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## Nanogels as a Basis for Network Construction

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### Summary

Reactive nanogels with diverse chemical and physical compositions were synthesized using solution free radical polymerization. Conventional monomer resins show a reduction in polymerization shrinkage and stress as well as improved bond strength when nanogels are used as a filler. Nanogels dispersed in inert solvent at appropriate concentrations form macroscopic networks with chemical compositions that are not directly available from the starting monomers.

### Keywords

mechanical properties; nanogels; shrinkage stress

### Introduction

Nanogels are globular polymeric nanoparticles with a characteristic internal network structure with overall dimensions well below 100 nm. Significant attention has been devoted to nanogels as multifunctional drug delivery systems due to their tunable chemical and physical properties.<sup>[1,2]</sup> More recently, investigation into the gel-like behavior of nanoparticle solutions<sup>[3]</sup> and the incorporation of micro/nanogels into polymeric macrogels,<sup>[4–6]</sup> has prompted further investigation into the use of nanogels as building blocks in polymer networks. We report on the free radical polymerization of mono- and di-(meth)acrylate monomers in solution with a sufficient quantity of chain transfer agent to prevent macrogelation to obtain discrete, high molecular weight, highly crosslinked structures.<sup>[7]</sup> Choosing monomers of varying polarity and modifying the ratio of mono- to divinyl and chain transfer agent concentration as well as solvent choice and content allows for control over nanogel properties such as size, branching density, and glass transition temperature. The inclusion of secondary functionality permits further post-polymerization modification such as the addition of reactive sites. Nanogels synthesized using this design strategy can be dispersed in monomer resins or in inert solvent to form networks with chemical and physical properties that are not directly available using conventional monomers.

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## Materials and Synthesis

Solution polymerization of multifunctional monomers will lead to macroscopic network formation unless primary cyclization and intramolecular crosslinking is sufficiently favored over intermolecular interactions.<sup>[8]</sup> Applying a thiol-based chain transfer agent to limit the primary chain length and choosing an appropriate solvent content results in the formation of nanogels. We have investigated isobornyl methacrylate (IBMA), hydroxyethyl methacrylate (HEMA), and ethoxylated hydroxyethyl methacrylate (EHEMA) as monovinyl components along with divinyls including urethane dimethacrylate (UDMA), ethoxylated bisphenol-A dimethacrylate (BisEMA), tetraethylene glycol dimethacrylate (TTEGDMA), and longer polyethylene glycol dimethacrylate (PEGDMA) to produce nanogels with varying solubility parameter, modulus, and glass transition temperature ( $T_g$ ). Including a heterofunctional thiol results in a high concentration of chain end functionality. For example, choosing mercaptoethanol (ME) places primary alcohols at chain ends which allows for facile incorporation of methacrylate groups using isocyanatoethyl methacrylate (IEM). Methyl ethyl ketone was used as a solvent, typically in four or six-fold volumetric excess, and azobisisobutyronitrile (AIBN) was used as thermal initiator in the synthesis. Characterization of hydrodynamic radius and molecular weight is conducted using triple detection gel permeation chromatography, which typically reveals particle sizes of 3–50 nm and molecular weights of  $10^4$ – $10^7$  Da with polydispersities ranging from less than 2 to more than 10.

## Nanogel-Modified Networks

The ability to create nanogels with diverse chemical and physical compositions leads to polymer networks with a wide range of final properties. The  $T_g$  of nanogels can be readily adjusted based on both monomer selection and the polymerization process (Figure 2). This leads to the potential to significantly affect local network properties and final polymer conversion. It is therefore critical to tailor nanogel properties according to the final material application.

