Self-Healing Metallo-Supramolecular Hydrogel Based on Specific Ni^{2+} Coordination Interactions of Poly(ethylene glycol) with Bistriazole Pyridine Ligands in the Main Chain

Xiaowen Xu, Valentin Victor Jerca, and Richard Hoogenboom*

In this study, a supramolecular hydrogel formed by incorporating the 2,6-bis(1,2,3-triazol-4-yl)-pyridine (btp) ligand in the backbone of a polymer prepared by copper(I)-catalyzed alkyne-azide cycloaddition (CuAAC) "click" polyaddition reaction of 2,6-diethynylpyridine and diazido-poly(ethylene glycol) is reported. The hydrogelation is selectively triggered by the addition of Ni^{2+} ions to aqueous copolymer solutions. The gelation and rheological properties could be tuned by the change of metal to ligand ratio and polymer concentration. Interestingly, the hydrogel exhibits a fast (within 2 min) and excellent repeatable autonomic healing capacity without external stimuli. This self-healing behavior may find potential applications for the repairing of metal coatings, in the future.

Supramolecular interactions such as hydrogen bonding,[1,2] host–guest interaction,[3–5] metal–ligand coordination,[6] and ionic interaction[7] have been considered as important forces in the construction of some natural phenomena and life process.[8–10] The most famous example in the supramolecular field was the discovery of the double helix DNA, where two separate strands of nucleotides are connected through hydrogen bonds.[11] Generally, such supramolecular interactions provide dynamics and directionality, and hence provide high accuracy in construction of molecular architectures.[12–14] Recently, the use of stable, yet thermoreversible metal–ligand coordination interactions for constructing supramolecular structures has received considerable attention.[15–17] Materials constructed based on metal–ligand coordination have found applications in different areas such as catalysis,[6,18] luminescent devices[19] as well as the biological field.[20–23] In the field of polymer science, the metal–ligand coordination has been widely used in the construction of macromolecular architectures like metallopolymers

or polymeric metal complexes.[24] Such metal–ligand based polymer systems open up the possibility for the preparation of various materials such as self-healing hydrogels, micelles, and vesicles.[25] Moreover, the use of metal–ligand coordination can provide the materials with additional functionalities related to metal ion.[26]

Various types of ligands such as 1,2,3-triazoles,[27,28] 2,6-bis(1,2,3-triazol-4-yl)-pyridine,[29] 2,6-bis(1'-methylbenzimidazolyl)pyridine,[30] terpyridine,[31] and polyethylenimine[32] have been used to prepare gels with transition metal ions or/and lanthanide ions.[33] Compared to other ligands, considerable progress has been made with 2,6-bis(1,2,3-triazol-4-yl)-pyridine (btp) units on account of its facile synthesis, versatile modification, and wide scope of coordination with metal ions.[23,34–37] The 1,2,3-triazole and pyridyl rings of btp unit offer nitrogen-based associating sites for a variety of *d* and *f* metal ions.[38] When the btp units were incorporated into polymers and then coordinated with transition metal ions, some unique reversible or irreversible properties have been accessed. For example, when the btp motifs were bound with Eu^{3+} or Ru^{3+}, the resulting complex were used for catalysis and luminescent devices.[34] So far, a range of btp-containing polymeric complexes with different architectures, for example, linear, star-shaped, dendritic, and even cylinder motifs, have been prepared.[29,35] Furthermore polymers containing btp units in the main chain have been reported for the synthesis of supramolecular organogels.[39,40] The gelation was triggered by the addition of different divalent metal ions and the organogels shown emissive, thermo- and chemo-responsive properties. However, the synthesis of hydrogels based on polymers containing the btp unit in the backbone has not been explored yet. Moreover, investigations regarding the complexation in water could provide more insights into the hydrogelation mechanism and reveal potential future applications as self-healing materials.
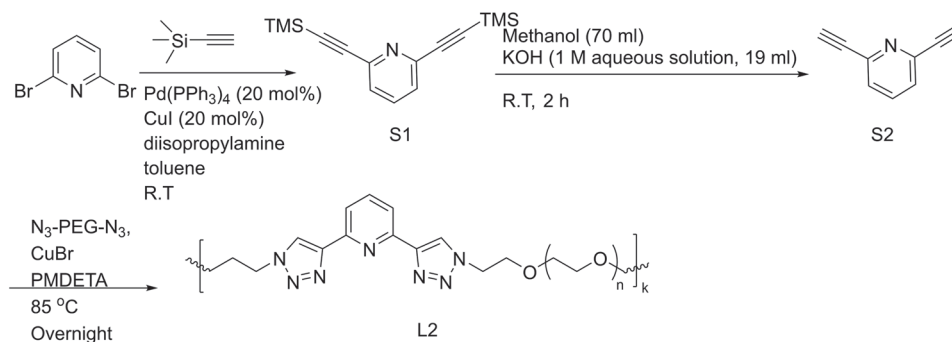
Herein, we report a simple and efficient approach to design autonomously fast self-healing metallo-hydrogels based on polyaddition between 2,6-diethynyl pyridine and PEG-diazide (**L2**), followed by metal complexation to form a metal complex cross-linked network. The hydrogelation was selectively triggered by metal–ligand coordination interactions between Ni^{2+} and btp moieties, while the addition of other divalent metal ions (e.g., Zn^{2+}, Fe^{2+}, Cu^{2+}, Mg^{2+}, Mn^{2+}, Ca^{2+}, and Cd^{2+}) only induced a color change or precipitation. The rheological properties of the

