary to pay particular attention to sprue design when planning titanium prostheses (Eylon *et al.*, 1990; Jaffee and Promisel, 1970). Common spruing guidelines described in the preceding paragraphs have not been published for dental titanium casting methods. Titanium and its alloys present unique casting characteristics that must be considered, such as the rapid solidification of the liquid metal and its low specific gravity. Titanium's specific gravity of 4.507 g/cm^3 results in low metallostatic pressure of liquid metal, and potentially decreases castability (Jaffee and Promisel, 1970).

When casting titanium, it has been recommended that the distance between the melting crucible to the mold be minimized (Jaffee and Promisel, 1970). This recommendation is contrary to beliefs about the relationship between the spruing requirements and the density of the metal being cast. Generally, it is recommended for alloys with greater density, the sprue-pattern access be greater. Therefore, a high density metal would require large diameter sprue ingates and a low density metal small diameter sprue ingates (Naylor, 1992).

Although the specific gravity of gold is more than three times greater than that of titanium (Dean, 1979), effective titanium casting requires reduced paths and wide channels to ensure rapid mold filling (Takahashi *et al.,* 1993c; Yamauchi *et al.,* 1988). Even with low internal mold pressure and high initial velocity, titanium's casting flow velocity drops quickly (Takahashi *et al.,* 1993c). Watanabe *et al.* (1991) observed that with pressure casting, the flow configurations were almost symmetrical with respect to the sprue direction. They suggested the rapidity with which the molten titanium enters and spreads through the mold cavity is one of the most important requirements for successful titanium casting. Yamauchi *et al.* (1988) recommended using a thicker wax pattern when casting a titanium RPD framework.

K. Radiographic Casting Evaluation

Undetected internal and external defects can precipitate failure of dental prostheses (Hargraves and Hobkirk, 1982; Lewis, 1978). Radiographic techniques allow for non-destructive evaluation of castings (ASTM Designation E1320, 1991; Mori *et al.,* 1993). These methods are easily accomplished and allow detection of internal and external casting defects of varying size and shape (Elbarbi *et al.,* 1985; Lewis, 1978; Mattila, 1964).

Radiographs can show more defects in clasps and major connectors than can be seen by the unaided eye, because many of the defects are completely enclosed within the component (Mohammed *et al.,* 1994). Wictorin *et al.* (1979) found casting defects of 0.1 mm can be detected radiographically in cobalt-chromium specimens less than 2 millimeters in thickness. In 1986, Zimmerman also found internal structural defects of approximately 0.1 mm could be described in terms of position, shape and size. In both investigation standard dental radiographic equipment was used to evaluate defects.

Titanium's density of 4.5 gm/cm^3, compared to cobalt-chrome alloys' 8.9 g/cm^3 and gold's of 19.3g/cm^3, allows for routine dental x-rays to pass through the titanium prostheses more easily than the other alloys (Wang and Boyle, 1993). Preclinical quality control checks can be accomplished in the dental laboratory with the standard dental radiograph machine (Elbarbi *et al.,* 1985; Lewis, 1978; Mori *et al.*, 1993). The images display excellent quality and record the most minute of defects. Blackman *et al.* (1994) suggested that the success of titanium castings is more predictable because the castings can be evaluated radiographically prior to acceptance. Hamanaka *et al.* (1989), Miyazaki and Tamaki (1992), Takahashi *et al.* (1993c), and Yamauchi *et al.* (1988), used dental radiography to evaluate titanium castings.

L. Digital Image Analysis

Accurate detection of abnormalities is one of the most fundamental tasks required of an imaging system (Ishida *et al.*, 1984). Recently digital image technology has gained importance in diagnostic radiology (Kassebaum *et al.*, 1989). As an offshoot of this application, many investigations are now using digital image analysis to quantify castability of dental test monitors (Cohen *et al.*, 1994, Cohen *et al.*, 1993; Cohen *et al.*, 1992; Kakar *et al.*, 1994; Miyazaki and Tamaki, 1992; Takahashi *et al.,* 1993c; Tamaki *et al.*, 1993).

One of the major problems in castability evaluations is the difficulty of precisely quantifying the information obtained. Sieve castability monitor studies have yielded considerable information, but quantification methods are based on counting techniques. This technique has two major limitations. First, the data may not always precisely quantify the castability due to omission of partially cast segments. Second, the counting techniques require significantly more time and are subject to human error (Cohen *et al.*, 1992).

Castability studies have recently employed digital image analysis procedures using macroscopic video images (Cohen *et al.*, 1992). Digitization consists of dividing the image into a series of small, equally spaced picture elements (pixels) and assigning gray levels to each of these pixels, according to the relative exposure at each corresponding point (Hildebolt *et al.,* 1990).

Current studies reported in the dental literature indicate the increasing use of digital image analysis methods (Cohen *et al.*, 1994; Cohen *et al.*, 1993; Kakar *et al.*, 1994; Miyazaki and Tamaki, 1992; Takahashi *et al.,* 1993c; Tamaki *et al.*, 1993). Results obtained using this technique encompass the total alloy area in the casting monitor instead of the total number of completed segments or boxes. Consequently, errors encountered during the segment counting process are eliminated (Cohen *et al.*, 1992). The determination of castability values are considerably more accurate. Takahashi *et al.* (1993c) also applied digital image analysis methods for the quantification of radiographic porosity.

III. Materials and Methods

This investigation was designed to evaluate the effect of five different sprue designs on the castability and porosity of titanium removable partial denture frameworks. The single categorical independent variable was sprue design. The experimental constants were the type of metal, investment, casting machine, burnout oven and sequence, argon pressure, vacuum pressure, and dimensions of the wax pattern. The sprue designs differ in the type of central sprue, number of sprues, addition of casting aids, and positioning (vertical or horizontal) of the refractory cast in the mold. Sprue designs were in accordance with the recommendations of dental casting companies.

A. Fabrication of Removable Partial Denture Wax Patterns

An **aluminum master die** (Figure 1, Plate 1) measuring 50 mm x 60 mm, with 4 mm elevations and 12 mm x 12 mm land areas was used. The angle of elevation from the first plane to the land areas was 45 degrees. The die simulated a Kennedy's Class III removable partial denture design. Duplication of the master die was accomplished with use of an additional cross-linked two component silicone (Neo-sil, Dentaurum Co., Newtown, PA) producing the master mold (Plate 2). Fifty standardized refractory casts were made with a phosphate-bonded investment (Rematitan, Dentaurum Co., Newtown, PA). The refractory casts were divided into five groups of ten and the wax patterns were the assembled.

The **wax pattern** (Figure 2, Plate 3) consisted of: a 30 mm x 35 mm x 0.87 mm major connector (22 gauge stipple sheet, 0.64 mm, with 0.23 mm relief wax), four minor connectors (1.4 mm x 3 mm x 7mm) from the major connector to the sieve areas, attached to four 10 mm x 10 mm, 1000 μm polyester sieve areas (Spectrum Medical Industries, Inc., Houston, TX), with 18 gauge runnerbars. Two 10 mm x 20 mm, simulated acrylic retentive mesh areas were placed on two sides of the major connector (Ticonium Corp., Albany, NY; pattern #73).

Each sieve area had 25 countable spaces and 60 countable segments for a total of 100 spaces and 240 segments. Each mesh area had 21 open spaces and 45 segments, for a total of 42 spaces and 90 segments.

