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The influence of casting technique on elongation and other mechanical properties of low-ductility dental casting alloys

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A study was made of the effect of mould orientation on the mechanical properties of eight dental cobalt-chromium alloys prepared by centrifugal casting. In general, tensile test bars cast with their length horizontal rather than vertical to the induced gravitational field yielded superior elongation and ultimate tensile strength values. Proof stress was less affected by casting conditions.

1. Introduction

The cobalt-chromium casting alloys invented in 1907 were introduced into dentistry by Erdle and Prange in the 1930s [1] where they are used to fabricate partial dentures. Failure in service is generally attributed to lack of adequate ductility although evidence has been advanced to show that failure is associated with poor castings [2].

The determination of the mechanical properties of these alloys is fraught with problems and that of elongation, a measure of ductility, is particularly difficult. There are systematic errors attributable to variation of casting conditions and random errors consequent on the chance orientation of large crystals in a casting [1, 3-8].

These alloys are prepared by centrifugal casting using the lost wax process. One important variable in casting technique is the shape of the tensile test specimens and their sprue patterns. A number of these have been proposed [5, 9-15]. The present authors in a preliminary report [14] had made a recommendation on optimum test pieces and sprueing systems which was adopted by the British Standards Committee preparing a Draft British Standard specification for "Dental Base Metal Casting Alloys, Part 1: Denture Base Alloys" [16]. More recently in a study of sprue forms Scott and Bates [15] substantiated this recommendation. This present paper reports our findings in detail.

Preliminary investigations showed that the sprue design contained in the American Dental Association Specification no. 14 [10] where molten alloy flows into a narrow mould against an applied centrifugal force was not entirely satisfactory, and since the fraction of specimens fracturing at the change of section was found to be high, a systematic study was not attempted.

Proportional test pieces as defined in the British Standard Specification B.S.18 [17] gave only a small fraction of unsatisfactory fractures when cast and were adopted for this work.

Two sprue designs were examined corresponding to the wax pattern (or final cast) shown in Fig. 1a and b. In the former, the length of the specimen bars lie in the direction of the applied centrifugal force and these are described in this paper as vertically cast bars and the technique used as vertical casting. In the case of Fig. 1b, the specimen lies at right angles to the direction of the applied centrifugal force and is referred to here as horizontal casting yielding, as product, a horizontally cast bar.

2. Materials and methods

2.1. Specimen preparation

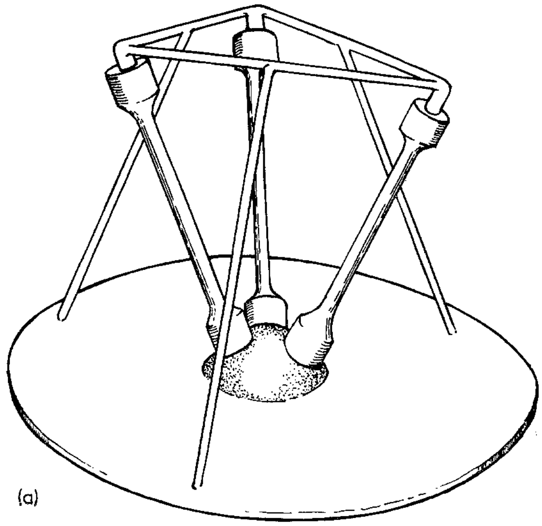
Test pieces having a cross-sectional diameter of 3 mm and a gauge length of 15 mm were fabricated from eight examples of commercial alloys (Table I) using a standardised procedure. Their dimensions corresponded to those of the proportional test specimens recommended in the British Standard Specification "Methods for tensile testing of metals Part 1. Non-ferrous metals" [17] and defined by the relationship:

Gauge length = 5.64 $\sqrt{}$(Original cross-sectional area).

Wax patterns of the test pieces were made by injecting wax* from a wax injection apparatus† at 70°C and 3500 N/m^2 into split brass moulds. Wax models were then prepared from three of these specimens (Fig. 1a and b) and treated with two coats of liquid investment‡ before being invested with a plaster§, contained by a open-ended cylindrical plastic former|| lined with asbestos paper, and set on a plastic base.

When the plaster had set, the plastic base, former and sprue-cone, but not the asbestos paper, were removed and the moulds placed in an oven held at 105°C. After 1 h, the temperature of the oven was raised to 220°C and held there for a further hour before the moulds were removed. By this time most of the wax from the moulds had drained away. Finally, the moulds were heated in a furnace to burn out residual wax and stored there at 1000°C for 1 h prior to casting operations.