Dr. X. Xu, Dr. V. V. Jerca, Prof. R. Hoogenboom
Supramolecular Chemistry Group
Centre of Macromolecular Chemistry (CMaC)
Department of Organic and Macromolecular Chemistry
Ghent University
Krijgslaan 281-S4, B-9000 Ghent, Belgium
E-mail: richard.hoogenboom@ugent.be
Dr. V. V. Jerca
Centre of Organic Chemistry "Costin D. Nenitzescu" Romanian Academy
Spl. Independentei 202B, 060023 Bucharest, Romania

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Scheme 1. The synthesis procedure of the macromolecular ligand (**L2**) via CuAAC step-growth polymerization.

obtained hydrogels were investigated, revealing that due to the dynamic and reversible nature of metal–ligand coordination interactions, the hydrogel showed self-healing properties. Upon damage, the hydrogel could be completely recovered in less than 2 min by simply rejoining the broken pieces or even in seconds when changing the strain in rheology.

Initial studies focused on the preparation of 2,6-diethynylpyridine, **S2**, following a modified procedure reported in the literature.[41] The macromolecular ligand, **L2**, was subsequently synthesized by a copper-catalyzed CuAAC polyaddition reaction between PEG-diazide (M_n = 10 kDa) and **S2** (**Scheme 1**). The resulting polymer had the number-average molecular weight (M_n) of 79.11 kDa with a relatively broad molecular weight distribution ($Đ$ = 2.16) as determined by SEC-LS analysis (Figure S6, Supporting Information).

If we consider that the M_n of the PEG-diazide is ≈10 kDa, we can estimate that around seven btp units are present on average onto a single polymer chain when compared with the M_n obtained from SEC with light scattering detector (M_n = 79.11 kDa, $Đ$ = 2.16) (Figure S6, Supporting Information). ^{1}H NMR spectroscopic analysis confirmed the successful formation of **L2** by the appearance of the triazole singlet at around 8.4 ppm. In addition, the signals assigned to the PEG chain protons can be found at 4.6 ppm and 3.9 ppm, respectively (Figures S5 and S7a, Supporting Information). Furthermore, the FT-IR analysis revealed that the band at 2100 cm^{-1} assigned to the azide groups disappeared, supporting the successful formation of the triazole ring and efficient CuAAc polymerization (Figure S7b, Supporting Information).

Further on we investigated the formation of hydrogels of **L2** upon the addition of metal ions. The influence of the following factors on the hydrogelation process and mechanical properties of the hydrogels was explored: i) the nature of the metal ion, ii) the ratio between metal and ligand, and iii) the polymer concentration.

The influence of the metal/ligand ratio was the first investigated parameter. Ni^{2+} was chosen as a model metal ion due to its high binding constant with btp units according to the previous report.[29] A series of hydrogels starting from 10 wt% **L2** solution were prepared with btp: Ni^{2+} ratios of 8:1, 4:1, 2:1, and 1:1, respectively. Preliminary gelation experiments were performed by the inverted test tube method (**Figure 1**a). As depicted in Figure 1a, stable hydrogels were obtained when more than 0.5 equiv. of Ni^{2+} were added, in accordance with the 2:1 btp:Ni^{2+} binding ratio. The time sweep rheological measurement revealed that the storage modulus (G') has a value of 2700 Pa and is higher than the loss modulus (G''), thus demonstrating the efficient formation of the metallo-supramolecular hydrogel (Figure 1b). The G' value decreased to 1970 Pa with increasing the Ni^{2+} content to 1 equiv., thus indicating the formation of more Ni^{2+}–btp mono-complexes. Consequently, further gelation studies were performed at a metal to ligand ratio of 1:2.