Figure 1: Aluminum Master Die Dimensions

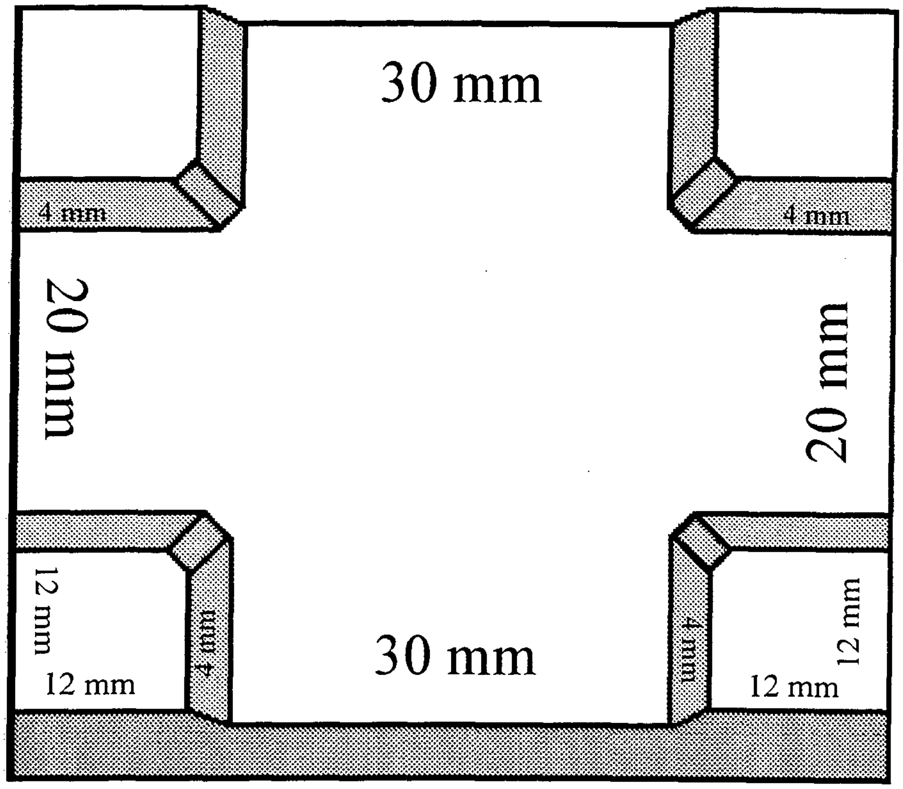

30 mm
4 mm
4 mm
20 mm
20 mm
12 mm
12 mm
4 mm
30 mm
4 mm
12 mm
12 mm

Plate 1: Aluminum Master Die

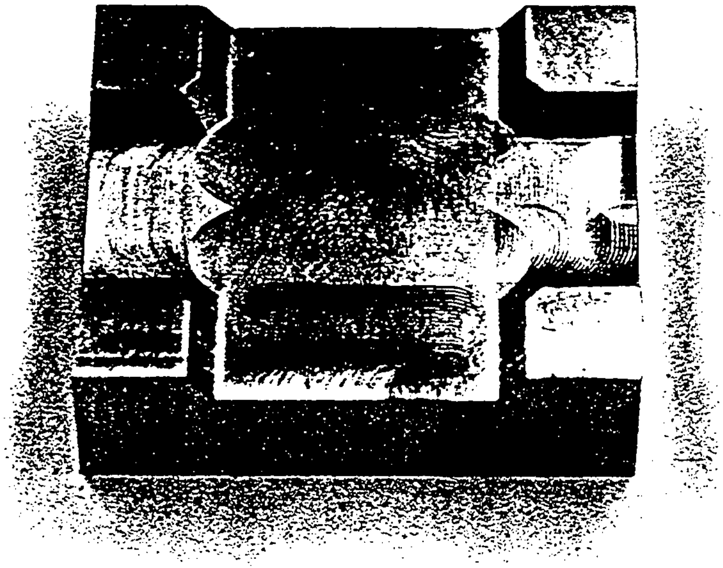


Plate 2: Silicone Mold

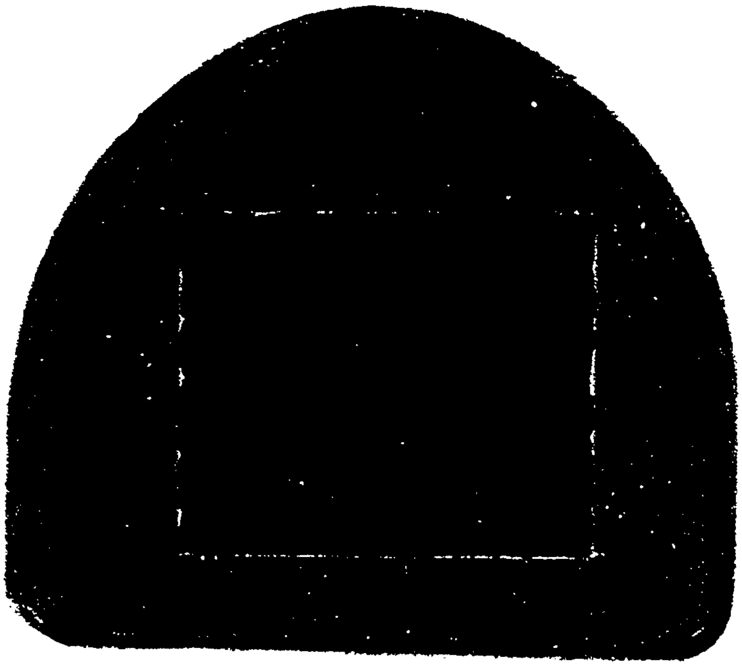


Figure 2: Wax Pattern Dimensions

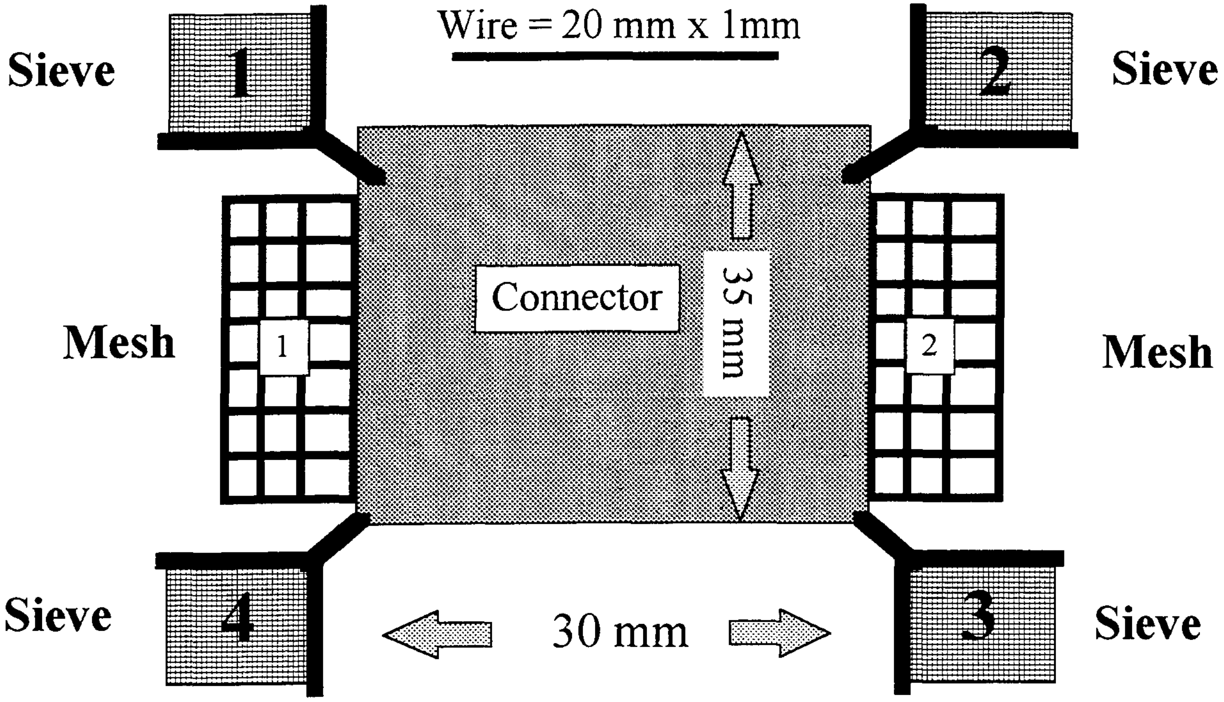
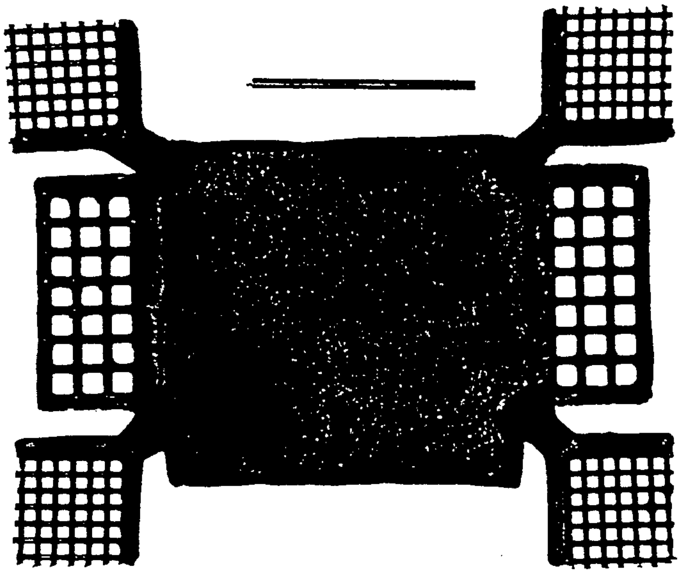

Wire = 20 mm x 1mm
Sieve
1
2
Sieve
Connector
35 mm
Mesh
1
2
Mesh
Sieve
4
30 mm
3
Sieve

Plate 3: Completed Wax Pattern

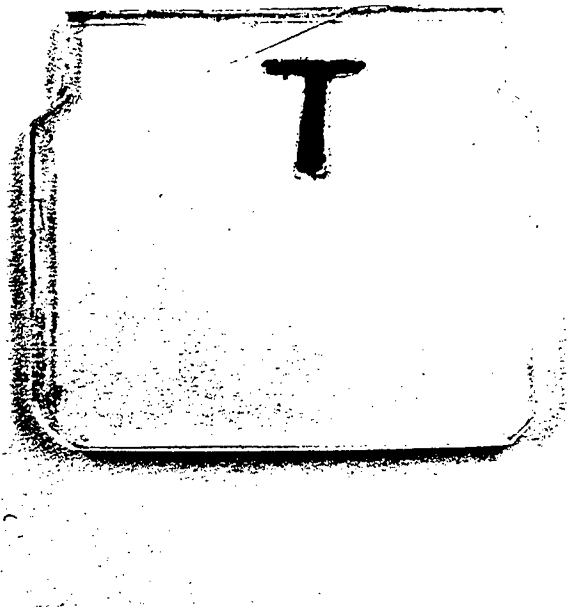


Standardized RPD patterns were constructed on the refractory casts. Major connectors were created by cutting prefabricated stipple sheets to a predetermined size with the aid of a template (Plate 4). The central sprues, major sprues (ingates), minor connectors, casting aids, and flared wedge connectors were fabricated via wax duplication using vinyl polysiloxane rubber molds (Plate 5). The polyester sieve material was cut to the dimensions previously stated (Plate 6). The runnerbars were cut to size from a roll of 18-gauge round wax. Element were assembled on a refractory die using accepted RPD fabrication techniques (Plate 3).

A reference wire, 20 mm x 1 mm, was placed next to the wax pattern (Figure 2). The wire allowed image calibration on the same scale. It was also used as a reference measure during the analysis phase. Once the photographs were completed, the sprues were attached.

Plate 4: Major Connector Template

Plate 5: Vinyl Polysiloxane Molds


T

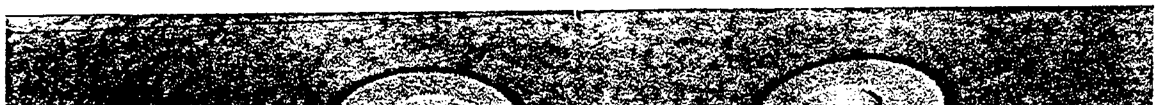
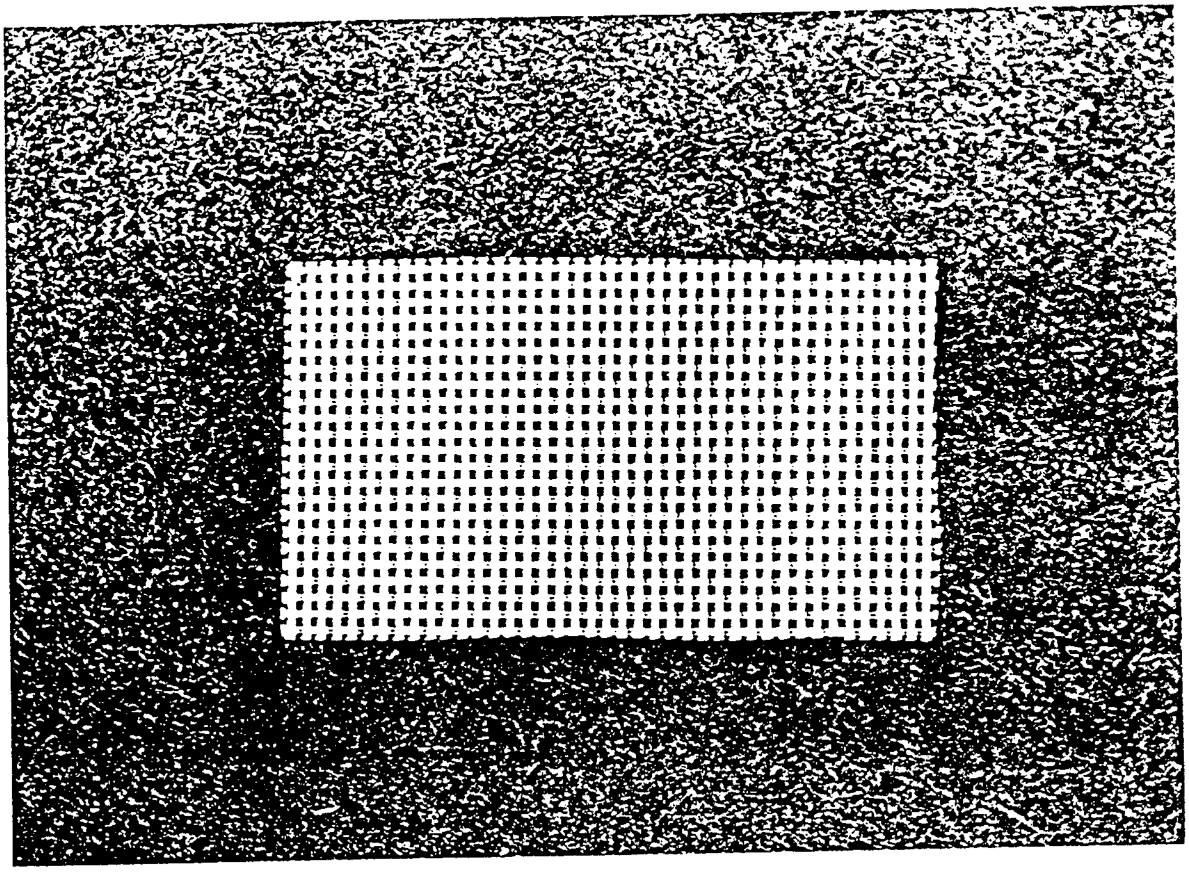


Plate 6: Sieve Material



B. Sprue Designs

The five sprue designs used were: overhead-direct (OD), overhead-indirect (OI), gooseneck (G), wedge (W), and rounded-wedge with flared attachment and casting aids (WA).

The overhead-direct design (OD) employed four 20 mm, 6 gauge main sprues attached to the minor connectors, without flaring. The central sprue was 20 mm in diameter and 30 mm in length. Connections between sprue elements displayed smooth transitions (Plates 7 and 8). The overhead-direct sprue design is described in the Ticonium manual and also is described by the Ohara Company for titanium casting procedures (Ticonium Corp., Albany, NY; and Ohara Co., Osaka, Japan).

The overhead-indirect design (OI) consisted of five, eight-gauge sprues, 25 mm in length, from the central sprue to the wax pattern. Three of these sprues were connected to the pattern via 1 mm x 4 mm x 5 mm external interface elements. The two other sprues were attached to the middle of the interface between the major connector and acrylic retention mesh areas. The central sprue was 20 mm in diameter and 30 mm in length (Plates 9 and 10). The overhead-indirect design is recommended for use with the Cyclarc casting machine (J. Morita Corp., Kyoto, Japan).

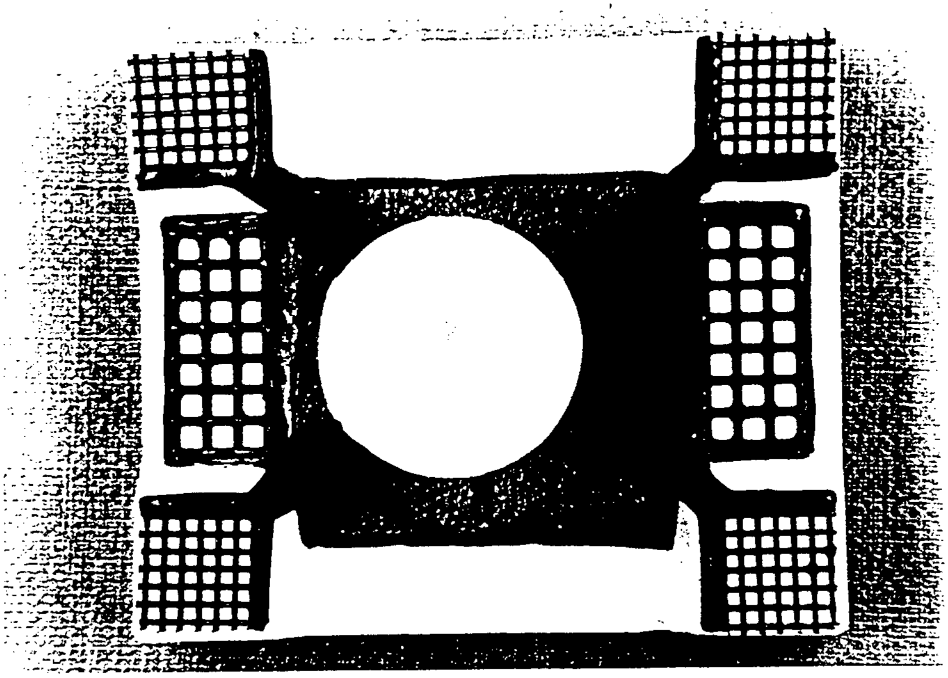
The gooseneck design (G) consisted of a 55 mm long by 5 mm diameter main sprue, attached to the posterior margin of the major connector. The connection interface was 10 mm in width. The central sprue was 20 mm in diameter and 30 mm in length (Plates 11 and 12). The gooseneck design is the spruing method recommended in the Rematitan manual (Dentaurum Co., Newtown, PA).

The wedge design (W) has the central sprue connected directly to the posterior margin of the major connector with a slightly flared attachment. The central sprue was 20 mm in diameter, 30 mm long, and displayed opposing flat sides which taped to 15 mm at the attachment to the pattern (Plates 13 and 14). The wedge design is recommended for use with Ni-Cr-Be dental alloys (Ticonium Corp., Albany, NY).

The wedge with flared attachment and casting aids design (WA) was similar to the wedge, but used a rounded central sprue 20 mm in diameter and 20 mm in length. The central sprue was attached to the pattern with a narrow flared wedge. The wedge attachment was 5 mm x 5 mm at the connection of the central sprue and flattened out to 20 mm in width at the connection to the pattern. The wedge portion was 10 mm in length. The design also used small, reservoir-like attachments to aid in the casting process. The casting aids were 1 mm in width and 4 mm in diameter, and were attached to the pattern with a minor connector measuring 2 mm in length and 1 mm in width (Plates 15 and 16). The sprue design is described in the Auto Cast HC-III titanium casting machine manual (GC International Corp., Tokyo, Japan).