High  $T_g$  nanogels based on IBMA and UDMA or BisEMA in particular have demonstrated potential for the improvement of polymeric dental adhesive performance. Conventional resins containing a mixture of hydrophobic BisGMA and more hydrophilic HEMA experience water-induced phase separation when applied to a wet tooth, which results in a water-rich HEMA phase with very low crosslinking density.<sup>[9]</sup> The addition of nanogels to the resin demonstrated an increase in bond strength due to copolymerization with the infused monomer and formation of a secondary overlapping network structure. Nanogels have further application in mitigating polymerization stress in dental resins. The polymerization of conventional monomer resins to yield glassy polymeric networks typically leads to the development of significant levels of volumetric shrinkage-induced stress.<sup>[10]</sup> The design of nanogels with particular size and functionality as well as the variation in the loading level used results in control over the interfacial surface area and rate of polymerization between the matrix monomer and nanogel phases. Nanogel addition potentially provides enhanced polymerization rates with increased limiting conversion while significantly reducing both the rate and extent of polymerization stress development (Figure 3).

## Nanogel-Based Networks

Reactive nanogels dispersed in inert solvent at concentrations at or exceeding the percolation threshold allow covalent inter-particle connections to be formed efficiently through photopolymerization to give monolithic network structures. The final network structure and density depends on the composition of the nanogel, nanogel loading level, and nanogel reactive group concentration. This approach to network formation results in densely crosslinked systems formed from components that individually may be incompatible in solution. A monomeric mixture of EHEMA10 and BisEMA, in 70:30 molar ratio, phase separates with the addition of approximately 8% water, and polymerization-induced phase separation occurs at even lower water content. However, a nanogel formed of the same monomer composition is fully miscible in water prior to polymerization and forms transparent, homogeneous polymers.

Nanogels formed from hydrophobic crosslinkers typically require copolymerization with quite hydrophilic monomers such as EHEMA10 for water compatibility (Figure 4) and will readily disperse into ethanol or acetone when EHEMA5 or HEMA are used as the monovinyl. Depending on size and functional group concentration, loading levels as low as 10 wt% but more commonly 15–30 wt% are sufficient to reach a percolation threshold and produce a continuous network, with nearly quantitative conversion occurring at nanogel loading of 50 to 70 wt% (weight and volume fractions are nearly equivalent for nanogels added to most monomers or solvents). The use of an inert, low-toxicity carrier to form networks with tunable chemistry and minimal extractables (Figure 5) makes nanogel-based materials attractive candidates for adhesives and coatings that function in aqueous environments.

## Conclusion

Solution free radical polymerization is a versatile route for the production of nanogels from a wide range of monovinyl and divinyl monomers. Control over the chemistry and branching density allows for selective control over the nanogel glass transition temperature and reactive group concentration. Nanogel-modified polymer networks display decreased shrinkage stress and improved bonding in adhesive formulations. Nanogels dispersed in inert solvent can be polymerized to high conversion and form highly cross-linked networks while avoiding water-induced phase separation.

