Chapter 34

BIOACTIVE GLASS-CERAMICS FOR LOAD-BEARING APPLICATIONS

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34.1. INTRODUCTION

One of the great challenges in biomaterials is developing a material that matches the biomechanical properties of bone and also has sufficient bioactivity to bond to living bone and soft tissues.[1,2] Biocomposites come close to achieving this goal but have been limited in clinical applications due to unstable interfaces between the phases, as discussed in Chapter 26. Another approach has been to improve the mechanical properties of bioactive ceramics by making a glass-ceramic, such as the A/W glass-ceramic (for example Cerabone®), discussed in Chapters 13 and 14. The high strength and high toughness of the A/W glass-ceramic makes it a load-bearing replacement for cortical bone loaded under compression. A/W glass-ceramic has been used successfully in more than 60,000 clinical cases, including vertebral replacement and iliac crest repair (Chapter 14). However, its elastic modulus is about one order of magnitude higher than that of cortical bone, giving rise to the possibility of long term stress shielding when the material is used as a bone replacement (Chapter 1).[3] Also, the level of bioactivity of A/W glass-ceramic is insufficient for bonding to soft connective tissues,[4] as needed for some clinical applications. This chapter describes a new approach to achieving high strength, high toughness glass-ceramics with bioactivity equivalent to the grandfather 45S5 bioactive glass.[1,2,5]

34.2. BIOACTIVE GLASS-CERAMIC COMPOSITIONS

The effects of crystallization on the *in vitro* activity of osteoblast cultures in simulated body fluid (SBF), in animals and humans, of monolithic and powdered glass-ceramics of the system P_2O_5–Na_2O–CaO–SiO_2 have been developed to exhibit similar levels of bioactivity as the "gold standard" 45S5 Bioglass.®[1,2,4,6] Glasses within the composition range $1Na_2O$–2CaO–$3SiO_2$ and $1.5Na_2O$–1.5CaO–$3SiO_2$ with 0-6% P_2O_5 showed that crystallization slows down, but does *not* inhibit, the development of a crystalline hydroxycarbonate apatite (HCA) layer, even on

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Table 34.1. Glass Compositions Studied (wt%).

Component	SiO_2	Na_2O	CaO	P_2O_5
1.07N2C3S	50.3	18.5	31.3	
1.5N1.5C3S	50.5	24.8	24.8	
1.5N1.5C3S + 4P	48.5	23.8	23.8	4.0
1.5N1.5C3S + 6P	47.5	23.2	23.2	6.0

fully crystallized glass-ceramics of these compositions.[1,2] Table 34.1 summarizes some of the glass compositions studied.[5]

34.3. *IN VITRO* TESTS OF BIOACTIVITY

The range of onset time for crystallization of HCA in *in vitro* tests using SBF-K9 varied from 8 h for a $1.5Na_2O–1.5CaO–3SiO_2$ glass containing 6% P_2O_5 to 32 h for a fully crystallized $1.07Na_2O–2CaO–3SiO_2$ glass-ceramic without phosphorous.[1,5] Nonetheless, *in vitro* HCA layer formation on these glass-ceramics, even for the least bioactive, is much faster than on partially- or fully-crystallized commercial bioceramics, such as sintered hydroxyapatite (HA) and A/W (Cerabone®), which usually takes at least seven days.[2] Peitl *et al*. concluded that two simultaneously-acting factors are responsible for the high bioactivity level of these glass-ceramics: a highly-soluble crystal phase (1N2C3S) and the existence of phosphorus ions in substitutional solid solution, which are able to be readily released from the crystal structure.[1,2] Both factors contribute to a faster HCA layer formation on glass-ceramics of this system by the same five stages of surface reaction mechanisms observed for the 45S5 Bioglass®, described in Chapter 3.

All five surface reaction stages go to completion within two–five hours for glasses and glass-ceramics of highest bioactivity in this system.[1–6]

34.4. MECHANICAL PROPOERTIES OF GLASS-CERAMICS: GENERAL

There is a large literature describing the mechanical properties of different types of glass-ceramics.[7–14] However, effects of the crystallized volume fraction at *constant* grain size and of varying grain size with *constant* crystallized volume fraction on mechanical properties of glass-ceramics have seldom been investigated. There are only a few studies of mechanical properties of bioactive glass-ceramics. Several papers compare the mechanical behavior of the parent glasses

with (almost) fully crystallized glass-ceramics but do not consider partially-crystallized glass-ceramics of varied microstructure.[7–9] Some studies compared the mechanical behavior of glass-ceramics, varying the crystal size for a fixed volume percentage of crystal phase, whereas others describe the effect of volume fraction of crystal phase, but neglect the crystal size effect.