Plate 7: Overhead-Direct Design

Plate 8: Overhead-Direct Design



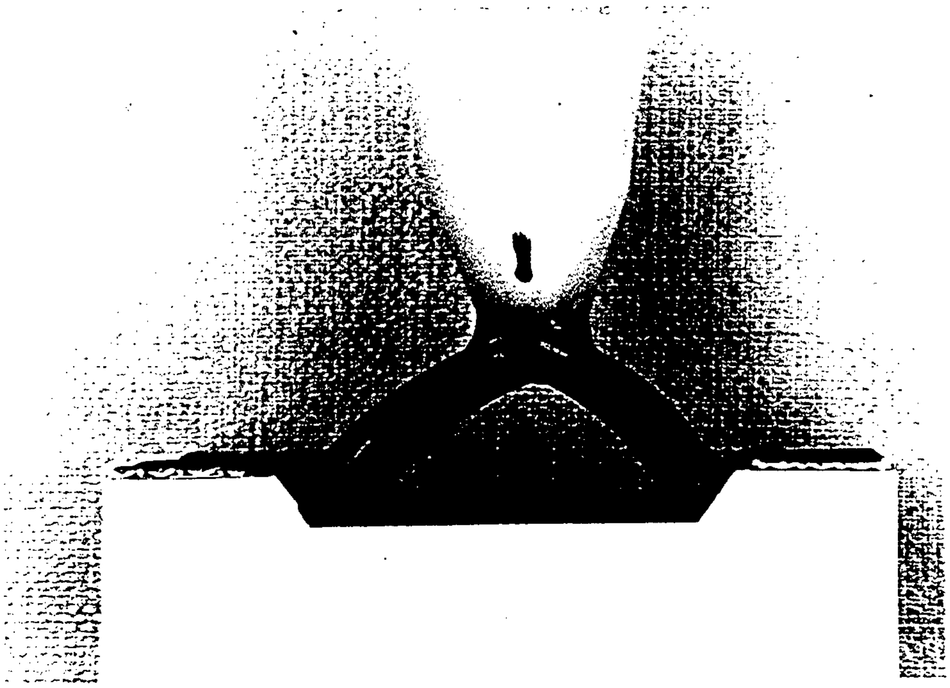
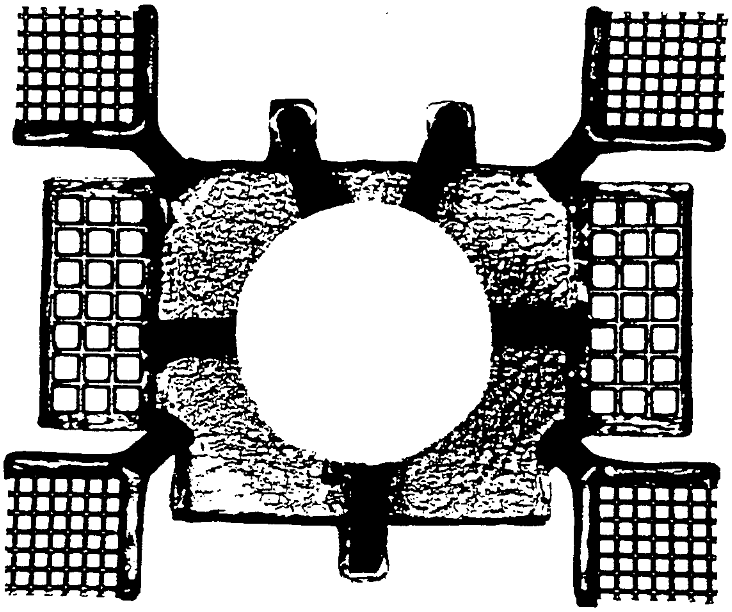


Plate 9: Overhead-Indirect Design

Plate 10: Overhead-Indirect Design



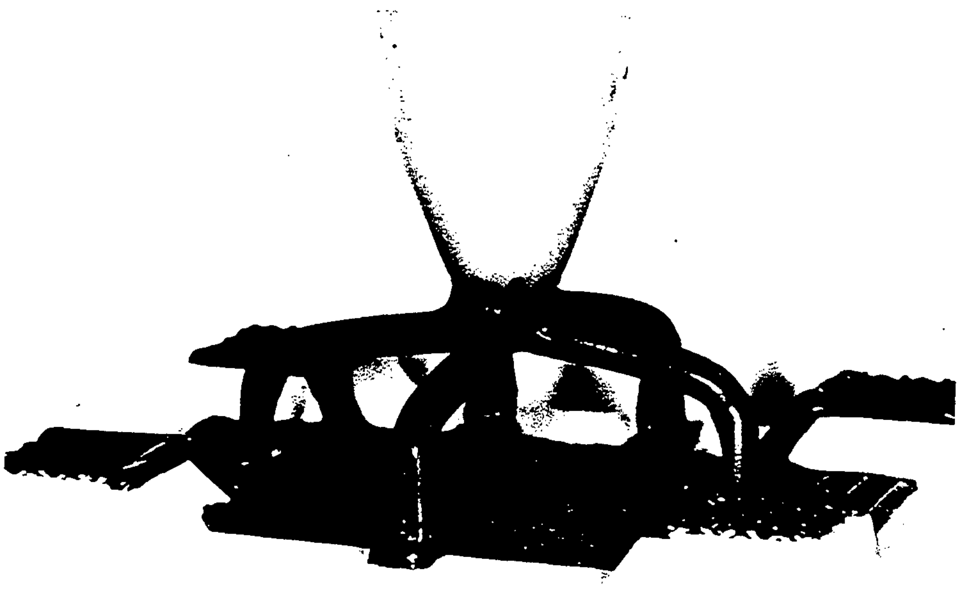


Plate 11: Gooseneck Design

Plate 12: Gooseneck Design

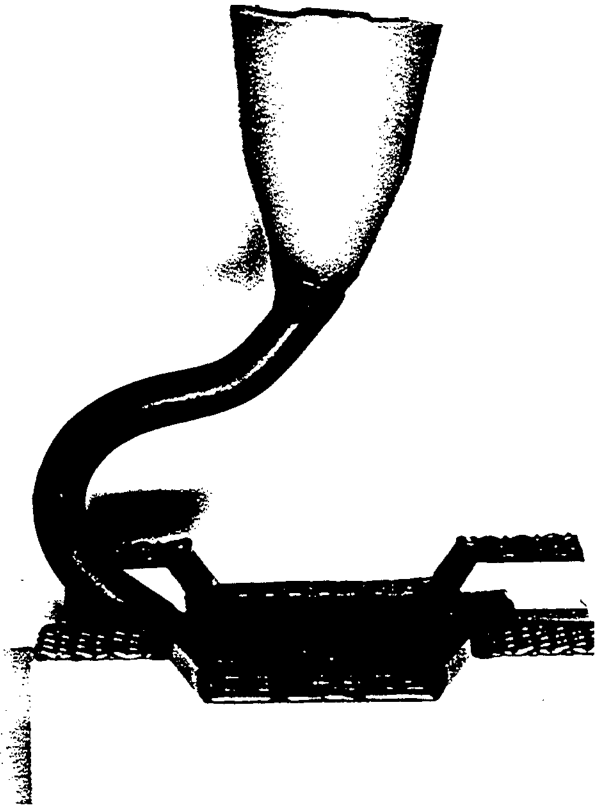
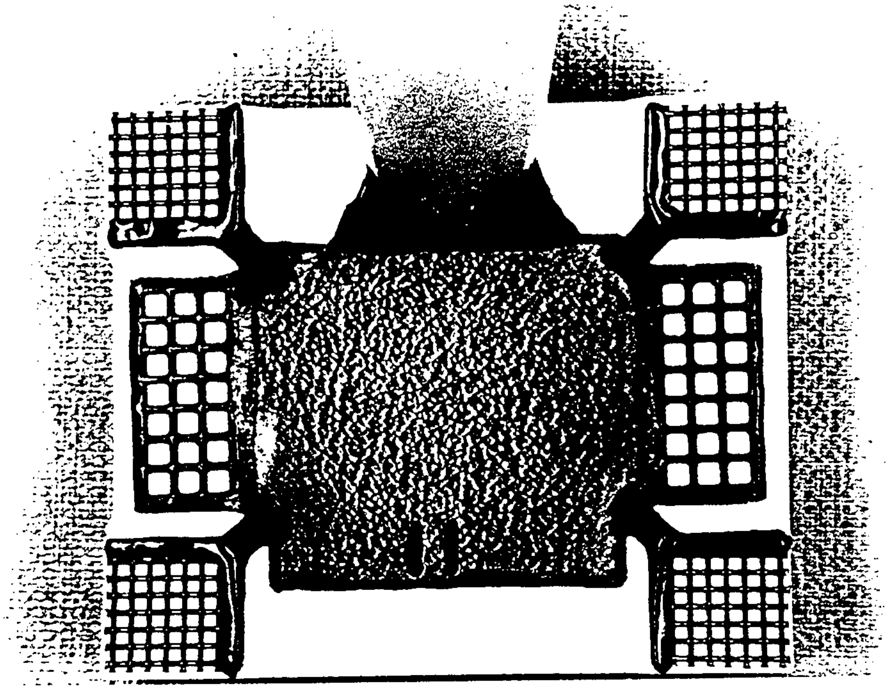


Plate 13: Wedge Design

Plate 14: Wedge Design



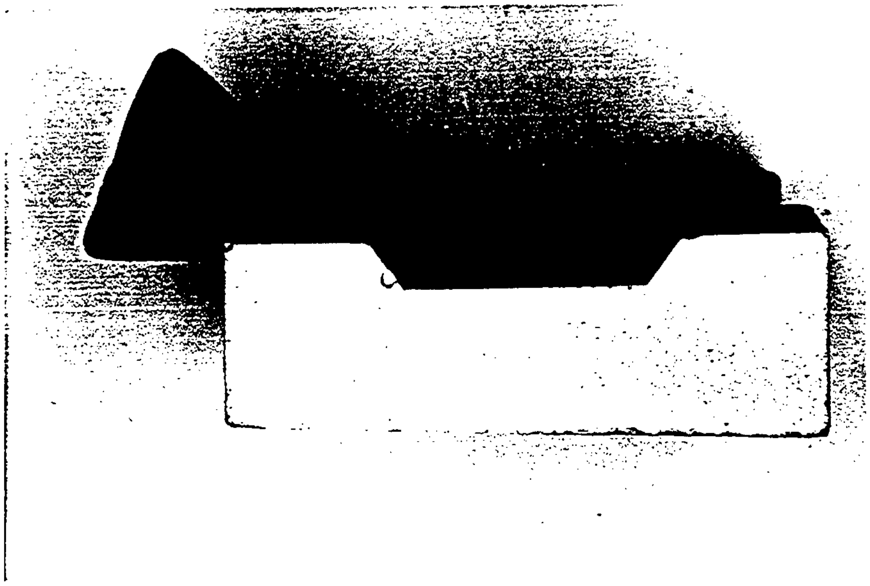
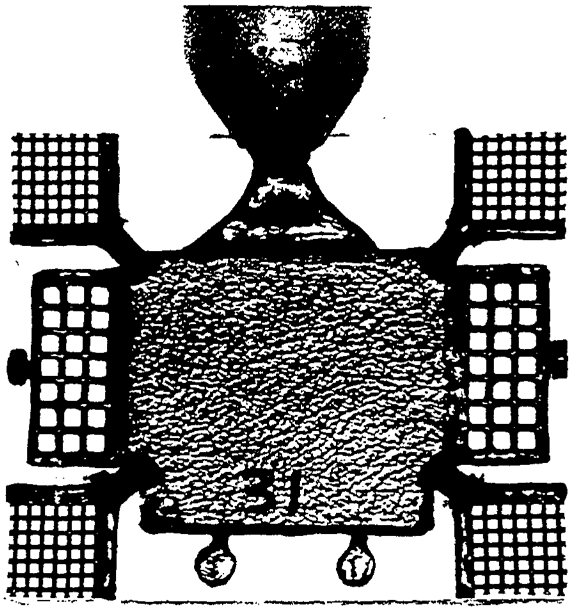
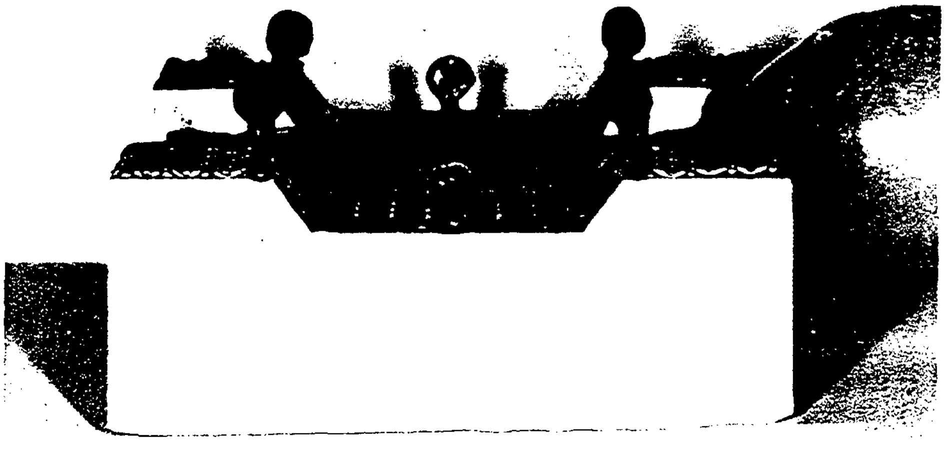


Plate 15: Wedge with Flared Attachment and Casting Aids Design

Plate 16: Wedge with Flared Attachment and Casting Aids Design



31

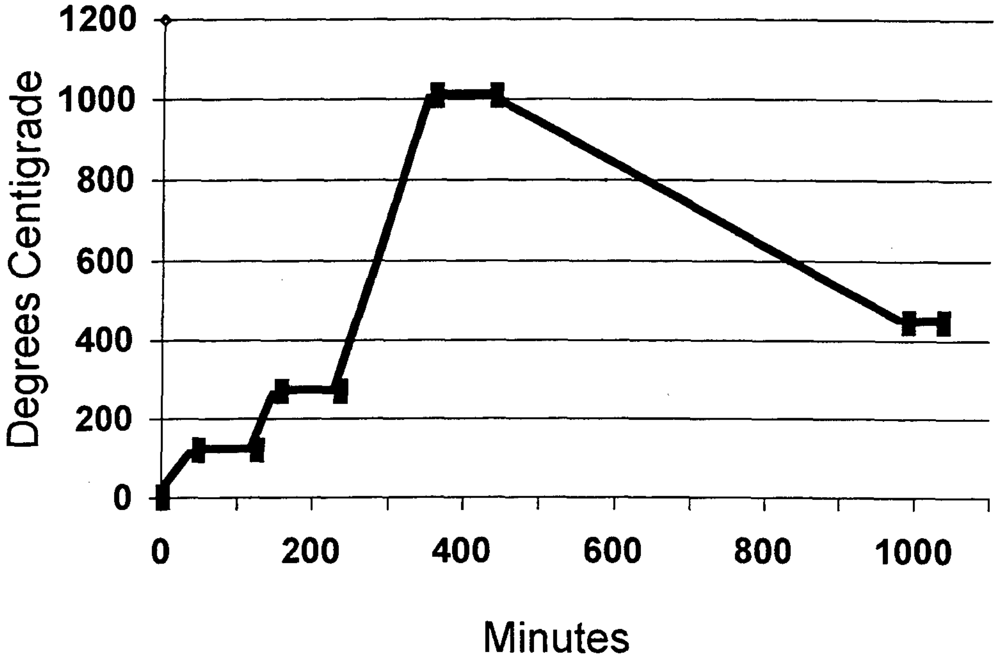


In a pilot study, it was observed that brushing each pattern with a surfactant minimized post-casting bubbles and flash within the sieve areas. Consequently, the wax patterns were lightly brushed with a surfactant, TiSol (Ticonium Corp., Albany, NY). Then, the patterns were invested with a phosphate-bonded investment (Rematitan Plus, Dentaurum Co., Newtown, PA) in accordance with the manufacturer's recommendations. A powder-to-liquid ration of 500 grams to 80 milliliters was used, and a ringless mold was created for each specimen. Both wedge sprue designs placed the pattern in a vertical relation in the mold. The overhead-direct, overhead-indirect and gooseneck designs placed the pattern horizontally. Following completion of the investment process, the burnout process was initiated.

