

# Thermal Performance of Mechanically Activated Tetracalcium Phosphate

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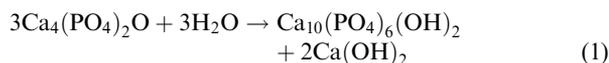
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**Prolonged high-energy ball milling of tetracalcium phosphate (TTCP) resulted in a mechanical activation with the formation of nanocrystalline or amorphous domains within the compound. This mechanically activated material demonstrated a completely different thermal behavior compared with highly crystalline TTCP. Differential scanning calorimetry (DSC) measurements indicated the presence of exothermic reactions between 370° and 480°C and between 630° and 930°C for 24 h-milled TTCP, which could be related to conversion to an apatitic phase and calcium oxide (CaO) and crystallization of these products during heating. X-ray diffraction analyses showed that mechanically activated TTCP began converting to an apatitic phase at ~200°C and fully converted to an apatitic phase and amorphous CaO at 600°C, and a crystalline phase of CaO subsequently appeared around 800°–1200°C. Reconversion to TTCP was observed between 1200° and 1400°C. In contrast, crystalline TTCP remained stable up to 500°C and decomposed to an apatitic phase and CaO around 600°–1000°C.**

## I. Introduction

TETRACALCIUM PHOSPHATE ( $\text{Ca}_4(\text{PO}_4)_2\text{O}$ ) (TTCP) is the only calcium phosphate phase with a Ca/P ratio greater than stoichiometric hydroxyapatite (HA).<sup>1,2</sup> It is therefore often a component of calcium phosphate cement (CPC) formulations leading to the formation of stoichiometric HA. In this application, TTCP is used as biocement reactant combined with acidic calcium phosphates such as dicalcium phosphate anhydrous (DCPA, monetite) or dicalcium phosphate dihydrate (DCPD, brushite).<sup>3–5</sup> The reactivity, however, toward self-hydrolysis of crystalline TTCP according to Eq. (1) was low due to the formation of a thin HA layer around the TTCP particles, which acted as a diffusion barrier inhibiting or slowing down further hydrolysis.<sup>3,4</sup>



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Mechanical activation, i.e., the formation of amorphous materials by mechanical energy input, is a well-established and investigated method for metals and ceramics,<sup>6</sup> which results in an increase of reaction rates and lowering of reaction temperatures of materials. In a recent study, we found an increase in the reactivity of TTCP by mechanical activation during high-energy ball milling, which enabled the preparation of single-component TTCP cements with a high conversion rate to HA in aqueous phase.<sup>7</sup> The mechanically induced phase transformation is linked to an increase both in solubility and formation enthalpy of the hydrolysis products. In this work, we studied in detail the thermodynamic and thermal behavior of mechanically activated TTCP by means of differential scanning calorimetry (DSC) and X-ray diffraction (XRD) measurements.

## II. Materials and Methods

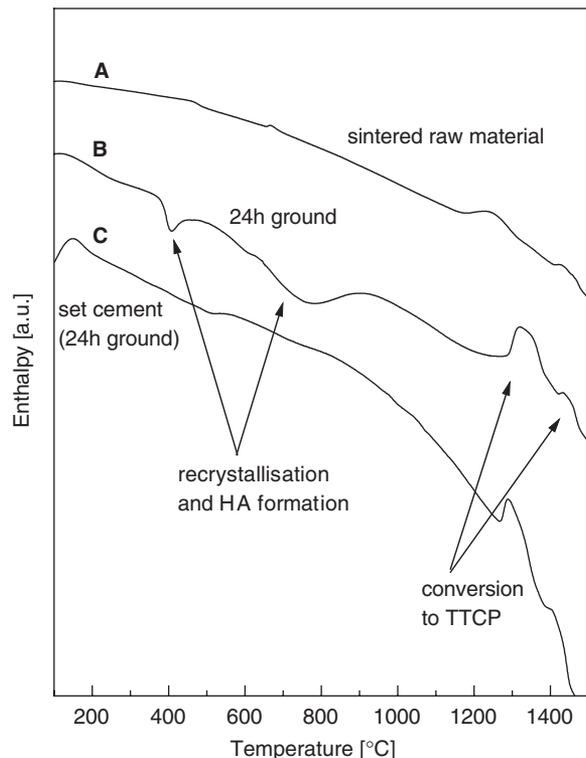
The synthesis of crystalline TTCP by sintering, crushing of the sintered cake, and high-energy ball milling in a planetary ball mill (PM400 Retsch, Haan, Germany) to produce mechanically activated TTCP has been described previously.<sup>7</sup>

X-ray diffraction (XRD) patterns of the starting TTCP, milled materials, and set cements were recorded using a diffractometer D5005 (Siemens, Karlsruhe, Germany). Data were collected from  $2\theta = 20\text{--}40^\circ$  with a step size of  $0.02^\circ$  and a normalized count time of 1 s/step. The phase composition was checked by means of JCPDS reference patterns for TTCP (PDF Ref. 25-1137) and HA (PDF Ref. 09-0432). Crystal sizes and quantitative phase compositions of the materials were calculated by means of total Rietveld refinement analysis with the TOPAS software (Bruker AXS, Karlsruhe, Germany). As references, the system internal database structures of TTCP and HA were used together with a *Chebyshev* fourth-order background model and a  $\text{CuK}\alpha$  emission profile. The lattice parameters were calculated by the TOPAS software on the basis of the refined diffraction patterns. DSC and thermogravimetric measurements (TG) were performed (Model STA 409, Netzsch, Selb, Germany) at a heating rate of  $20^\circ\text{C}/\text{min}$  up to  $1500^\circ\text{C}$ . Recrystallization experiments for phase analysis were performed by heating 5 g of crystalline TTCP raw material and 24 h-milled TTCP at the same heating rate to temperatures between  $300^\circ$  and  $1500^\circ\text{C}$  immediately followed by quenching to room temperature in air.