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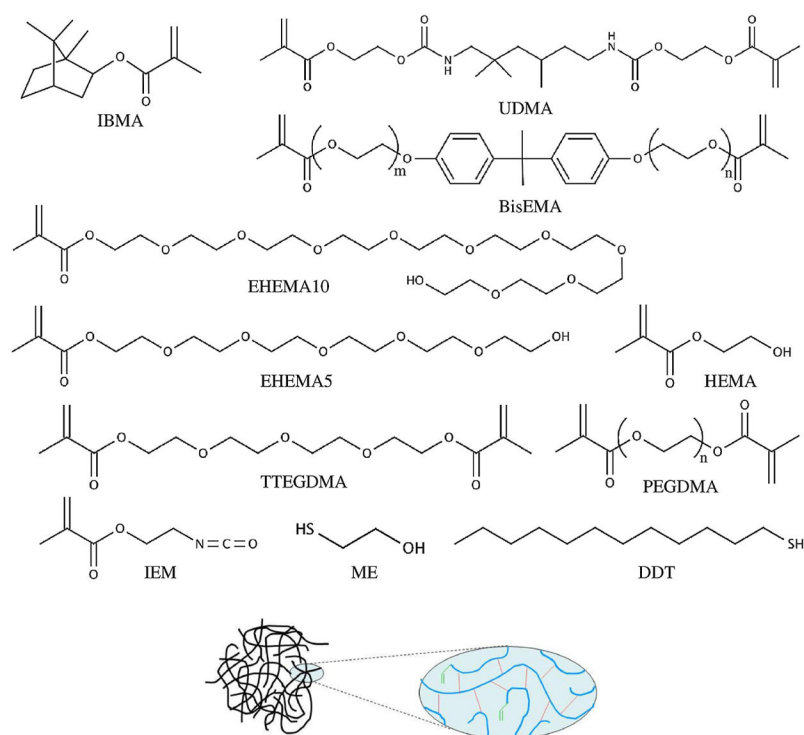
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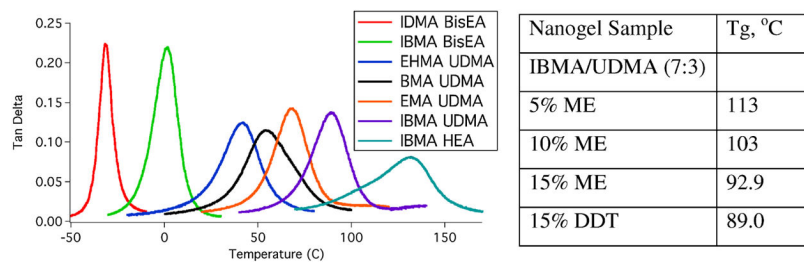
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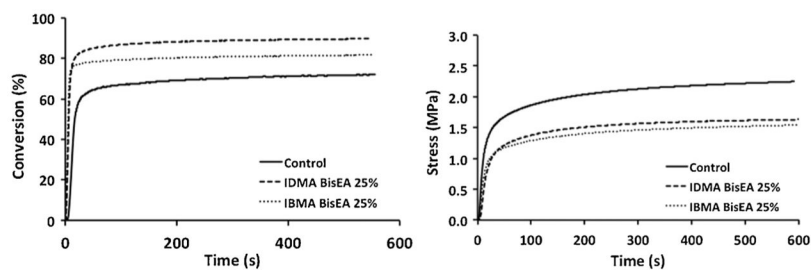


**Figure 1.** Monovinyl, divinyl, and thiol monomers used in nanogel syntheses with a schematic of an internally crosslinked nanogel with chain-end methacrylate functionality.