C. Burnout Sequence and Casting Procedure

A room-temperature mold was placed into the burnout furnace (Circulating Air Preheating Furnace, Dentaurum Co., Newtown, PA), and the temperature was raised to 150°C using a heating rate of 5°C/min. This temperature was maintained for 90 minutes to permit thorough heating of the mold. Subsequently, the mold temperature was elevated to 250°C using a heating rate of 5°C/min. Again, the temperature was maintained for a period of 90 minutes. Then the temperature was raised to a soak temperature of 1000°C (using the same elevation rate), and maintained for 60 minutes. In turn, the mold was slow cooled to 430°C at a rate of 1°C/min. This temperature was maintained for 30 minutes. Hence, the burnout sequence required a total of 17 hours to complete (Figure 3). At the end of this period, casting procedures were initiated.

Figure 3: Burnout Sequence


1200
1000
800
600
400
200
0
Degrees Centigrade
0
200
400
600
800
1000
Minutes

An automatic, two-chamber argon-arc, vacuum-pressure type casting machine was used (Castmatic CM 330 System, Iwatani Co., Osaka, Japan).

The transfer of the mold to the casting machine required less than 20 seconds. The casting machine had an upper melting chamber and lower casting chamber, connected by a vertical channel. The melting process required that compressed argon (Ar) gas (0.8 bar argon pressure) be fed into the upper chamber to create an inert environment. The lower chamber was kept under vacuum (-76 cm Hg vacuum) causing a pressure gradient between the upper and lower chambers. An arc was generated between the tungsten electrode and a 31 gram ingot of commercially pure titanium, DIN 3.7065 Grade 4 (Rematitan Ti-4, Dentaurum Co., Newtown, PA). Upon completion of the melting process, the copper crucible automatically tipped, emptying the melt down the vertical channel and into the mold, completing the process (Ida *et al.,* 1982).

In this investigation, the melt chamber was purged with argon gas three times prior to the automatic casting cycle of the machine. The purging procedure was used to minimize the contamination of the melt. The ingot melting time was 36 seconds and arc intensity was set at 10.

Following completion of the casting procedure, investment was removed from the metal framework by sandblasting with 110 μm aluminum oxide material at 40 psi. Sprues were then removed using a separating disk and water coolant. Areas of sprue attachment were smoothed with a tungsten carbide bur. The casting preparation process was completed by repeating the sandblasting process.

Castings were then placed on a white plaster die. The 20 mm x 1 mm wire was placed adjacent to each casting and standardized photographs were made. Photographs of the wax patterns and castings were made utilizing a copystand, Nikon 6006 camera with macro lens (Nikon Inc., Melville, NY), and Kodak T-Max 100 black and white film (Kodak, Rochester, NY).

Subsequently, castings were radiographed. A Gendex unit (Gendex Corp., Milwaukee, WI) and the Allied automatic developer (Fischer Products Co., Inc., Geneva, IL) were used. Kodak D speed size 4 film (Kodak, Rochester, NY) was used, and was processed at 85 °F for five minutes. Each casting was placed on a film packet. The same 20 mm x 1 mm reference wire was placed next to each castings. In a pilot study, it was determined that the optimum radiographic settings for these casting were: 60 kVp, 15 mA, 12 impulses, and 14 inches focus film distance. All radiographs were accomplished and processed on the same day.

D. Digital Image Analysis

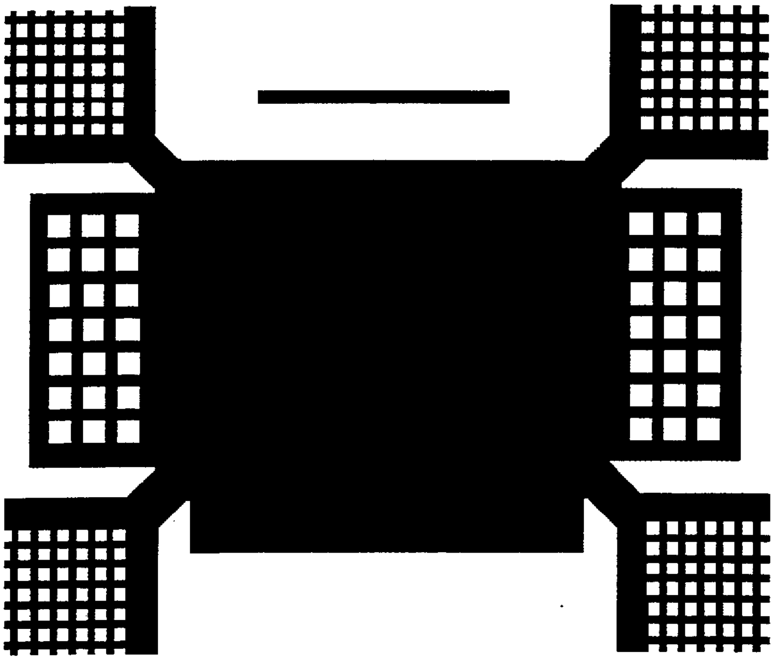
Digital image analysis was accomplished to determine the castability and porosity values for each casting. Equipment used for the analysis of the photographs and radiographs include a Macintosh 6100/60 computer (Apple Computer Corp., Cupertino, CA), Microtek XRS scanner (Microtek Lab Inc., Torrance, CA), Microtek Scan Maker Plug-in (Version 2.06; Microtek Lab Inc., Torrance, CA) and the public domain NIH Image program (Version 1.57, developed at the U.S. National Institutes of Health, Springfield, Virginia, part number PB95-500195GEI).

The initial phase of quantification was to analyze the photographs. To avoid problems with differences of processing magnification within the wax pattern photos, all of the photos were submitted and processed concurrently. Furthermore, all fifty photographs of the castings were processed at the same time. Each image had the same 20 mm x 1 mm wire adjacent to it, to serve as a reference standard. This wire was measured, in pixels, to ensure accurate comparison of all images.

Photographs of wax patterns and the castings were scanned into the computer. Each image was scanned with the same contrast and brightness. Early in the investigation, it was found that the sandblasted surface of the titanium castings produced areas of high value. These areas produced contrast problems between the white background die and the casting. Therefore, the castings were lightly dusted (one spray pass) with a black acrylic paint (Krylon, Solon, OH). This coating created sufficient contrast between the casting and the background die.

Subsequently, a density slice was performed for each image. The image was converted into a black and white binary image (Plate 17). Black pixels represented areas of the wax pattern or casting, while white pixels represented spaces (voids and/or open areas in the grids). The binary image was used in the quantification procedure.

Plate 17: Black and White Binary Image



The first stage in analysis of each binary image was to measure the 20 mm x 1 mm wire. For all the wax patterns, the wire measured 174 pixels in length. It was then calculated that each pixel of these images equaled 0.115 mm (0.115mm/pixel). In casting photographs, the wire measured 204 pixels in length (or 0.098 mm/pixel). The same wire measured 120 pixels (or 0.167 mm/pixel) in the radiographic images. The measurements are summarized in Table 1.

Table 1: Reference Measurements for Digitized Images

IMAGE	Wire Length	Wire Length in Pixels	mm/pixel
Wax Pattern	20 mm	174	0.115
Casting	20 mm	204	0.098
Radiograph	20 mm	120	0.167

The wax pattern and casting images were divided into three analysis areas: sieve, mesh, and connector (Figure 2). The sieve areas were analyzed by creating a selection box large enough to include the total area of each sieve image (Plates 18). The measurement of this box was recorded and used for each sieve area of the wax pattern and casting images. The same procedure was used to analyze the mesh (Plate 19) and connector areas (Plate 20). Table 2 summarizes the box sizes used for each area analyzed. Using the NIH image program, the total pixels of black and white areas were measured. The program also calculated the percentage of the total area which was white and the percentage of the total area which was black. The measurements of the sieve, mesh, and connector areas were recorded.

Table 2: Analysis Selection Box Sizes

IMAGE	Sieve Box Size (Pixels x Pixel)	Mesh Box Size (Pixels x Pixels)	Connector Box Size (Pixels x Pixels)
Wax Pattern	90 x 90	78 x 190	285 x 280
Casting	106 x 106	91 x 223	334 x 328

Plate 18: Image Analysis of Sieve Area

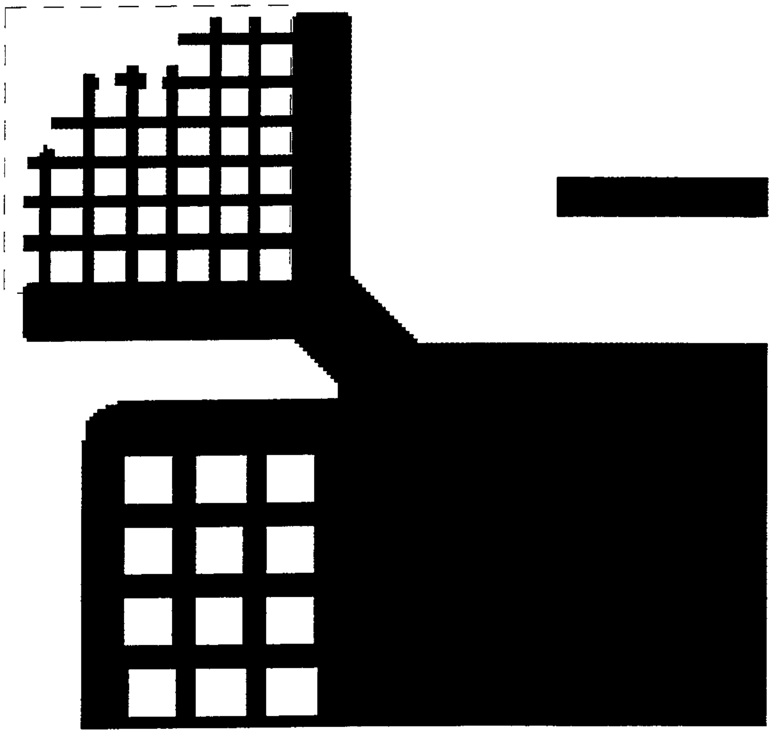


Plate 19: Image Analysis of Mesh Area

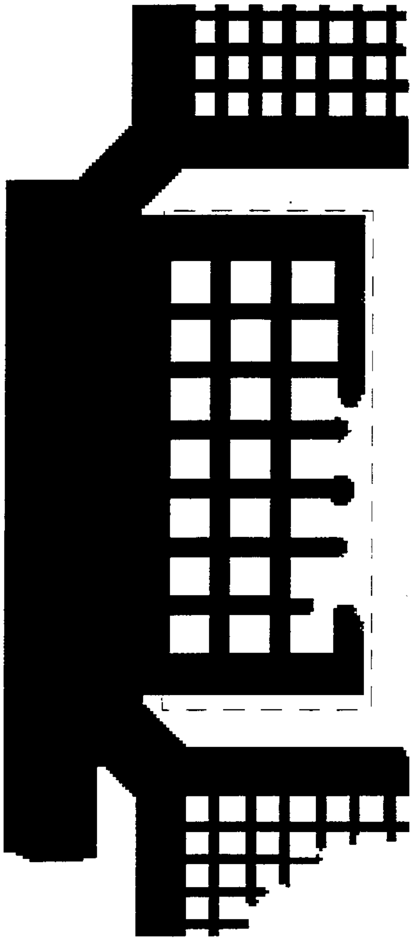
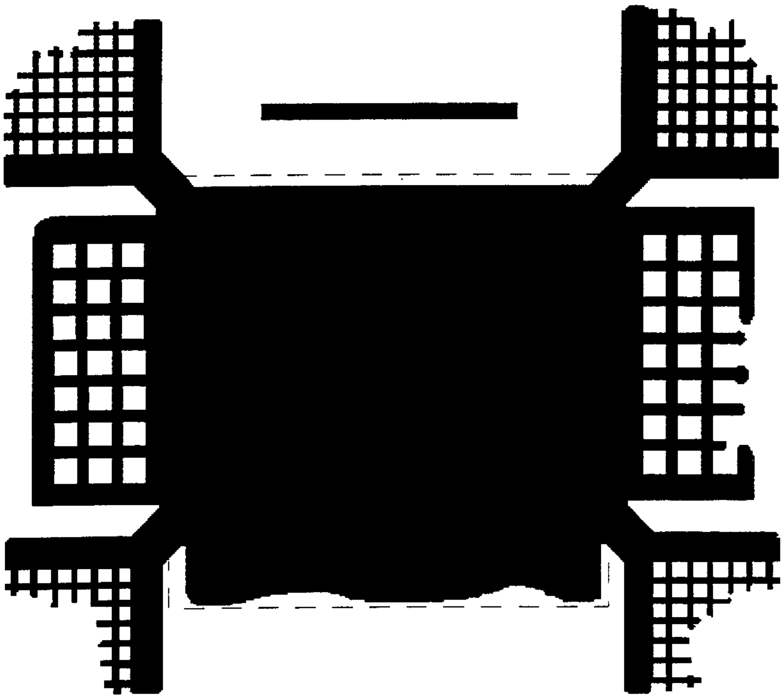


Plate 20: Image Analysis of Connector Area



The radiographs of castings were analyzed using a similar method. The images were scanned into the computer. A density slice was accomplished and converted to a binary image. Again, the black represented the metal and the white represented the porosity and spaces. The reference wire was measured and recorded (Table 1). Using the program's outlining tool it was possible to select the total area, in pixels, corresponding to metal. The selection equaled the total area cast. The sieve, mesh, and connector areas were combined. The result was the total number of pixels possible for the casting image. Following this, the selection tool was used to select areas of porosity, excluding the normal spaces in the casting sieve and mesh. To aid in the selection of minute areas of porosity, the image was magnified 2-to-1. The porosity values were recorded in pixels.