Casting was carried out in a centrifugal casting machine with induction heating¶. The alloy charge, contained in a sillimanite crucible seated in the induction coil was pre-heated and the mould placed in position. The alloy was then melted and 5 sec after the shadow on the molten surface when viewed through a blue glass had disappeared, the induction coil was removed, the centrifuge started and the metal cast into the mould. After cooling overnight the cast specimens were removed from the mould, trimmed and sand blasted to a smooth finish. At least six specimens of each alloy were prepared for test. Each test piece was inscribed with six gauge marks along the length of the parallel portion so dividing it into five equal sections labelled b, c, d, e, f in Fig. 2.


(a)

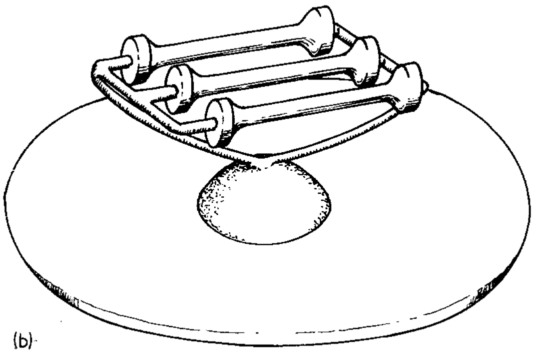

(b)

Figure 1 (a) Wax patterns for "vertically" cast bars (3 mm diameter). (b) Wax patterns for "horizontally" cast bars (3 mm diameter).

2.2. Measurement

Elongation, proof stress and ultimate tensile strength were taken from stress-strain curves recorded to fracture, a technique which is now made practical by the use of electronic extensometers and load cells coupled to an *X-Y* recorder [8]. Elongation was measured by deducting the component for elastic strain from the reading for the total strain at fracture. This is the method recommended in the Draft B.S.S. and is to be preferred to other methods for small specimen sizes of alloys low in ductility [8]. An extensometer with a span of 15 mm was employed and the test specimens were pulled at the rate of 0.5 mm min^{-1} in a screw-loaded tensile testing machine**. The position of fracture was recorded for each test specimen using the inscribed marks. Values for elongation obtained on bars which fractured in the shoulder regions "a" and "g" were rejected.

Some fractured test specimens were sectioned

*Fascim industrial wax 147/73, Wilkins Campbell and Co Ltd, Britannia Works, West Drayton.
†Nesorette 5, Nesor Products Ltd.
‡Liquid Investment, Fried. Krupp, Essen, Germany.
§Aqua Vest, Chaperlin and Jacobs, North Cheam, Surrey.
||Castoform Casting Rings, Fried. Krupp, Essen, Germany.
¶Williams Induction Casting Machine.
**Type TTCM Instron Universal Tester.

TABLE I Commercial alloys studied

Alloy	Name	Supplying agent	Composition*, wt %			
			Co	Cr	Ni	Mo
B	Wironit	Metrodent Ltd, Huddersfield	65	27	0.6	5.1
E	Croform 44	Davis, Schottlander and Davis, London	64	29	0.2	5.0
F	Niranium Hard	Dental (Surgical and Laboratory) Supplies Ltd, London	63	27	2.8	5.5
K	C and J No. 6	Chaperlin and Jacobs, North Cheam, Surrey	64	29	0.3	5.5
M	Virilium X	Virilium Co Ltd, Watford, Herts	64	26	2.4	5.4
N	Wisil	Panodent, London SE1	65	27	0.5	5.0
P	Wisil m	Panodent, London, SE1	66	26	0.5	5.6
U	Virilium S	Virilium Co Ltd, Watford, Herts	64	28	0.3	5.4

B.S. 3366 requires Co + Cr + Ni > 85%; Cr > 20%.
*By Atomic Absorption Spectrometry.