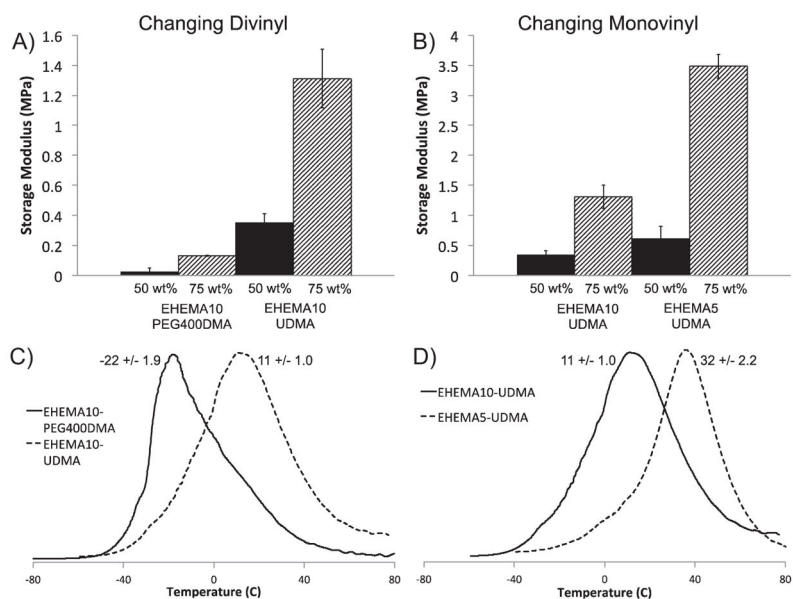


**Figure 2.**

DMA-based  $\tan \delta$  and  $T_g$  of bulk nanogels as a function of monomer composition or chain transfer agent concentration used during synthesis. The monomers used are isodecyl methacrylate (IDMA), ethoxylated bisphenol A diacrylate (BisEA), isobornyl methacrylate (IBMA), 2-ethylhexyl methacrylate (EHMA), urethane dimethacrylate (UDMA), butyl methacrylate (BMA), ethyl methacrylate (EMA), and a hybrid acrylate/methacrylate prepared by the reaction of hydroxyethyl acrylate (HEA) with isocyanatoethyl methacrylate (IEM).

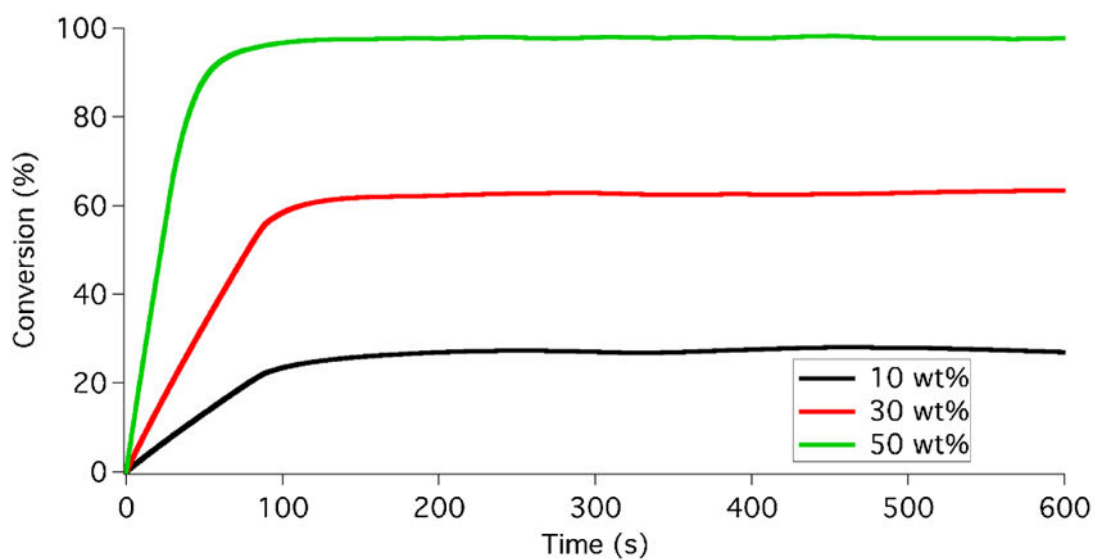


**Figure 3.** Real-time conversion and polymerization stress profiles for the photopolymerization of ethoxylated bisphenol A dimethacrylate/triethylene glycol dimethacrylate (7:3 by mass; control) and the same resin with 25 wt% added nanogel prepared from either IDMA or IBMA with BisEA.



**Figure 4.** A: Storage modulus of networks formed from EHEMA-PEG400DMA or EHEMA-UDMA dispersed in water at 50 or 75 wt%. B: Storage modulus of networks formed from EHEMA-UDMA dispersed in water or EHEMA5-UDMA dispersed in ethanol at 50 or 75 wt%. C,D: Tan delta curves and glass transition temperatures of networks formed from EHEMA-PEG400DMA or EHEMA-UDMA dispersed in water or EHEMA5-UDMA dispersed in ethanol at 50 wt%. All materials were formed using 1 wt% Irgacure 2959 as photoinitiator and irradiated at 10 mW/cm<sup>2</sup>.





**Figure 5.** Methacrylate conversion monitored using real-time infrared spectroscopy for 10, 30, or 50 wt% EHEMA10-BisEMA in water. All materials were formed using 0.1 wt% Irgacure 2959 as photoinitiator and irradiated at 10 mW/cm<sup>2</sup>.