For the calculations, the pre-casting photograph of the wax pattern provided the total possible area **(C_T)**. The post-casting photograph provided the total area of the casting **(C_C)**. Using these two areas, a castability value **(C_V)** was calculated.

$$\mathbf{C_V = (C_C \div C_T) \times 100\%}$$

The radiograph was used to quantify the porosity. The porosity value **(P_V)** is the ratio of the area of total porosity **(P_T)** to the area of the casting **(C_C)**.

$$\mathbf{P_V = (P_T \div C_C) \times 100\%}$$

E. Statistical Analysis

The analysis of the multifunctional test pattern resulted in three castability values: sieve (Table 3), mesh (Table 6), and connector (Table 8). It also provided a porosity value for each casting (Table 10). The mean values obtained for each sprue design are summarized in Table 12. The independent variable was sprue design. The response variables were castability and porosity.

Because this investigation dealt with single categorical independent variables, One-Way ANOVA was selected for statistical comparison. Following determination of significant differences, a post-hoc analysis, Tukey-B test, was performed to ascertain which groups displayed statistically significant differences.

IV. Results

Ten titanium removable partial denture frameworks were cast using each of five different sprue designs, forming fifty experimental units. Using digital image analysis technology, the total areas of the wax patterns, castings, and radiographic porosity of each casting was quantified. Comparing the differences between each unit's wax pattern and casting resulted in highly accurate castability values. The castability values are recorded in Tables 3, 6, and 8. Furthermore, digitization of a standardized radiograph of each casting resulted in accurate determination of the amount of porosity, see Table 10.

A. Castability

The castability values for the sieve areas are shown in Table 3. Sieve areas mean castability comparisons for each sprue design are presented in Figure 4. A One-Way ANOVA test, with a significance level of 0.05, was used in analyzing the five groups (Table 4). The results indicated a statistically significant difference in the mean castability values (Cv) of the sieve areas among the groups ($p<0.00001$). Thus, sprue design affects the castability of the sieve areas and the null hypothesis was rejected. To determine the groups that were significantly different from one another, a post hoc comparison was accomplished using the Tukey B test. The results of the Tukey B test, with a level of significance of 0.05, showed castings produced using the overhead-direct (OD) and the wedge (W) groups were statistically significantly different from the other sprue design groups (Table 5). However, there was not a statistically significant difference between the overhead-direct (OD) and wedge (W) groups. Figure 4 provides a graphical representation of the mean sieve castability for each sprue configuration examined.

Table 3: Castability Values for Sieve Areas

SIEVE	OD	W	G	WA	OI
	96.80135	78.91755	71.86869	64.95458	44.45832
	88.43180	81.64901	56.97055	88.96045	29.24528
	85.57925	87.78453	29.11184	66.01211	63.91775
	87.50527	85.44651	27.26767	93.90186	39.26212
	85.72781	79.41331	61.98902	51.27994	48.45869
	55.65168	79.31427	67.53205	36.16558	57.84751
	78.40222	86.59076	61.18022	42.94113	40.38328
	73.87781	78.88558	57.20899	47.22222	34.22511
	79.48465	86.48961	33.90805	0.471698	33.92522
	82.26973	82.21949	37.92526	35.24129	39.69719
Mean Cv	81.3732	82.6711	50.4962	52.7151	43.1420
Std Dev	11.0206	3.5799	16.7009	27.4328	10.9036

Table 4: ANOVA for the Sieve Areas ($\alpha=0.05$, $p<0.0001$)

ANOVA	source	SS	df	MS	F
	between	13767.55	4	3441.886	13.39634*
	within	11561.73	45	256.9274	
	TOTAL	25329.28	49		
	F(.05,4,40)= 2.61 F(.05,4,60)= 2.53	*Reject null hypothesis; a significant difference exists among the means.			

Table 5: Tukey B Test for Sieve Areas ($\alpha=0.05$)

TUKEY'S TEST of difference						
		OI 43.14205	G 50.49624	WA 52.71509	OD 81.37316	W 82.671061
41-50	43.14205		7.354189	9.573039	38.23111	39.5290142
21-30	50.49624			2.21885	30.87692	32.1748255
31-40	52.71509				28.65807	29.9559754
1-10	81.37316					1.29790517
11-20	82.67106					

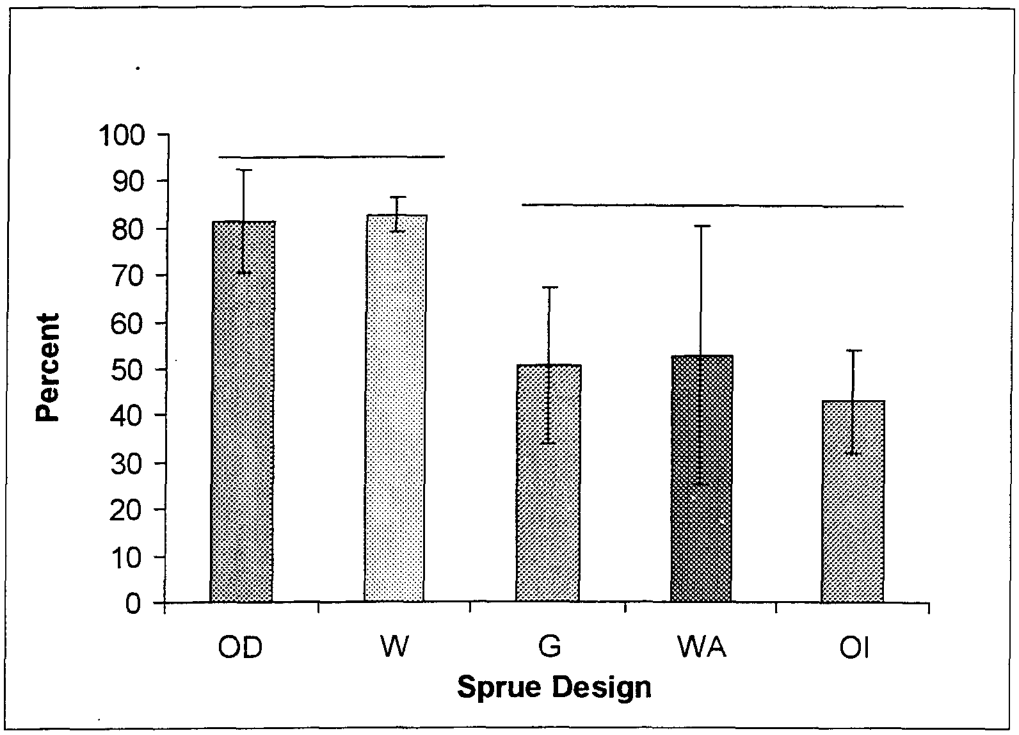
HSD = q(.05),4,45 * Square Root of (MSw/nj)

q(.05) @ 5,40 = 4.04 MSw = 256.9274

q(.05) @ 5,60 = 3.98 nj = 10 HSD = 20.27507

Therefore, OD is statistically significantly different from OI, WA, and G. Also, W is statistically significantly different from OI, WA, and G.

Figure 4: Bar chart of the mean sieve castability. Cross marks indicate standard deviation. Horizontal lines indicate groups not significantly different.


100
90
80
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50
40
30
20
10
0
Percent
OD
W
G
WA
OI
Sprue Design

Castability values for the mesh areas are presented in Table 6. A One-Way ANOVA test, with a significance level of 0.05, was used to analyze the five groups. The results indicated no significant difference in mean castability values (Cv) among the groups (p=0.20). No statistically significant difference existed among the groups, thus, the null hypothesis was accepted (H_0: that sprue design does not influence castability of the mesh areas). Table 7 indicates results of the One-Way ANOVA and Figure 5 provides a graphical representation of the mean mesh castability for each sprue configuration examined.

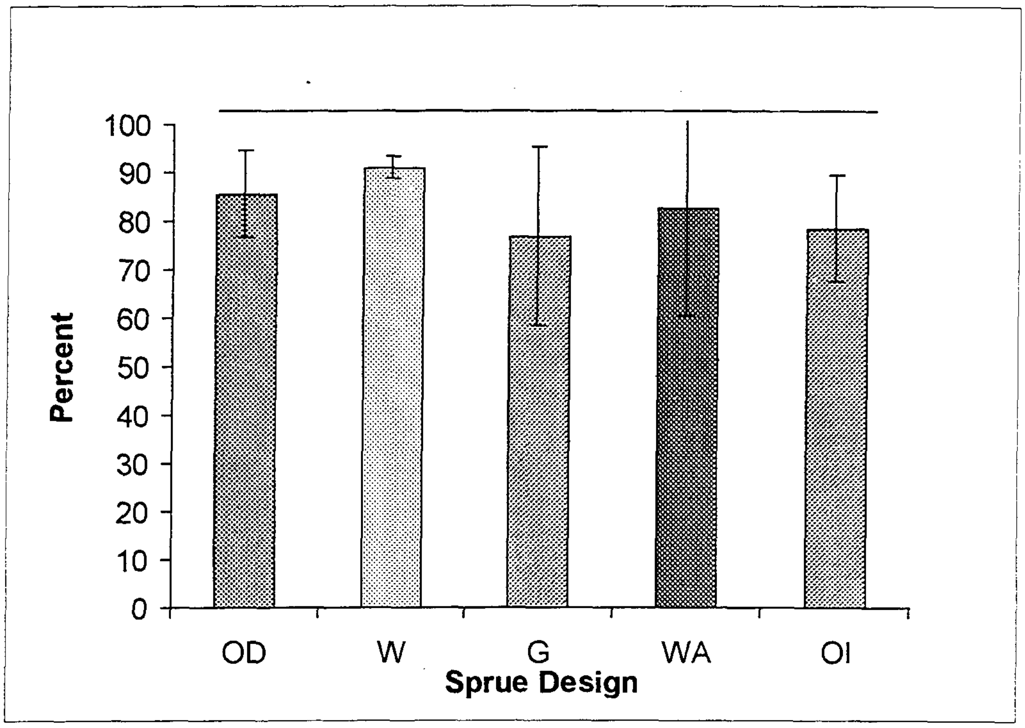
Table 6: Castability Values for Mesh Areas

MESH	OD	W	G	WA	OI
	94.49283	89.90232	94.64962	97.58065	81.76230
	88.90881	90.15152	89.23077	94.39240	57.32323
	92.89082	90.11481	42.18750	98.33333	91.19304
	90.57540	88.28125	50.75758	94.36764	66.09290
	88.98810	86.50794	67.96875	93.50873	88.73276
	88.82488	92.23443	92.85714	86.36593	86.93438
	91.88260	92.96875	93.84615	75.59199	70.67689
	68.25754	93.54839	87.78176	86.87424	77.64977
	76.38815	93.64919	71.82984	25.06252	86.31592
	74.81491	92.23558	77.34375	72.42944	78.22581
Mean Cv	85.6024	90.9594	76.8453	82.4507	78.4907
Std Dev	9.0137	2.3735	18.6230	22.0198	10.9193

Table 7: ANOVA for the Mesh Areas (α=0.05, p=0.20)

ANOVA	source	SS	df	MS	F
	between	1285.56	4	321.39	1.548422
	within	9340.188	45	207.5597	
	TOTAL	10625.75	49		
	F(.05,4,40)= 2.61 F(.05,4,60)= 2.53	There were no statistically significant differences at the 0.05 level.			

Figure 5: Bar chart of the mean mesh castability. Cross marks indicate standard deviation. Horizontal lines indicate groups not significantly different.


100
90
80
70
60
50
40
30
20
10
0
Percent
OD
W
G
WA
OI
Sprue Design

The castability values for the connector areas are given in Table 8.. A One-Way ANOVA test, with a significance level of 0.05, was used to analyze the five groups. The results indicated no statistically significant difference in mean castability values (Cv) among the groups (p=0.08). The null hypothesis was accepted that sprue design does not influence castability of the connector area. Results of the One-Way ANOVA are presented in Table 9. Mean connector castability comparisons for each sprue design are presented graphically in Figure 6

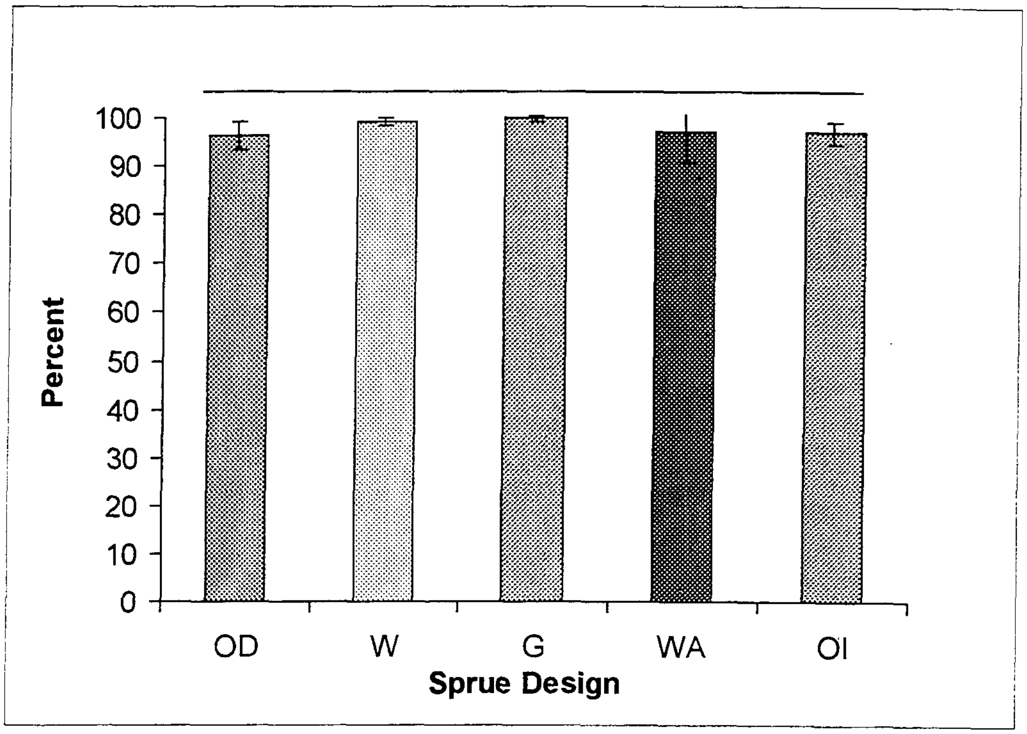
Table 8: Castability Values for Connector Areas

CONNECTOR	OD	W	G	WA	OI
	97.93814	98.96907	100.0000	100.0000	96.90722
	100.0000	98.96907	100.0000	100.0000	97.93814
	97.93814	98.96907	100.0000	93.75000	98.95833
	97.93814	98.96907	98.96907	100.0000	92.78351
	96.93878	100.0000	100.0000	100.0000	97.93814
	90.72165	100.0000	100.0000	100.0000	95.87629
	91.75258	98.95833	100.0000	100.0000	100.0000
	95.74468	100.0000	98.97959	98.96907	95.87629
	97.91667	97.95918	100.0000	80.00000	94.84536
	94.84536	98.95833	100.0000	97.91667	98.96907
Mean Cv	96.1734	99.1752	99.7949	97.0636	97.0092
Std Dev	2.9594	0.6484	0.4325	6.3091	2.1966

Table 9: ANOVA for the Connector Areas (α=0.05, p=0.08)

ANOVA	source	SS	df	MS	F
	between	96.74761	4	24.1869	2.239727
	within	485.9569	45	10.79904	
	TOTAL	582.7045	49		
	F(.05,4,40)= 2.61 F(.05,4,60)= 2.53		There were no statistically significant differences at the 0.05 level.		