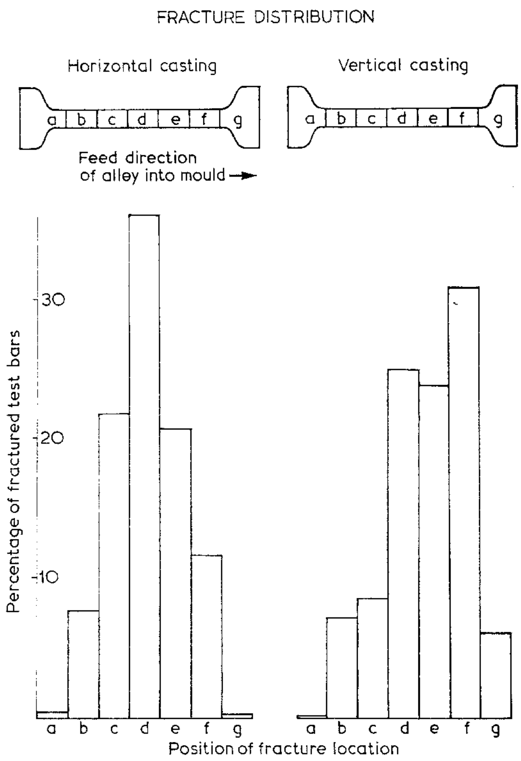


Figure 2 Histogram showing the distribution of the position of fracture along the axis of a test specimen, comparing "vertically" and "horizontally" cast bars.

longitudinally, mounted in opaque resin and polished for microscopic examination.

3. Results

3.1. Fracture distribution

A survey of the position of fracture of all test pieces are tabulated (Table II) and illustrated by the histogram (Fig. 2). These results show that the fracture distribution for vertically cast bars is skewed away from the feeder end and more scattered than is the case for horizontally cast bars; the proportion of bars breaking outside the centre section c, d, e is 43.3% compared with 10.9%, 5.9% breaking in the shoulder region. A microscopic examination of a shoulder fracture was made on a sectioned and polished specimen (Fig. 3). The location of the fracture is shown in Fig. 3a and porosity is clearly visible within the immediate area of the fracture (Fig. 3b and c). The porosity can be seen in the interstices of the dendritic growths (Fig. 3c).

3.2. Elongation

The results and statistics of the elongation measurements are presented in Table III. Values obtained when a specimen fractured in the shoulder regions (Fig. 2a and g) were rejected. Statistical analysis of results, using the Student's "t" test shows that horizontally cast bars have significantly higher mean elongation values than those cast vertically.

Some alloys appear to be more sensitive to casting conditions than others. Only in the case of alloy E was a significant difference found between variances (using the "F" test at the 5% level). The "t" test was applied although not strictly applicable.

3.3. Proof stress and ultimate tensile strength (UTS)

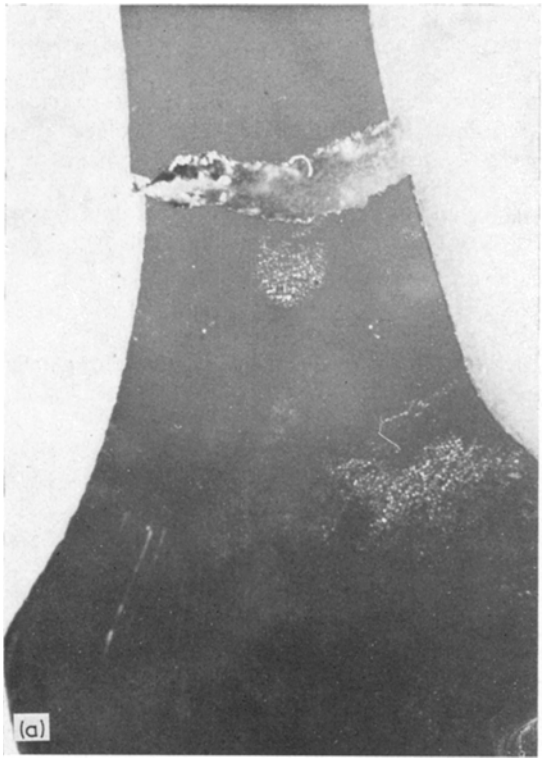
Values and statistics for 0.1 and 0.2% proof stress values are given in Tables IV and V. The "F" test (5% level) showed that for most alloys, casting conditions did not significantly affect the variance of results. The "t" test, when valid, was applied to the mean values obtained using both casting techniques and indicated that only in the case of alloy U were proof stress values demonstrably sensitive to casting conditions.

UTS values and statistics are given in Tables IV and V. The variance of results is unaffected by casting condition except in the case of alloy

TABLE II Fracture distribution

	Position of fracture							
	a*	b	c	d	e	f	g	Total
Test bars cast vertically								
No. of fractures	0	6	7	21	20	26	5	85
% of fractures	—	7	8	25	24	30	6	
Test bars cast horizontally								
No. of fractures	2	27	75	124	71	40	1	340
% of fractures	0.6	7.9	22.0	36.4	20.9	11.8	0.3	

*Feed end.