In this work, we studied *independently* two important microstructural factors that affect the material's mechanical behavior: crystalline volume fraction (at constant crystal size) and crystal size (at constant crystallized volume fraction). Production of tailored microstructures by controlling internal nucleation and growth (and the resulting level of internal residual stress) was the biggest challenge. This study is the first to focus on these two interdependent microstructural effects, plus the possible effect of residual stress on the mechanical behavior of glass-ceramics in general and bioactive glass-ceramics in particular.[5] Our goal is to obtain an optimized bioactive glass-ceramic that combines improved mechanical properties, such as relatively low elastic modulus, high fracture strength and relatively high toughness, with a bioactivity level comparable to that of 45S5 Bioglass®. Successful development of these mechanical and bioactivity properties in a fine-grained bioactive glass-ceramic resulted in a patent filed in the USA and in the European Community.[15] Recent efforts describe the optimized mechanical properties and interpretation of the mechanical behavior of this glass-ceramic system.[5]

34.5. EXPERIMENTAL PROCEDURES

High purity silica and reagent-grade calcium carbonate, sodium carbonate and sodium phosphate were used to obtain glasses of approximate compositions 1.07N2C3S and $1.5Na_2O–1.5CaO–3SiO_2$, with 0, 1, 2, 4 and 6 wt% P_2O_5. The exact nominal compositions are given in Table 34.1. Details are given in the references1, 2, 5 and 15. The strategy used to study and control crystallization follows that proposed by Kalinina and Filipovich,[16] who employed a two-step heat treatment to measure nucleation rates. The procedure consists of growing the nuclei formed in the first step by a second heat treatment at a higher temperature.[1,2,5]

Crystal growth rates were determined by optical microscopy, considering the size of the biggest crystal (the *primogenitus*) as function of time and temperature of the second treatment. Measurements were taken on polished and hydrofluoric acid (HF) etched surfaces. Table 34.2 shows the range of temperatures and times used to develop the desired microstructures. The glass-transition temperatures (*Tg*) were determined using differential scanning calorimetry (DSC) to study the effect of P_2O_5 content on the nucleation rates. From the DSC curves, the Hruby parameter *KGL* was calculated to estimate the glass stability against crystallization during heating.[5]

Table 34.2. Thermal Treatment Ranges Used to Produce Different Microstructures for the Compositions Studied.

Composition	Nucleation		Growth		Volume (%)
	T (°C)	t (min)	T (°C)	t (min)	Crystallized
1.07N2C3S	600	960	690	60	100
1.5N1.5C3S	520–560	3–180	620–640	6–22	10–100
1.5N1.5C3S +4P	540–590	30–6000	650–700	5–80	5–100
1.5N1.5C3S +6P	540–590	60–9000	650–700	10–70	10–100

Some mechanical properties — flexural strength, elastic modulus, microhardness and indentation fracture toughness — were measured using rectangular bars with dimensions of $5 \times 3.5 \times 35$ mm^3. The effect of the crystalline volume fraction with a constant grain size was evaluated for five different percentages of crystals, 0, 15, 34, 60 and 100%, with an average grain diameter of 13 μm (with a very narrow grain size distribution). For the crystalline volume fractions that presented the best flexural strength and indentation fracture toughness, we developed thermal treatments to produce microstructures having the widest possible range of crystal sizes without adding any nucleating agent. In this way, microstructures with crystal sizes in the range 5–21 μm and with constant crystalline volume fraction had their mechanical properties investigated.[5]

34.6. MECHANICAL PROPERITES OF OPTIMIZED BIOACTIVE GLASS-CERAMICS

Bioactive glasses having chemical composition between $1Na_2O$–$2CaO$–$3SiO_2$ (1N2C3S) and $1.5Na_2O$–$1.5CaO$–$3SiO_2$ (1N1C2S), containing 0, 4 and 6 wt% P_2O_5, were crystallized through double-stage thermal treatments. By carefully controlling these treatments it was possible to separate and optimize the effects of two important microstructural features, crystallized volume fraction and crystal size, on the mechanical properties. Fracture strength, elastic modulus and indentation fracture toughness were measured as a function of crystallized volume fraction for a *constant* crystal size. Glass-ceramics with crystalline volume fraction between 34 and 60% exhibited improvement of three times in fracture strength, as illustrated in Fig. 34.1, and an increase of 40% in indentation fracture toughness compared with the parent glass.[5]

For the optimal crystalline concentration (34 and 60%), these mechanical properties were then measured for *different* grain sizes, from 5 to 21 μm. The

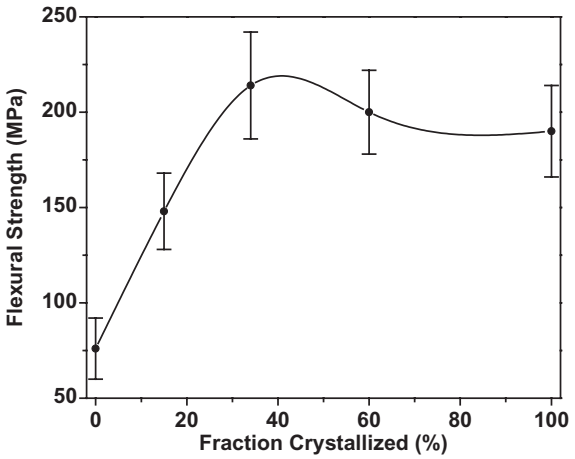

Figure 34.1. Dependence of flexural strength on percent crystallinity for 1.5N1.5C3S+4P glass-ceramics with 13 μm crystal size.