The second parameter that was investigated is the concentration of **L2**, which was varied between 1 and 15 wt%. Hydrogel formation occurred for solutions with a macromolecular ligand content higher than 2 wt% (Figure 1c). Additional rheological investigations revealed that the G' was larger than G'' for the investigated hydrogels. Moreover, the mechanical strength of the metallo-supramolecular hydrogel could be easily tuned up between 60 and 6800 Pa (Figure 1d,e) by adjusting the concentration of the polymer solution. As expected at lower polymer concentration, the metallo-hydrogels showed lower G' due to the lower cross-linking density. Subsequently, a temperature sweep was performed on Ni^{2+}–btp hydrogel with a concentration of 10 wt% to investigate the stability of the hydrogel. As depicted in Figure S8, Supporting Information, the mechanical stability of the hydrogel cross-linked with Ni^{2+} was not affected by the temperature in the investigated interval, thus suggesting the very high thermodynamic stability of Ni^{2+}–btp complexes.

Further analysis on the water absorption capacity was conducted. All the hydrogels showed increased swelling rate and very low dimensional stability (**Figure 2**a). The swelling degree decreased as the polymer concentration increased from 2 to 15 wt% due to the higher cross-linking density resulting in less water absorption.

Degradability is an important factor in evaluating the stability of the hydrogels, which also provides valuable information about the stability and inertness of the metal–ligand complexes. The metallo-supramolecular hydrogels showed rather low stability when immersed in excess water. The hydrogels swollen in deionized water were completely solubilized after 60 min, revealing relatively low kinetic stability of the Ni^{2+}–btp complexes (Figure 2b). As expected, the degradation rate was dependent on the initial concentration of the **L2** macroligand, whereby the hydrogels at higher concentration showed increased stability.

The morphologies of the freeze-dried Ni^{2+}–btp hydrogels were investigated using scanning electron microscopy. The
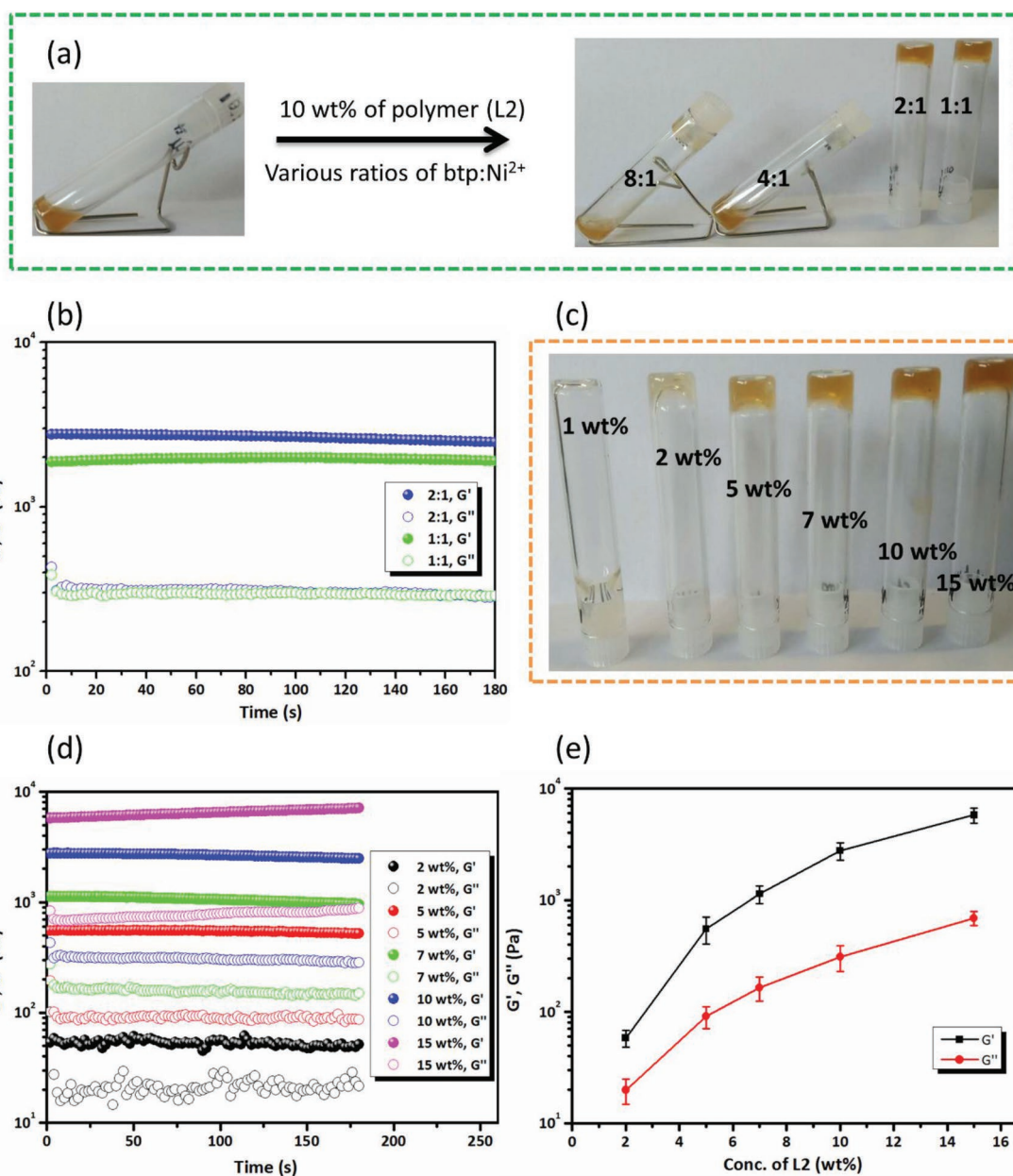
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Figure 1. Preparation and mechanical characterization of the metallo-supramolecular hydrogels. a) Photographs of the metallo-supramolecular hydrogels with various amounts of $NiCl_2$ (from left to right btp:Ni^{2+} 1:0, 8:1, 4:1, 2:1, and 1:1); b) Time sweep experiments of metallo-supramolecular hydrogels measured using a fixed strain of 1% and a frequency of 1 rad s^{-1} at 25 °C for 3 min; Metallo-supramolecular hydrogels with various **L2** concentrations at fixed btp:Ni^{2+} ratio of 2:1 c) photographs, and d) time sweep experiments measured using a fixed strain of 1% and a frequency of 1 rad s^{-1} at 25 °C for 3 min; e) G' and G'' dependence on the polymer concentration.