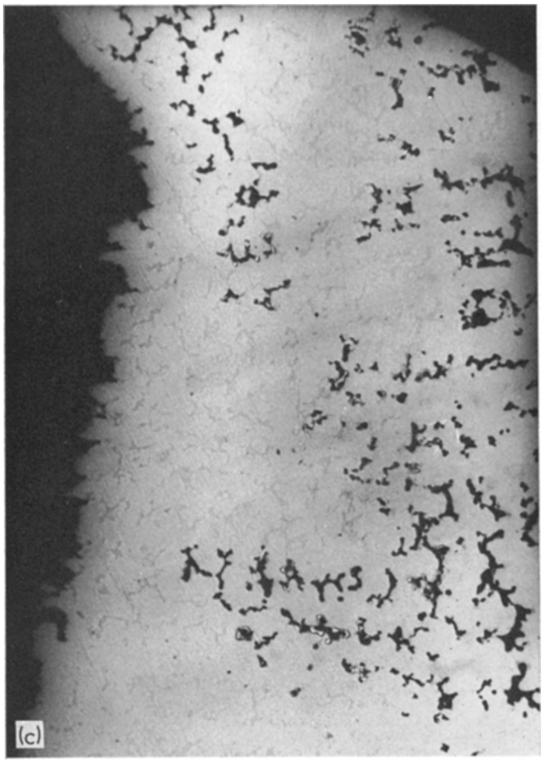


Figure 3 Photographs of a polished section showing the location of porosity near the line of fracture (a) general photograph of the area of study, (b) detail showing the area of porosity (1 mm across) and (c) detail within the area of porosity showing dendritic growth of crystallites. Note: diameter of the bar in (a) is 3 mm.

B. Mean values are significantly increased by a change from vertical to horizontal casting, although for alloy M the difference is only probably significant.

3.4. Correlation between elongation and UTS

In Fig. 4, individual values of elongation for alloy P are plotted against corresponding UTS values. Elongation is seen to be positively correlated with UTS. However comparisons between alloys show a negative correlation, the high elongation alloy M, having the lowest UTS (Tables III and IV).

4. Discussion

4.1. Fracture and elongation

Results show that horizontally cast bars exhibit improved fracture distribution characteristics over vertically cast bars. Since it is normal to

TABLE III Elongation values % and statistics

Alloy 3 mm bars	Statistics on all values: (1) Vertical casting, Mean value*	(1) Vertical casting, Coeff. of variation %	(2) Horizontal casting, Mean value*	(2) Horizontal casting, Coeff. of variation %	Comparison of means (1) and (2) Student's "t" test	Significance level
B	2.35 ± 1.02(6)	43.1	3.77 ± 1.42(6)	57.7	−1.99	nS
E	3.71 ± 2.19(8)	59.1	5.96 ± 1.11(20)	18.6	(−3.63)†	S
F	3.55 ± 1.22(18)	36.4	6.25 ± 1.21(17)	19.3	−7.06	hS
K	0.86 ± 0.37(6)	43.2	1.97 ± 0.59(6)	29.9	−3.90	S
M	6.54 ± 1.10(8)	16.9	8.81 ± 2.12(16)	24.1	−2.82	S
N	2.03 ± 0.97(5)	47.7	5.59 ± 0.71(18)	12.8	−9.19	nS
P	2.23 ± 0.57(9)	25.6	3.01 ± 1.14(8)	38.0	−1.82	hS
U	1.49 ± 0.54(6)	36.2	2.93 ± 0.84(15)	28.6	−3.86	S

*Includes best estimate of the population standard deviation.
Number of determinations on which mean values are based are given in parenthesis.
Significance code: hS = highly significant (significant at the 0.01% level)
S = significant (significant at the 0.1% level)
nS = not significant (not significant at the 5% level).
†"F" test indicated unequal variances.