Figure 6: Bar chart of the mean connector castability. Cross marks indicate standard deviation. Horizontal lines indicate groups not significantly different.


Percent
100
90
80
70
60
50
40
30
20
10
0
OD
W
G
WA
OI
Sprue Design

B. Porosity

The porosity values (Pv) for each casting are given in Table 10. A One-Way ANOVA test, with a significance level of 0.05, was used to analyze the five groups, Table 11. Comparison of the mean porosity values indicated no statistically significant difference among the groups (p=0.54). Therefore, the null hypothesis was accepted that sprue design does not influence the amount of porosity produced in titanium removable partial denture frameworks. Mean porosity value comparisons for each sprue design are presented graphically in Figure 7

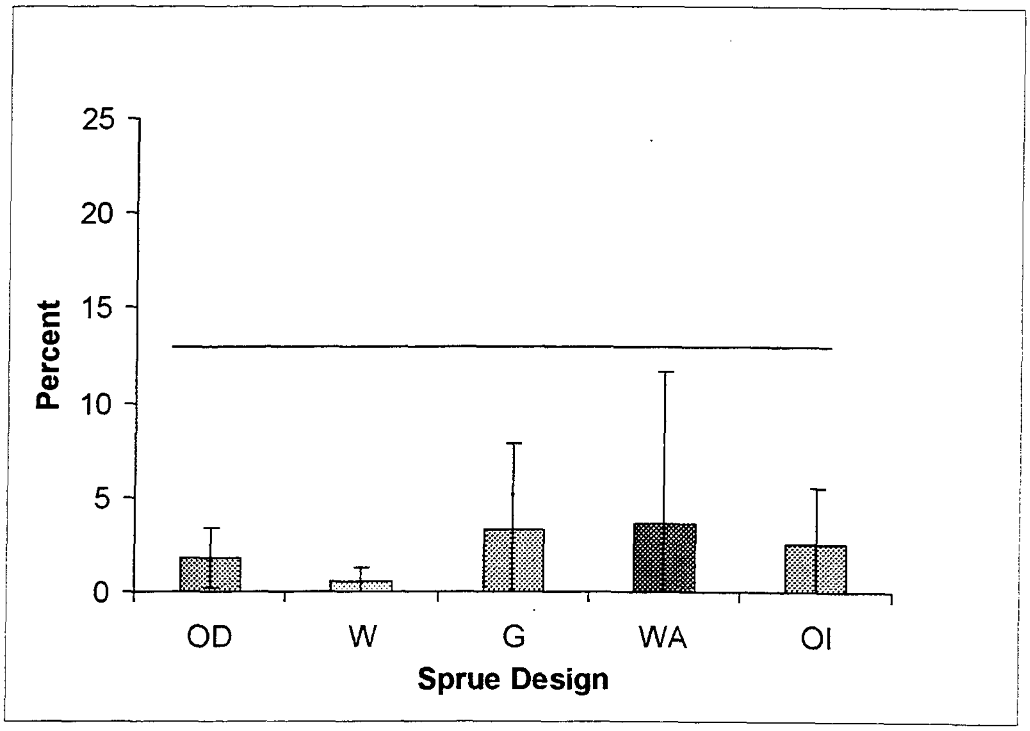
Table 10: Porosity Values (Pv)

Porosity	OD	W	G	WA	OI
	0.873503	0.354679	14.91048	26.14439	1.038998
	0.184441	2.565282	0.838362	2.739633	5.077815
	0.118618	0.003261	0.016453	4.189690	1.744017
	0.913374	0.094016	0.392766	0.353647	3.323568
	1.216120	1.163845	0.288210	0.482721	1.181577
	4.324061	0.174813	5.624303	1.005524	0.515877
	4.477300	0.146702	2.563697	0.633057	0.641602
	2.908864	0.265647	2.688784	0.162467	1.302367
	1.448400	0.381409	0.388008	0.008109	9.973363
	1.561922	0.183416	4.930568	0.580239	0.173888
Mean Pv	1.80266	0.533307	3.264163	3.629948	2.497307
Std Dev	1.576604	0.783685	4.553524	8.020503	3.015778

Table 11: ANOVA for the Porosity Values (α=0.05, p=0.54)

ANOVA	source	SS	df	MS	F
	between	60.95513	4	15.23878	0.783422
	within	875.3203	45	19.45156	
	TOTAL	936.2755	49		
	F(.05,4,40)= 2.61 F(.05,4,60)= 2.53	There were no statistically significant differences at the 0.05 level.			

Figure 7: Bar chart of the mean porosity values. Cross marks indicate standard deviation. Horizontal lines indicate groups not significantly different.


Percent
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OD
W
G
WA
OI
Sprue Design

The summary of the grand means for the castability and porosity values are presented in Table 12. Table 13 provides a summary of the high and low ranges. Photographs of the five casting groups are shown in Plates 21 through 25.

Table 12: Summary Table for Castability and Porosity Values

Mean values in percent. (Std Dev)	OD	W	G	WA	OI
Porosity Value	1.80 (1.58)	0.53 (0.78)	3.26 (4.55)	3.63 (8.02)	2.50 (3.02)
Castability Value Sieve Areas(S)	81.37 (11.02)	82.67 (3.56)	50.50 (16.70)	52.72 (27.43)	43.14 (10.90)
Mesh Areas(M)	85.60 (9.01)	90.96 (2.37)	76.85 (18.62)	82.45 (22.02)	78.49 (10.92)
Connector Area(C)	96.17 (2.96)	99.18 (0.65)	99.79 (0.43)	97.06 (6.31)	97.01 (2.20)

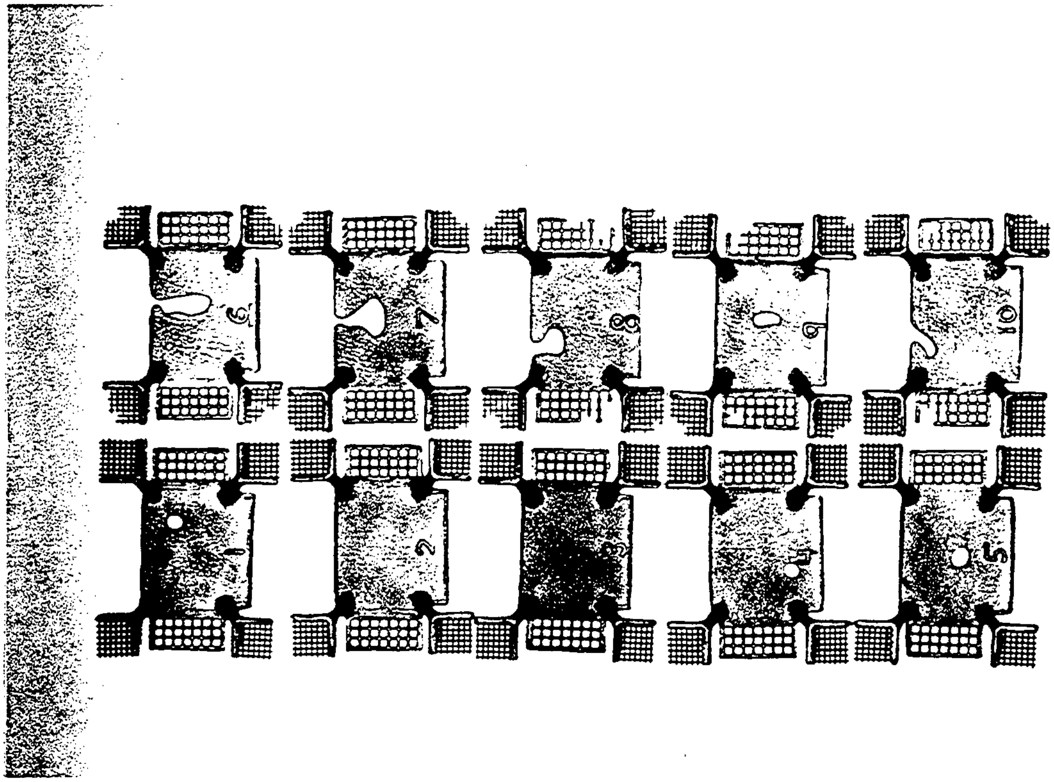
Table 13: Summary Table with High and Low Ranges

Sieve	Mean Castability	Std Dev	Range Low	Range High
OD	81.3732	11.0206	55.652	98.60
W	82.6711	3.57995	78.886	87.78
G	50.4962	16.7009	27.268	71.87
WA	52.7151	27.4328	35.241	93.90
OI	43.1420	10.9036	29.245	63.92
Mesh	Mean Castability	Std Dev	Range Low	Range High
OD	85.60240	9.013746	68.258	94.49
W	90.95942	2.373490	86.508	93.55
G	76.84529	18.62298	42.188	94.65
WA	82.45068	22.01979	72.429	98.33
OI	78.49070	10.91931	57.323	91.19
Connector	Mean Castability	Std Dev	Range Low	Range High
OD	96.17	2.959	90.72	100
W	99.18	0.648	97.96	100
G	99.79	0.432	98.97	100
WA	97.06	6.309	80.00	100
OI	97.01	2.197	92.78	100

XR Analysis	Mean Porosity	Std Dev	Range Low	Range Highi
OD	1.802260	1.576604	0.118618	4.477300
W	0.533307	0.783685	0.003261	2.565282
G	3.264163	4.553524	0.016453	14.91048
WA	3.629948	8.020535	0.008109	26.14439
OI	2.497307	3.015778	0.173888	9.973363

Plate 21: Overhead-Direct Design Castings

Plate 22: Wedge Design Castings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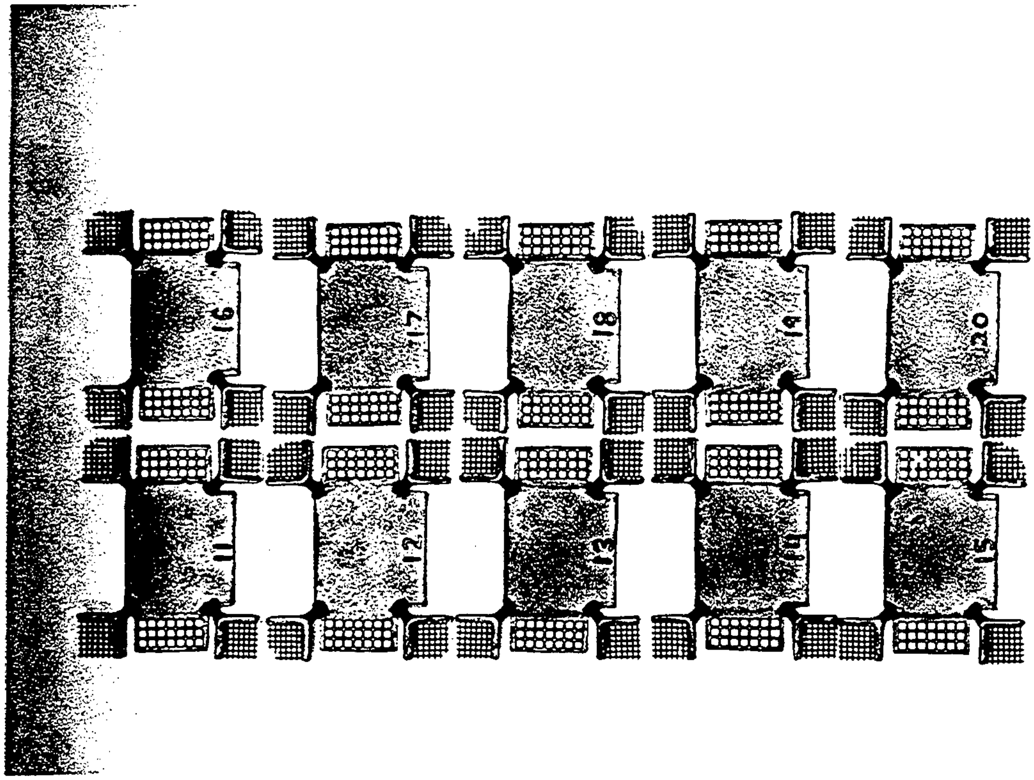
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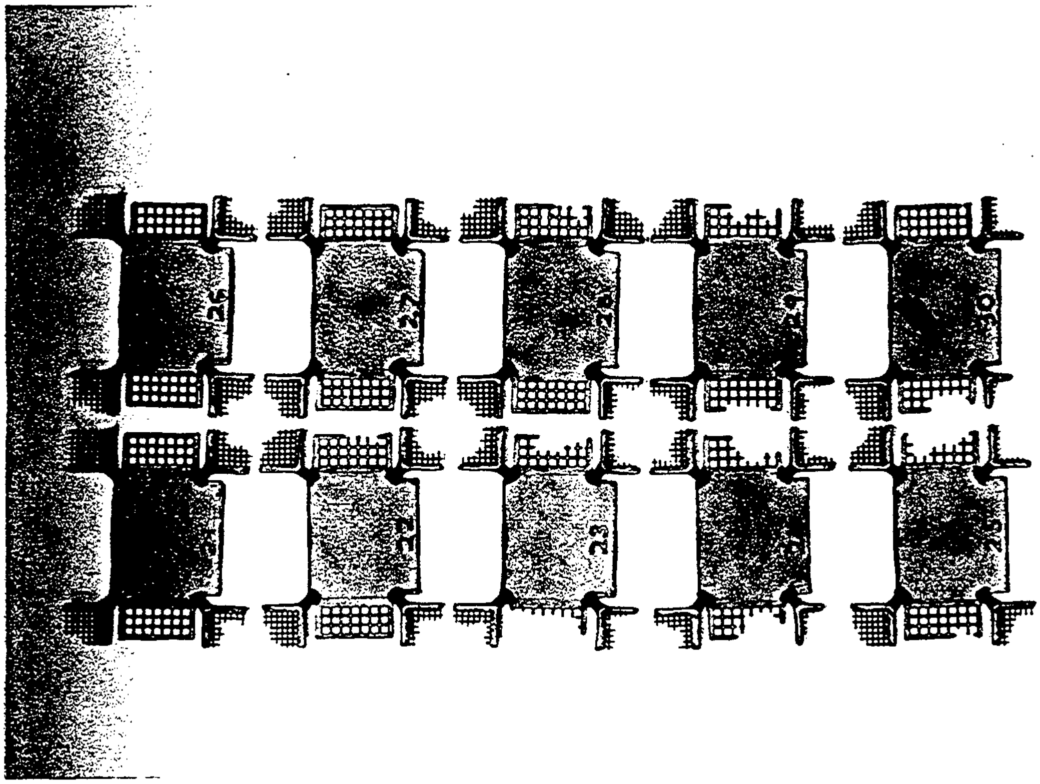
Plate 23: Gooseneck Design Castings