hydrogel obtained at 2 wt% polymer concentration showed a porous structure (Figure S9a, Supporting Information), most likely due to the specific ice crystal size formation during freeze drying. Increasing the polymer concentration to 5 wt%, resulted in a hydrogel with fibrous structure (Figure S9b, Supporting Information), while hydrogels with a smooth surface as well as compact and continuous structure were obtained at polymer concentration higher than 5 wt% because of the decreased free water content (Figure S9c–e, Supporting Information).

Next, the influence of different divalent metal ions on the gelation of **L2** was investigated. The concentration of the macromolecular ligand was kept constant at 10 wt%, and 0.5 equiv. of metal ions were added. However, surprisingly, none of the other divalent metal ions tested induced the gelation. The addition of Zn^{2+}, Cu^{2+}, and Fe^{2+} only resulted in an increase in viscosity (**Figure 3**a). The selective gelation induced by Ni^{2+} can be explained by the higher overall association constant β of the complexes in water, which has been reported to be in the order $Ni^{2+} > Fe^{2+} > Zn^{2+} > Cu^{2+}$, if we consider that metal
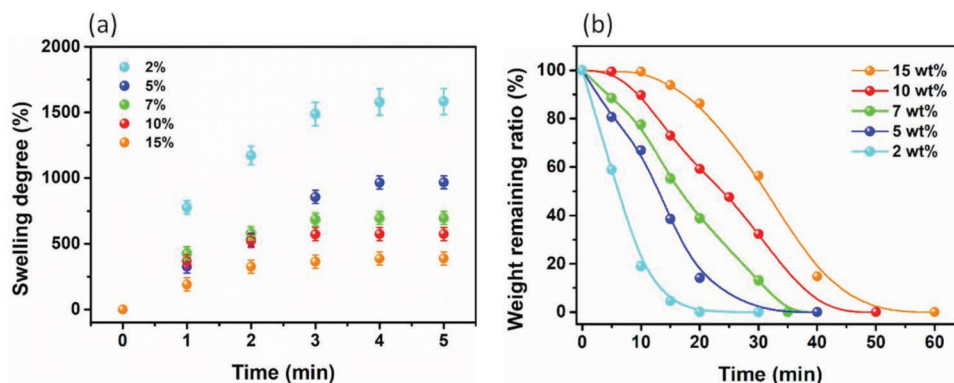
Figure 2. a) Swelling degree time plots in deionized water, and b) hydrolytic degradation of the Ni^{2+}–btp hydrogels at 25 °C, with various **L2** concentrations at fixed btp:Ni^{2+} ratio of 2:1.