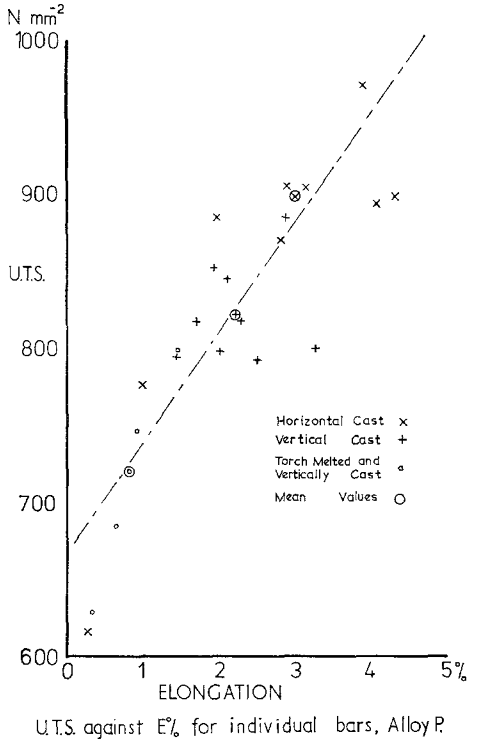


Figure 4 Correlation between elongation and UTS values for alloy P.

reject results from specimens which fracture outside the gauge length, adoption of horizontal casting is clearly advantageous. The skewed form of the fracture pattern for the vertically cast bars is an additional disadvantage and indicative of non-uniformity in cast bars. Taken together with the higher elongation values obtained with horizontally cast bars, these results strongly suggest that these bars contain fewer and more evenly distributed flaws.

4.2. Elongation and solidification

The higher values for elongation and improved fracture distribution shown by horizontally cast bars when compared with vertically cast bars is best explained by considering the mechanism of solidification. The controlling rate of solidification is the transfer of heat from the metal to the refractory mould so that the quantity of alloy deposited from the liquid phase is proportional to the specific heat of freezing of the deposited composition. As solidification of the alloy proceeds there will be accompanying changes in volume and a tendency for liquid to flow in order to compensate for volume changes. Since the metal alloy freezes by a dendritic mechanism, microporosity will result if the movement of the liquid phase is restricted. Thus microporosity is clearly inversely related to the ability of the liquid to flow.

To overcome this resistance to flow a driving force must be applied; under the conditions used for dental cobalt chromium alloys, this force is the hydrostatic head ot the metal which is a function of the induced centrifugal force. Its

TABLE IV Proof stress and ultimate tensile strength values (N mm^{-2}) and statistics

Alloy	Vertical casting						Horizontal casting					
	0.1% P.S. Mean, $\hat{\sigma}$	CV%	0.2% P.S. Mean, $\hat{\sigma}$	CV%	UTS Mean, $\hat{\sigma}$	CV%	0.1% P.S. Mean, $\hat{\sigma}$	CV%	0.2% P.S. Mean, $\hat{\sigma}$	CV%	UTS Mean, $\hat{\sigma}$	CV%
B	590 ± 70(6)	11.9	639 ± 53(6)	8.3	807 ± 41(6)	5.1	578 ± 23(6)	4.0	634 ± 24(6)	3.75	864 ± 14(6)	1.6
E	546 ± 40(8)	7.4	594 ± 35(8)	5.9	793 ± 38(8)	4.75	548 ± 29(21)	5.3	595 ± 27(21)	4.5	848 ± 35(20)	4.1
I	527 ± 36(18)	6.8	584 ± 30(18)	5.1	788 ± 46(18)	5.8	523 ± 30(18)	5.75	575 ± 25(18)	4.3	865 ± 56(17)	6.6
K	552 ± 21(6)	3.75	621 ± 10(6)	1.6	807 ± 31(5)	3.8	561 ± 29(6)	5.25	634 ± 26(6)	4.15	864 ± 38(6)	4.4
M	474 ± 29(8)	6.15	518 ± 23(8)	4.3	725 ± 29(8)	4.0	460 ± 58(17)	12.6	513 ± 43(17)	8.4	744 ± 45(6)	6.0
N	470 ± 39(5)	8.35	541 ± 31(5)	5.8	761 ± 27(6)	3.6	468 ± 69(18)	14.7	577 ± 26(18)	4.45	834 ± 37(18)	4.4
P	477 ± 75(9)	15.6	571 ± 48(9)	8.4	823 ± 32(9)	3.8	512 ± 66(9)	12.8	588 ± 40(9)	6.8	886 ± 55(8)	6.2
U	483 ± 46(6)	9.5	554 ± 33(6)	5.9	777 ± 58(6)	7.5	538 ± 44(15)	8.2	599 ± 35(15)	5.9	851 ± 36(15)	4.3

P.S. – Proof stress.
UTS – Ultimate tensile strength.
$\hat{\sigma}$ – Best estimate of population standard deviation.
CV% – Coefficient of variation, per cent.
Sample size is given in parenthesis.