glass-ceramic with the highest fracture strength and indentation fracture toughness had 34% crystallized volume fracture and 13 μm crystals, as shown in Fig. 34.2.[5] Compared to the parent glass, the average fracture strength of this glass-ceramic was increased from 80 MPa to 220 MPa, which is substantially greater than the flexural strength of cortical bone. The indentation fracture toughness increased from 0.60 to 0.95 MPa.m$^{1/2}$, as discussed in Peitl *et al*.[5]

The increase in indentation fracture toughness was analyzed with different theoretical models, which demonstrated that it is due mainly to crack deflection. Residual stresses do not significantly contribute to toughening; in fact they cause a decrease in toughness at low volume fraction of crystals due to the increased average tensile stresses in the glass matrix.[5] The estimated fracture toughness of our 34% crystallized glass-ceramic is about half that of commercial glass-ceramics A/W and Bioverit, but it is twice as large as that of 4555 Bioglass®. The partially-crystallized bioactive glass-ceramics with high strength and high toughness are reasonably machinable; i.e. they can be easily cut or drilled by a surgeon using a hand tool with no cracking or spalling. Importantly, the bioactivity level is equivalent to that of the gold standard 45S5 Bioglass® and by far the highest of all glass-ceramics.[2]

Fortunately, the elastic modulus, *E*, of the optimized bioactive glass-ceramic increased only slightly, from 60 to 70 GPa, for the strongest glass-ceramic with 34% crystal phase, as shown in Fig. 34.3. This is an important finding since the *E* of biomaterials should be as close as possible to that of

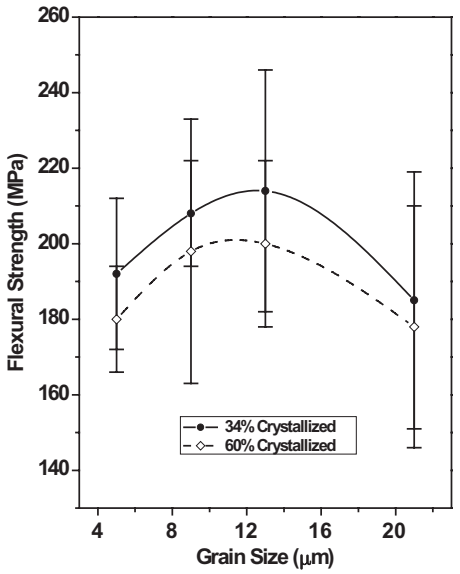

Figure 34.2. Flexural strength (S_F) for 1.5N1.5C3S+4P partially-crystallized glass-ceramic, as function of the crystal size. Solid line = 34% crystallinity, dotted line = 60% crystallinity.

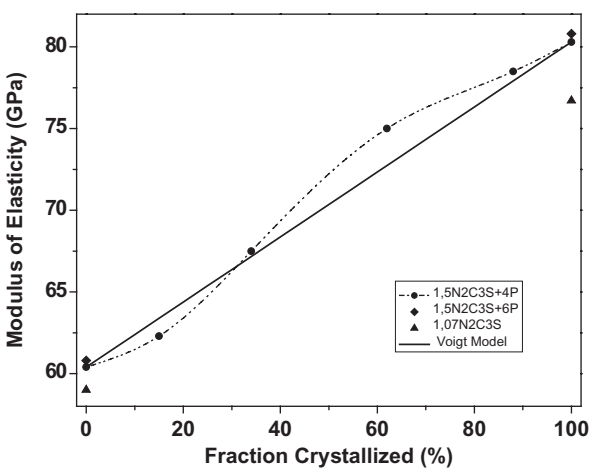

Figure 34.3. Young's modulus as function of volume percentage of crystallinity for three compositions.

cortical bone to avoid stress shielding in load-bearing applications. Thus, the best glass-ceramic is a unique bioactive ceramic that combines excellent mechanical properties with a high level of bioactivity. Clinical trials of this biomaterial are now underway.[17,18]

34.7. CONCLUSION

The flexural strength of the optimized bioactive glass-ceramic is significantly greater than that of cortical bone and comparable to that of apatite-wollastonite (A/W) bioactive glass-ceramic, which has been used successfully in orthopedic compressive load-bearing applications for decades. The optimized bioactive glass-ceramic described in this chapter has the advantage that it exhibits a much lower elastic modulus than A/W glass-ceramic and has an elastic modulus similar to that of cortical bone. The level of bioactivity of the partially-crystallized glass-ceramics that exhibit high strength and toughness is equivalent to that of 45S5 Bioglass®. These results thus demonstrate that it is possible to design bioactive glass-ceramics with improved microstructures that should be possible to use clinically in flexural as well as compressive load-bearing applications. However, prior to extensive clinical trials it is necessary to conduct studies of static and dynamic fatigue of these materials in simulated clinical load-bearing environments to ensure that the mechanical properties do not degrade over time.

ACKNOWLEDGEMENTS

The authors are grateful to Brazilian funding agencies CNPq, Capes (NanoBiotech research network) and Fapesp (Thematic grant # 07/08179-9).

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