complexation with btp is analogous to terpyrdine.[42] Moreover, the high chain length of the PEG could also interfere with the hydrogel formation by interacting with the metal ions, which is consistent with the recent work of Weng et al. on btp based organogels.[43]

Nonetheless, it is well documented that Fe^{2+} formed very stable bi-complexes with such N-heterocyclic ligands due to its high association constants. Consequently, it is hypothesized that the Fe^{2+} might be oxidized to Fe^{3+} during the hydrogelation procedure leading to the failure of hydrogelation. To verify this aspect, Fe^{2+} dissolved in an ascorbic acid aqueous solution was used. However, the addition of Fe^{2+} with ascorbic acid to a 10 wt% solution of **L2** only induced the increase of viscosity, while no hydrogel formation was observed (Figure 3b). This result further supports the hypothesis that the use of long PEG indeed interfered with the hydrogelation by interacting with metal ions.

To gain more insight into the selectivity towards Ni^{2+}, we synthesized a model organic compound that resembles the structure of the macromolecular ligand **L2**. 2,6-bis(2-(2-(2-(2-methoxyethoxy)ethoxy)ethyl)-2H-1,2,3-triazol-4-yl)pyridine (**V1**) was prepared by CuAAC click reaction between 2,6-diethynyl pyridine and 1-azido-2-(2-(2-methoxyethoxy)ethoxy) ethane (TEG-N$_3$) (Figure S10a, Supporting Information).

The structure of **V1** was confirmed by NMR spectroscopy (see Supporting Information).

The complexation of the model compound, **V1**, with Ni^{2+} was further evaluated by a UV–vis titration in aqueous solution. It should be noted that the metal ions used here are their chloride salts. In Figure S10b, Supporting Information, the characteristic absorption displayed a significant bathochromic shift and broadening with increasing equivalents of Ni^{2+}, suggesting the complexation with btp. The maximum absorption was reached around 0.5 equiv. after which no significant change was observed, indicating that **V1** coordinated with Ni^{2+} to form a 1:2 metal–ligand complex. Similar results were found for Fe^{2+}, Zn^{2+}, and Cu^{2+} complexes while no complexation was observed upon addition of Mg^{2+}, Ca^{2+}, Mn^{2+}, and Cd^{2+} (Figure S10c, Supporting Information). These results demonstrate that the model compound does form metal complexes, thereby indirectly supporting the proposed mechanism that competition with PEG is responsible for the lack of complexation of **L2**. These results also demonstrate the importance of the polymeric linker in the construction of metallo-supramolecular hydrogels.

Next, we investigated the self-healing properties of the Ni^{2+}–btp hydrogel. The macromolecular ligand concentration was 10 wt%, while the btp:Ni^{2+} ratio was 2:1. The hydrogel showed
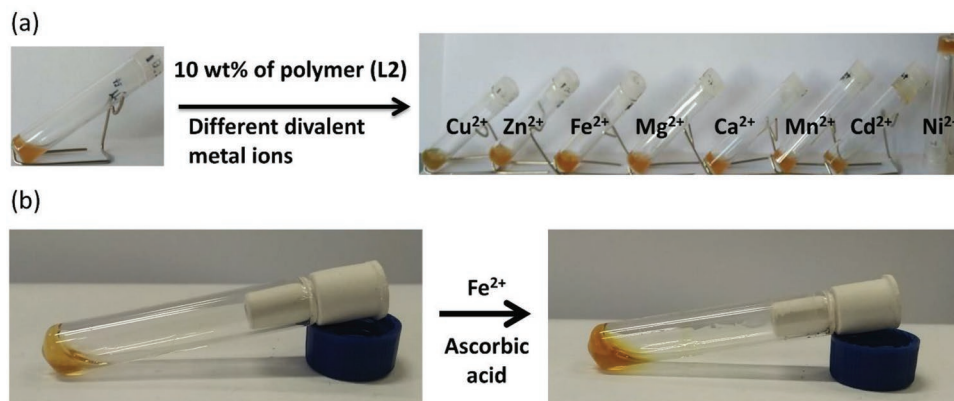