TABLE V Student's "t" test applied to proof stress and UTS results

Alloy	0.1% Proof stress	0.20% Proof stress	UTS
B	NA	NA	NA
E	nS, −0.211 (27)	nS, −0.120 (27)	hS, −5.890 (26)
I	nS, +0.448 (34)	nS, +1.204 (34)	hS, −5.776 (33)
K	nS, −0.901 (10)	NA	S, −3.893 (9)
M	NA	nS, +0.741 (23)	pS, −2.277 (22)
N	nS, +0.181 (21)	S, −2.921 (21)	hS, −4.298 (22)
P	nS, −1.305 (16)	nS, −0.985 (16)	hS, −4.998 (15)
U	hS, −4.192 (19)	hS, −4.663 (19)	hS, −4.579 (22)

NA, "F" test (5% level) showed that the "t" test was not applicable.
hS, highly significant (0.1% level).
S, Significant (1% level).
pS, probably significant (5% level).
nS, not significant at 5% level.
Degrees of freedom are given in parenthesis.

value depends on the effective acceleration G of the mould. Simple compensation for volume contraction continues until the dendritic growth fronts nearly meet; thereafter, the length of bar which is fully fed is controlled by the inter-dendritic spacing and the viscosity of the liquid alloy. This is the point at which the orientation, proportion and feeding of the bars becomes critical. For the proportional test bar, the parallel portion fed from one end presents an initial aspect ratio (length/diameter) of about 6:1; this ratio increases rapidly as freezing progresses. The bars quoted in the present ADA specification and B.S. 3366 have an initial aspect ratio of 16.4:1 and have a shorter feeding time, due to the smaller section; these are noted for premature failure, often breaking close to the change in section. The horizontal bar, being fed from both ends, has its effective aspect ratio halved. The effect of the higher aspect ratio of the vertically fed bar is that the flaw concentration as indicated by the fracture distribution histogram is concentrated in the lower portion of the bar away from the feeder head. The flaws, i.e. microporosity, develop once the pore size between the dendrites prevents the flow of liquid alloy along the full length of the bar due to the viscosity of the molten metal. The lower portion of the bar then freezes as a closed system with porosity concentrated in the lowest portion of the gauge length. A secondary factor is that the horizontal bar is subjected to a more uniform effective force and a higher than the mean force for the vertical bar.

4.3. Proof stress and UTS

UTS, like elongation, another property measured at fracture, is markedly affected by changes in orientation of casting. Both are influenced by flaws such as microporosity and grain-boundary films which limit both ductility and strength at fracture and are reduced by horizontal casting. This correlation between these two properties is illustrated by results shown in Fig. 4 and Table IV where UTS increases with elongation for a single alloy of fixed composition.

It is important to distinguish between this positive correlation found for individual results from a single alloy with the inverse relationship obtained when comparing these properties in different alloys [17]. When the alloy composition is changed, improved elongation is usually obtained at the expense of UTS (this is different from the effect of flaws). Of course under certain conditions the composition of an alloy could be changed during casting – loss or gain of carbon – thus affecting the positive correlation found here.

Proof stress is not a fracture parameter but a property of the structure of the casting which is little influenced by flaws, hence it is to be expected that its value is less affected by charges in casting technique.

5. Conclusions

The orientation of the mould for a specimen and its feeds when centrifugally casting dental cobalt chromium alloys by the lost wax process is important. Properties associated with fracture, elongation UTS and fracture distribution are, for most alloys, significantly improved when the length of the cast specimen or its mould lies at right angles to, rather than in-line with the centrifugally induced force. This phenomenon is attributed to the presence of flaws which have a similar effect on all fracture properties and whose concentration is reduced by casting horizontally. The concentration of flows can be seen as a function of the restriction of flow of the liquid which tends to compensate for the contraction of the alloy while it is freezing. Proof stress which is not a fracture property is less influenced by casting technique, although alloys differ in this respect.

In dental specification testing, mould orientation is a factor which must be defined. Improved casting techniques will ensure that the full potential of the material, in this case elongation and UTS, can be achieved. These findings may be important in the design of dental appliances and perhaps outside the field of dentistry as well.

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