Plate 24: Wedge with Flared Attachment and Casting Aids Castings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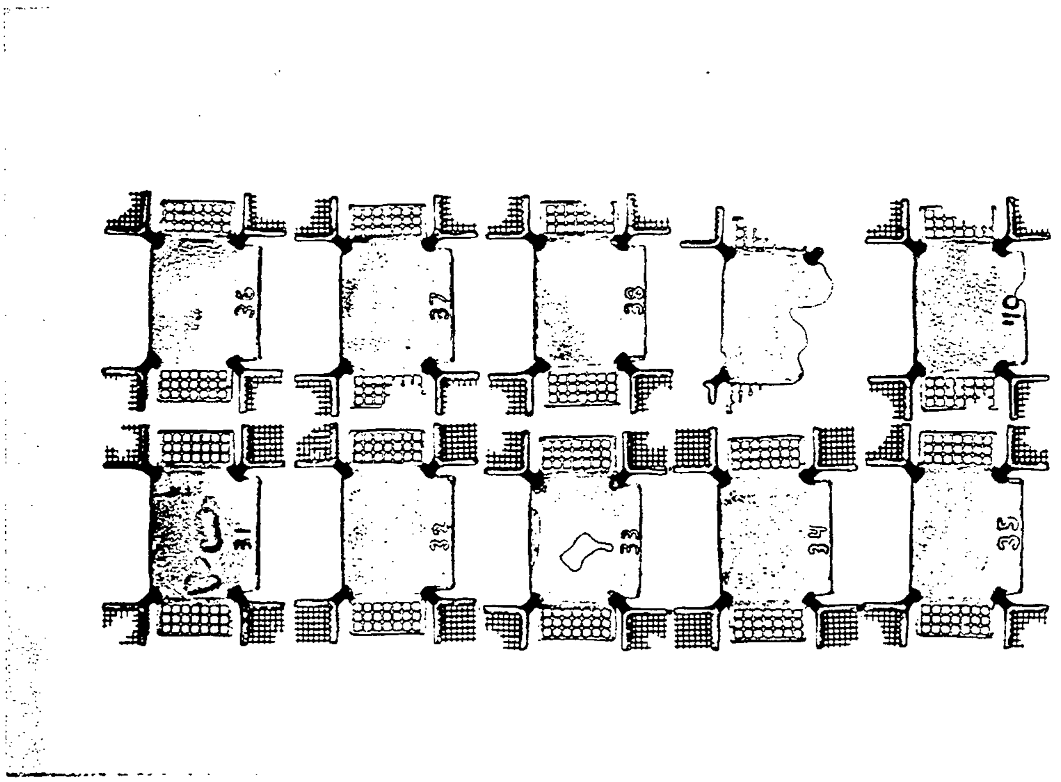
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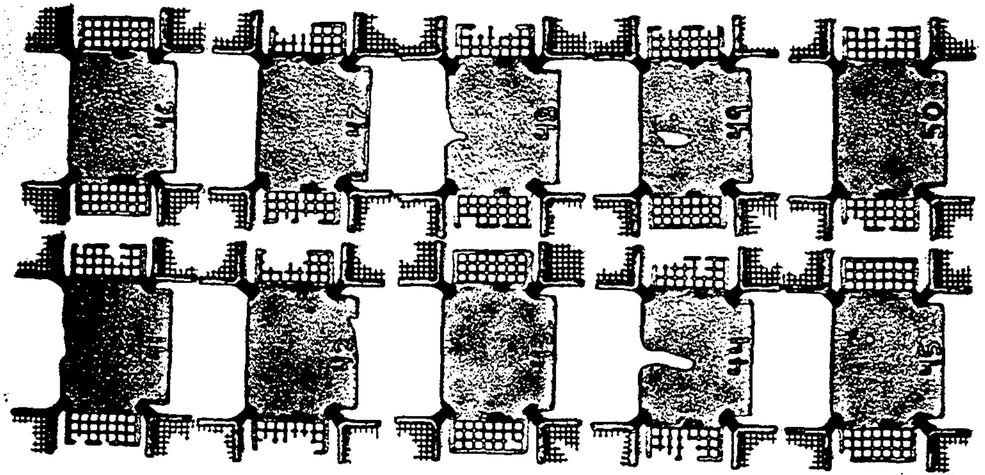
Plate 25: Overhead-Indirect Design Castings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V. Discussion

The physical and chemical properties of titanium make it very attractive for use in dentistry. Titanium is well suited for removable partial denture frameworks because of its low weight, high strength, and exceptional biocompatibility. This investigation was undertaken to determine the effects of sprue design on castability and porosity of a titanium removable partial denture framework.

Castability

Many castability monitors have been developed to test the commonly-used dental alloys, such as gold and base metals (Asgar and Arfaei, 1985; Howard and Sheldon, 1980; Nielsen, 1977; Preston and Berger, 1977; Vincent *et al.,* 1977; Whitlock *et al.,* 1981). Current castability studies for titanium continue to use the classic tests (Bessing and Bergman, 1992; Chung *et al.,* 1994; Greener *et al.*, 1986; Ida *et al.,* 1982; Mueller *et al.,* 1990; Takahashi *et al.,* 1993a-c; Watanabe *et al.,* 1991). However, removable partial denture frameworks present many casting demands. Consequently, removable partial denture frameworks are extremely difficult to cast.

Typically, removable partial denture frameworks display thick and thin areas as well as multiple fine components. Major connectors tend to be thick and wide, increasing the likelihood for internal porosity and casting shrinkage. Acrylic resin retention components usually are moderately fine meshes or half-round lattice areas. These areas have many extreme turns and thin sections that can easily miscast. The most important and most difficult areas to cast are the clasping components. Clasp assemblies are generally on a different plane than the major connector, accessed by narrowing minor connectors, and represent the termination point for the molten metal. These areas have been reported to have the highest amounts of casting deficiencies and porosities, which can result in failure of the dental prosthesis (Elbarbi *et al.,* 1985; Lewis, 1978).

Therefore, an RPD castability test monitor must address the specific characteristics of the framework. Classic castability tests fall short when used to evaluate the castability of RPD frameworks, because they are not configured like an removable partial denture framework and are generally much smaller. The significance of the castability test monitor presented in this investigation is that it tested large, thick areas similar to those used in major connector, acrylic resin retentive mesh areas, and fine peripheral areas like the clasp assemblies.

The 30 mm x 35 mm x 0.87 mm major connector used in this investigation approximate those used in clinical prostheses (Rudd *et al.,* 1986). The major connector dimension of the castability monitor in this investigation was similar to the wax plate test monitor used by other investigators (Chung *et al.,* 1994; Hamanaka *et al.,* 1989; Ida *et al.,* 1982; Takahashi *et al.,* 1993a,b; Tamaki *et al.,* 1993; Yamauchi *et al.,* 1988). The monitor also included acrylic resin retentive meshes to test the elements with middle-range casting difficulties. The monitor had an added dimension in that it contained an elevated 1000 μm polyester sieve area on a second plane. Such a sieve has been used for evaluation of castability in many recent investigations (Cohen *et al.,* 1992; Greener *et al.,* 1986; Hinman *et al.,* 1985; Takahashi *et al,* 1990; Takahashi *et al.,* 1993c; Watanabe, *et al.,* 1991; Yamauchi *et al.,* 1988). In this investigation the sieve areas were connected to the major connector with a 7 mm long minor connector and had two 18 gauge runner bars on each side. The runner bars approximated the thickness of RPD clasps. The sieve was added to increase the casting difficulty and provide additional areas for evaluation. Therefore, this castability monitor incorporated many of the potential casting demands of a typical dental RPD framework.

The wedge (W) configuration resulted in a mean castability value of 99% for the major connector. These results were similar to those reported by Takahashi *et al.* (1993a,b) and Tamaki *et al.* (1993). Both investigations reported castability values of approximately 96% for wax plates of similar dimensions. The results suggest titanium had good castability for thicker areas of RPD frameworks. Yamauchi *et al.* (1988), recommended using a thicker wax pattern when casting titanium.

The wax pattern used in this investigation had a 0.87 mm thick major connector. Although the thickness was greater than that used for nickel-chrome-beryllium RPD frameworks, it was comparable to the thickness recommended for Type IV gold RPD frameworks (Rudd *et al.,* 1986).

The wedge (W) method also showed high castability values for the acrylic resin retentive mesh areas, 91%. The mesh was the same as that used for RPD frameworks. It was considerably larger than the polyester sieve and was expected to cast better than the sieve areas.

The sieve castability for the wedge (W) method resulted in one of the two highest mean values, 83%. An earlier investigation by Mueller *et al.* (1990), reported comparable values of 85% for a 1000 μm sieve. Takahashi *et al.* (1993c), however, reported castability values of less than 10% with a 1000 μm sieve and a two chamber casting machine. The illustration of the castability monitor used by Takahashi *et al.* (1993c) was similar to the Whitlock grid (Hinman *et al.,* 1985). In Takahashi's investigation the sprue connection was directly to the runner bars of the sieve castability monitor. The distance traveled by the molten titanium was minimal and more complete castability could be expected.

In the current investigation, with the wedge (W) sprue design, the molten metal traveled through the major connector and minor connector areas prior to reaching the sieve areas. The distance traveled is much farther than the two studies cited above. Considering the distance, the mean castability value of 83% was quite satisfactory.

According to the results the wedge (W) sprue design showed the least variability when examining the standard deviation. The reason the wedge (W) sprue configuration performed so well may be related to the close approximation of the large central sprue to the actual pattern. This method does not contain ingate sprues between the central sprue and the pattern. The funnel shaped sprue allowed for faster delivery and spread of the molten metal. Watanabe *et al.* (1991), suggested that one of the most important requirements for casting titanium is the rapidity with which the molten metals enters and spreads through the mold cavity.

It has been recommended that the sprue provide the molten metal a pathway as direct as possible to the distant areas (Jaffee and Promisel, 1970). The wedge (W) method provided a greatly reduced path for the molten titanium to travel from the crucible to the mold cavity. Furthermore, the flow of metal was directed toward the most distant areas. The wedge design provided a pathway directly into the mold, with minimal impact on the investment walls by molten titanium. Consequently, the wedge pathway may have prevented investment erosion and decreased the possibility for inclusions. The wedge design eliminated pocket areas within the ingates where the molten metal could pick up gases resulting in gas inclusions.

Another important aspect of the wedge (W) configuration was the vertical relation of the wax pattern within the mold. The investigation used an argon arc/vacuum pressure casting machine. It has been suggested by Watanabe *et al.* (1991) that the flow of molten metal in this type of pressure casting machine is laminar and not turbulent like centrifugal casting machines. Therefore, the vertical relationship of the mold space may have allowed for the steady streamline flow of metal from the most distal edges back to the central sprue. The vertical relation may have also aided in the egress of gases, minimizing gas entrapment.

The overhead-direct (OD) design resulted in a sieve mean castability of 81%. Of all the designs examined, the overhead-direct configuration placed the sprue connections closest to the sieve areas. Ingate interfaces were positioned at the bases of the minor connectors, thereby minimizing the distance for the molten metal to travel to reach the sieve areas, thus resulting in a high castability value.

The overhead-direct (OD) method also showed greater than 85% mean castability of the acrylic retentive mesh areas and slightly greater than 96% mean castability for the major connector. Nevertheless, a large central void was present in the middle area of each major connector. It is believed these central voids were produced by a pincer-like advance of molten metal, which trapped gas centrally. In turn, the rapid cooling of the metal probably occurred before the retained gas could diffuse through the investment. Further investigation is needed to explain this occurrence.

Another concern with connecting the overhead-direct (OD) sprue to the pattern with a large sprue was the possibility of localized shrinkage or suck-back porosity. The large 6-gauge ingate sprue used in this study did not produce localized shrinkage porosity at the sprue connection.

The overhead-indirect (OI) design produced a mean castability of the major connector of 97%. However, the design's inability to permit casting of sieve and mesh areas resulted in poor mean castability values of 43% and 78%, respectively. Poor castability may have been due to the long, and narrow ingate sprues. These sprues also flared at the external interface. The flaring could potentially slow the flow of molten titanium and result in uncast sections. Furthermore, the overhead-indirect (OI) design required the molten metal to make three abrupt turns along its pathway to the pattern. Pathways with abrupt turns can result in investment erosion, dead spaces, premature cooling, decreased castability, and increased internal porosity (Suschil and Plutshack, 1988).

The gooseneck (G) design resulted in a very high mean castability value for the connector, 99.79%. However, its 55 mm x 5 mm long sprue proved to be inadequate to direct molten metal to peripheral areas. The castability of sieve and mesh mean areas dropped to values of approximately 50% and 77%, respectively. The poor castability of the sieve and mesh areas probably was due to the length of the sprue configuration and the narrow, 10 mm attachment to the wax pattern. The long and narrow sprue caused early metal solidification on the walls of the sprue, and resulted in a decrease the cross-sectional diameter of the ingating sprue. The decrease in sprue diameter caused a slowing of the molten metal and decrease the ability of the titanium to reach the distant areas. Furthermore, the decrease in sprue diameter diminished the reservoir of molten metal contributing to incomplete castings.