Figure 3. a) Photographs of 10 wt% solutions of **L2** in the presence of 0.5 equiv. of divalent metal ions from left to right: chloride salt of Cu^{2+}, Zn^{2+}, Fe^{2+}, Mg^{2+}, Ca^{2+}, Mn^{2+}, Cd^{2+}, and Ni^{2+}; b) photographs of 10 wt% solutions of **L2** in the presence of 0.5 equiv. of $FeCl_2$ with 0.5 equiv. of ascorbic acid.
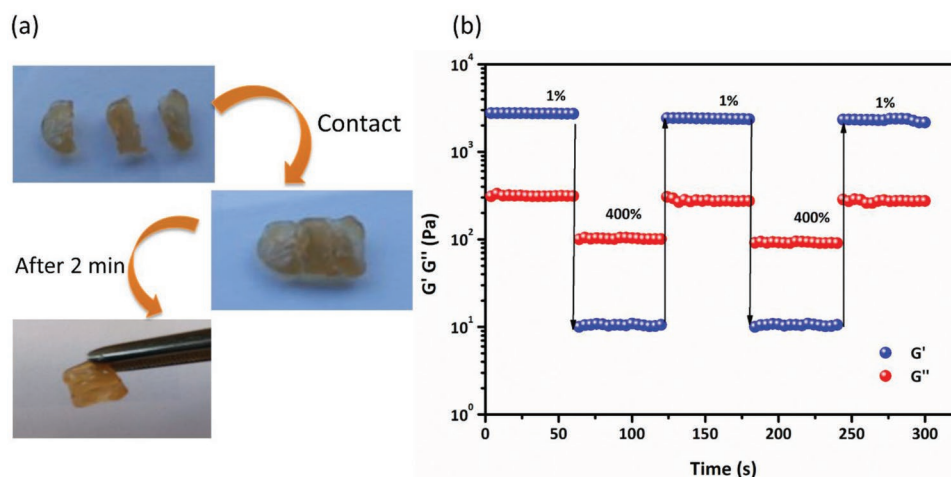
Figure 4. a) Visual evidence of the self-healing of Ni^{2+}–btp hydrogel by rejoining the pieces together for 2 min at room temperature, without any external stimulus. b) Cyclic strain time sweep rheology experiments of Ni^{2+}–btp hydrogel using a fixed frequency of 1 rad s^{-1}.

impressive self-healing properties, which were not anticipated based on the strong complexation of btp with Ni^{2+}. As shown in **Figure 4**a, the hydrogel was first cut into three pieces, and then the pieces were recombined together by continuous contact for 2 min at ambient temperature without any external stimulus. The resulting hydrogel was completely healed, and the scars were no longer visible. The self-healing properties were also investigated by rheology using cyclic strain time sweeps (Figure 4b). No noticeable difference was observed between the different cycles, indicating that the hydrogel was totally recovered after breaking within seconds. Moreover, the hydrogel can sustain multiple cycles of healing and separation without compromising its mechanical properties. Successive strain and frequency sweep measurements provided additional insight into the self-healing process of the metallo-supramolecular hydrogels. Reversed strain sweep measurements between 0.1% and 450% strain (Figure S11a, Supporting Information) demonstrated that the network reformation is possible. No hysteresis was observed and the G' reached the initial values, thus suggesting full recovery of transient cross-links. The frequency sweep measurements applied after the reversed strain showed no hysteresis compared to the first measurement, also indicating the full self-healing properties of the hydrogels (Figure S11b). This excellent and repeatable self-healing capability might find many potential applications, including but not limited to the healing of the metal coatings, reshaping, and regeneration of hydrogels.[39]

In conclusion, we have developed a self-healing hydrogel based on the specific Ni^{2+} coordination with a polymeric ligand made by polyaddition of 2,6-diethynyl pyridine and PEG-diazide. The selectivity towards Ni^{2+} is ascribed to the high chain length of the polymeric linker, which hampers the formation of efficient intermolecular cross-links for the metal–btp complexes with lower thermodynamic stability. The hydrogelation and the mechanical properties of the hydrogel could be controlled by the metal to ligand ratio as well as by the polymer concentration. Owing to the dynamic nature of the Ni^{2+}–btp complexes, the hydrogel exhibited an excellent repeatable autonomic healing capability.

Conflict of Interest

The authors declare no conflict of interest.

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