The wedge with flared attachment and casting aids (WA) resulted in a mean castability for the connector area of 97%. However, the sieve areas mean castability of 52.7% was significantly lower than the wedge and the overhead-direct methods. Possible reasons for the poor castability values could be related to the constriction of the ingating wedge at its connection with the central sprue. Molten titanium striking the constriction could cause investment erosion. Furthermore, the wide 20 mm wedge attachment element distal to the central sprue also may have created areas for eddies, or dead spaces, to occur. These two characteristics of the wedge with flared attachment and casting aids (WA) sprue design could result in decreased castability and increased porosity. As previously stated, it was important to have the pathway as direct as possible. Although the wedge with flared attachment and casting aids (WA) design appeared to be direct, in essence the constriction following the central sprue did not satisfy this requirement.

The wedge with flared attachment and casting aids (WA) configuration placed the pattern in a vertical relationship. The relationship would seem to allow for gas escape out the wedge ingate and central sprue area. However, when removing the ingate, considerable amounts of porosity were noted in this area. The porosity extended into the major connector. Further investigation is needed to determine the cause of the porosity at the sprue attachment.

The addition of casting aids did not seem to improve castability. The rationale for casting aids was to provide reservoirs of molten metal to feed the solidifying peripheral areas. Instead, the casting aids caused distortions in the acrylic mesh areas. The distortion appeared to be suck-back into the individual casting aids. The thickness of the casting aid caused metal to flow from the pattern into itself, instead of providing a reservoir for the pattern.

It is interesting that three miscasts occurred with the wedge with flared attachment and casting aids (WA) design. All three miscasts were due to mold splitting. The splits were all parallel to the pattern space. The most likely reason for the split molds was the increased size of the mold space due to the multiple casting aids and a large rounded central sprue. The large space resulted in a weakening of the mold in the long axis. When placed in the mold chamber and elevated with the jack, the splitting occurred. No other design caused mold splitting.

The ringless mold system was recommended by the investment manufacturer for use with the vacuum-pressure casting apparatus. However, to prevent mold breakage when casting a large pattern, the use of a casting ring may be necessary.

Upon recovery, all castings displayed a heavy scale layer. The scale indicated a reaction of the molten titanium with the investment. The removal of the scale by sandblasting resulted in very clean castings. Future investigations should continue to study investments, with a goal of minimizing the reaction of mold materials with molten titanium.

An important consideration when selecting a sprue design is the laboratory process necessary to fabricate the wax pattern, as well as to remove the sprues. A disadvantage of the overhead-direct (OD), overhead-indirect (OI) and wedge with flared attachment and casting aids (WA) designs was the increased laboratory time to fabricate, attach, and remove the sprues and casting aids from the specimens. The fabrication of the overhead-direct (OD) design was similar to standard RPD procedures. However, the overhead-indirect (OI) design required time to create the interface elements and attach the five ingates to the central sprue and interfaces. Moreover, removal of the five sprue attachments required appreciable care and time.

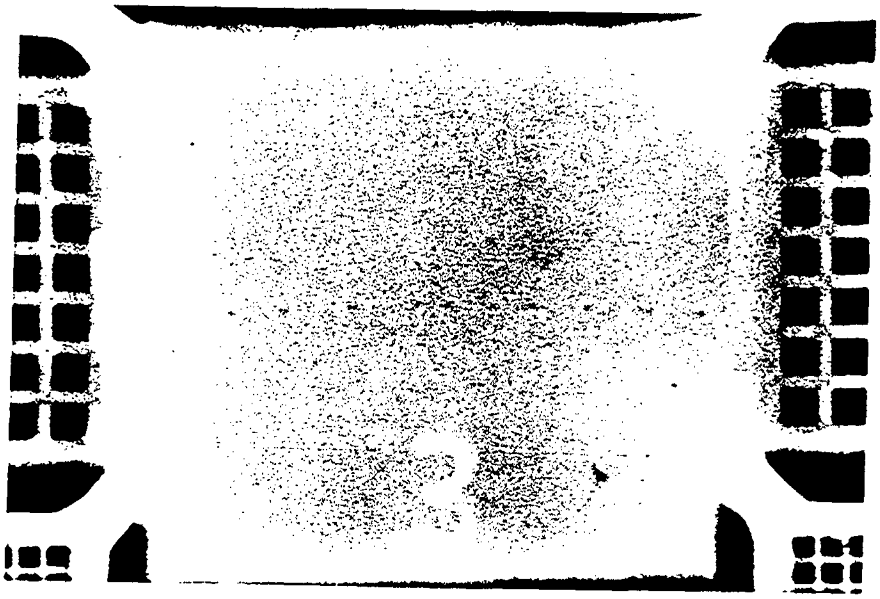
The wedge with flared attachment and casting aids (WA) design fabrication also required considerable time. Although the central sprue was relatively simple to attach, each of the casting aids required precise waxing techniques. Removal of the eight aids created a high potential for damage to the casting. The need for these aids may be questioned when examining the results. The advantage in the laboratory for using the wedge (W) or the gooseneck (G) sprue designs was the ease in fabrication, attaching, and removing sprues. The wedge (W) and gooseneck (G) designs required the least amount of time for fabrication.

Porosity

Previous studies have reported that titanium castings can have considerable amounts of porosity (Blackman *et al.*, 1994; Hero *et al.*, 1993; Voitik, 1991). Castings produced in the current investigation indicated a relatively low incidence of porosity (Figure 7, Plates 26 and 27). The low amount of porosity was in agreement with results presented by Yamauchi *et al.* (1988). Yamauchi and co-workers suggested that porosity generally was not serious enough to be damaging. Although the mean porosity values were not significantly different, isolated castings did show extreme amount of internal porosity (Plates 28 and 29). The total amount of porosity may be irrelevant, because the location of the defect would be more critical to the success of a prosthesis. Porosity occurring in the major connector might be inconsequential. However, if porosity was located at the proximal portions of the clasps, the probability of failure would be extremely high (Lewis, 1978).

Plate 26: Radiograph of Casting #3

Plate 27: Radiograph of Casting #13



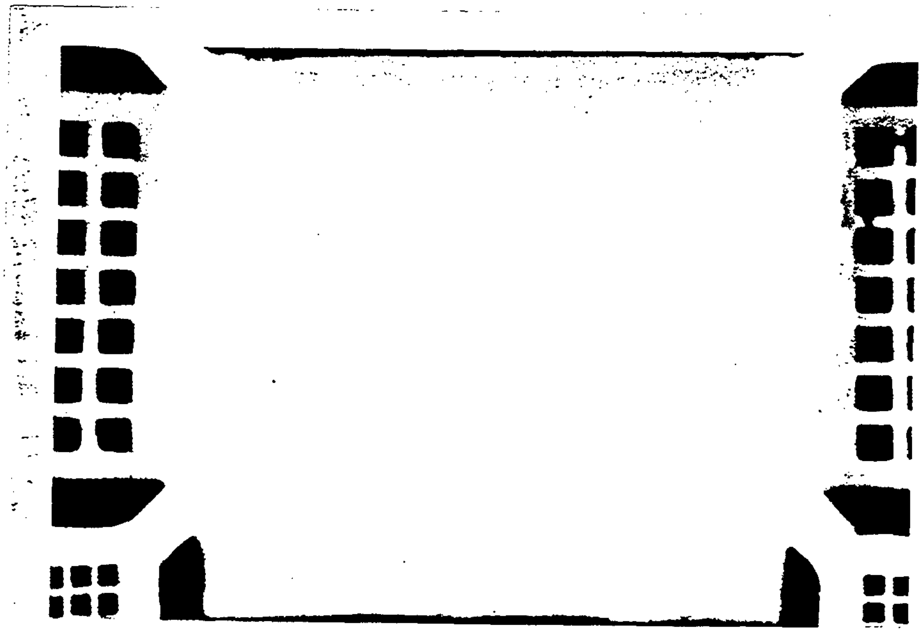
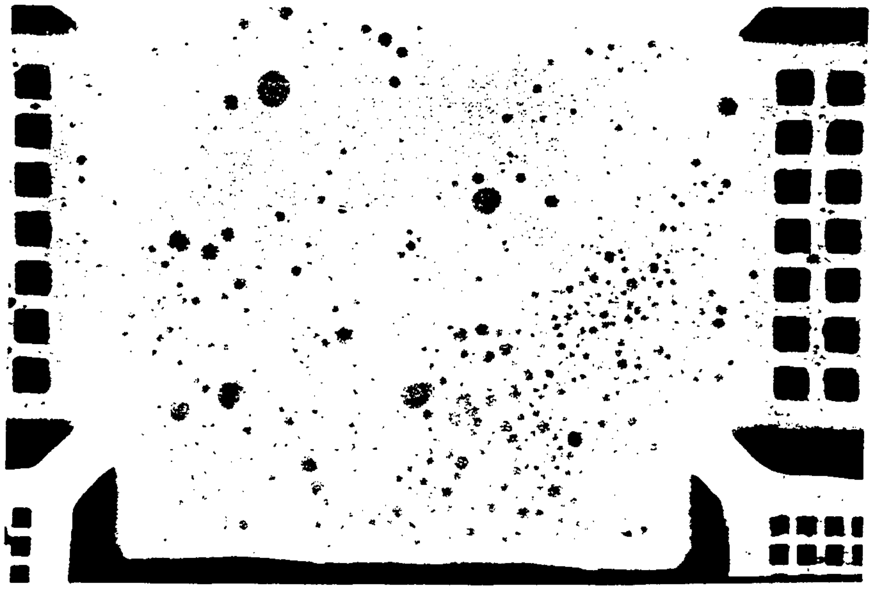


Plate 28: Radiograph of Casting #21

Plate 29: Radiograph of Casting #31



Mean porosity values ranged from 0.53% to 3.63%. Individual values ranged from a low of 0.003% to a high of 26.1% (Table 13). Similar values were reported by Miyazaki and Tamaki in 1992. The highest individual value, 26.1%, occurred with the wedge with flared attachment and casting aids (WA) method of spruing. The lowest individual value, 0.003%, occurred with the wedge (W) method of spruing. Suschil and Plutshack (1988) suggested areas of abrupt turns or moderate flaring may cause low-pressure or "dead" regions. These regions can cause air aspiration and entrapment. The wedge (W) design was funnel shaped up to its attachment to the pattern. The metal flow in this instance had no abrupt turns and little chance for the creation of "dead" regions. The overhead-indirect (OI), gooseneck (G) and wedge with flared attachment and casting aids (WA) sprue designs had notable areas of abrupt turns and flaring of the attachments. There was not a significant difference in mean porosity values among the different sprue designs.

Radiographic Evaluation

Titanium's low density allowed for non-destructive evaluation of internal defects with simple radiographic methods (ASTM Designation E1320, 1991; Mori *et al.,* 1993; Wang and Boyle, 1993). The radiographic film used had high resolution and permitted the detection of minute areas of porosity. It was visually noted that the majority of castings appeared to have completely cast sections. However, radiographs of these castings revealed that considerable amounts of internal porosity were present (Plates 28 and 29). Blackman *et al.* (1994) reported using machine settings of 70 kVp and 15 mA or 10 mA for radiographic assessment of titanium castings. Yamauchi *et al.* (1988)

evaluated a cast titanium plate of similar thickness to that used in this investigation, with radiographic machine settings of 80 kVp, 3 mA and a time of 0.8 seconds. However, in the current investigation, a pilot study found settings of 60 kVp, 15 mA, 12 impulses (12/60 seconds), film-focus-distance of 14 inches produced optimal image quality for the specimens examined.

Digital image analysis

Advantages of digital image analysis when evaluating the castability and porosity of castings were: 1) its exactness; and 2) the elimination of tedious counting methods (Cohen *et al.*, 1992). By digitizing images, evaluation areas consisted of picture elements (pixels). Although, all photographs of the wax patterns and the castings were made with the same camera and focus distances, it must be noted that there were unavoidable differences in image magnification due to photograph processing. The number of millimeters per pixel for the groups of images varied due to the time lag between wax pattern fabrication and casting completion.

However, using the 20 mm standard length of the wire, differences in images sizes could be determined, corrected, and compared on the same scale. The analysis method allowed for the detection of casting accuracies of less than 0.01 mm^2, unlike the segment counting method described by Hinman *et al.* (1985), which disregarded segments partially cast. The partially cast segments contain metal that should be included in the castability evaluation.

The use of digital image analysis for quantification of radiographic porosity was a new and simple method. The radiographic images displayed high contrast and adequate resolution. The total area, in pixels, of the casting was easily obtained by using the program's selection tool. Then by using magnification, 2 to 1, the image, small areas of porosity could be selected within the titanium castings, to less than 0.03 mm^2. By comparing the total area of the casting to the total area of porosity an accurate determination of the amount of porosity within the titanium castings was quantified.

Summary

The purpose of this investigation was to determine the effects of sprue design upon castability and porosity of titanium removable partial denture frameworks. Sprue design significantly affected the castability of the fine peripheral areas of titanium removable partial denture frameworks. Sprue design did not significantly effect the castability of large major connectors or acrylic retentive mesh areas. In addition, sprue design did not significantly effect the amount of casting porosity.

From this investigation five main conclusions can be drawn:

1) When casting titanium removable partial denture frameworks, it was important to have the central sprue in close proximity to the wax pattern.

2) To improve castability, the titanium removable partial denture framework wax pattern should be slightly thicker than the thickness of a nickel-chromium base metal framework pattern and more equivalent to thickness used for Type 4 gold frameworks.

3) It has been recommended for lightweight metals to use thinner and longer sprues. However, for casting titanium, larger diameter sprues appear to produce more

favorable results. It is suggested that ingating sprues be short. Sprues that are long, winding, and narrow should be avoided.

4) Results indicate the wedge and overhead-direct sprue designs significantly improve the castability of the fine peripheral areas. These areas represent clasp assemblies, a highly critical component of a removable partial denture.

5) Porosity does not seem to be a significant problem when casting titanium removable partial denture frameworks.

The castability test monitor used in this investigation proved to be an excellent design for evaluating the castability of titanium RPD frameworks. Digital image analysis is an exceptional method for quantification of castability and porosity. Finally, because porosity may be present in titanium castings at variable locations, non-destructive radiographic evaluation should be performed on all cast titanium dental prostheses.

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