Two hundred milligrams TTCP, milled for 24 h and thermally recrystallized at different temperatures, was mixed with 200 mL double distilled water and the equilibrium pH was measured (Mettler, Toledo, OH) in order to detect CaO.

## III. Results

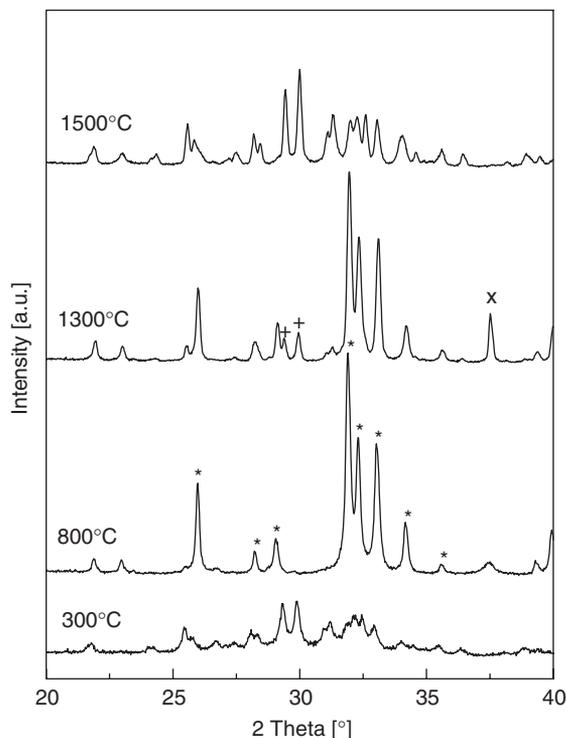
Typical DSC heating curves are displayed in Fig. 1 for mechanically activated TTCP, the crystalline raw material and set HA



**Fig. 1.** DSC patterns of (A) crystalline tetracalcium phosphate (TTCP) raw material showing reconversion to TTCP indicated by endothermic peak  $\sim 1150^{\circ}\text{C}$  after slow decomposition; (B) TTCP 24 h milled showing clear exothermic peaks at  $\sim 400^{\circ}$  and  $700^{\circ}\text{C}$ , and (C) control material, i.e., mechanically activated TTCP previously reacted in water to form nanocrystalline HA and CaO, illustrates the absence of exothermic peaks.

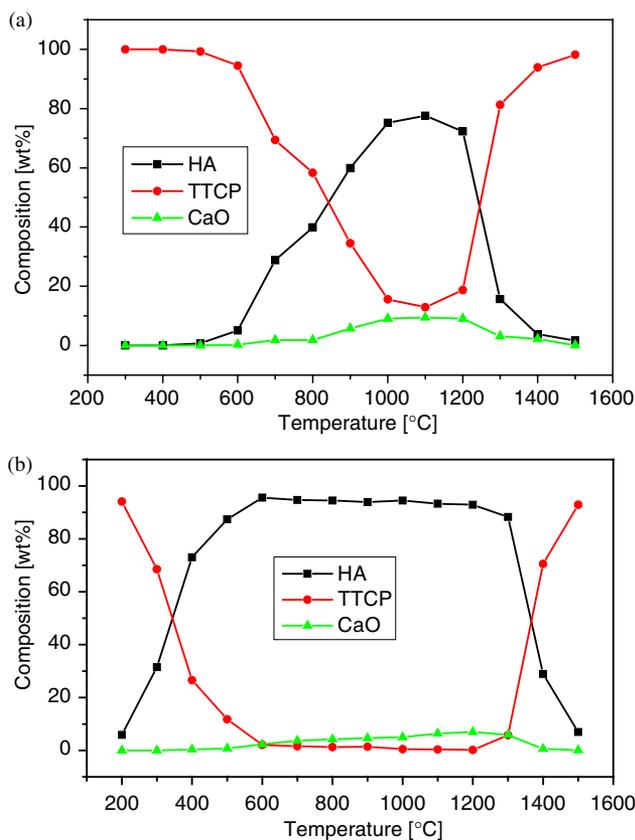
cement being made of 24 h-milled TTCP. During heating of the crystalline TTCP to  $1500^{\circ}\text{C}$ , at first weak endothermic reactions occurred between  $430^{\circ}$ – $490^{\circ}\text{C}$  and  $650^{\circ}$ – $700^{\circ}\text{C}$  with an enthalpy of 2–2.5 J/g, followed by strong endothermic peaks between  $1170^{\circ}$ – $1330^{\circ}\text{C}$  and  $1400^{\circ}$ – $1500^{\circ}\text{C}$  with formation enthalpies of 47 and 16 J/g, respectively. A completely different thermal behavior was observed for the 24 h mechanically activated material. Initially strong exothermic reactions were found  $\sim 370^{\circ}$ – $480^{\circ}\text{C}$  (45 J/g) and  $\sim 630^{\circ}$ – $930^{\circ}\text{C}$  (171 J/g) and the endothermic reaction peak shifted to higher temperatures ( $1250^{\circ}$ – $1400^{\circ}\text{C}$ ) compared to the unmilled sample, combined with a higher enthalpy of 110 J/g compared with the crystalline TTCP. For the second high temperature peak between  $1400^{\circ}$  and  $1500^{\circ}\text{C}$ , (17 J/g), there were no significant differences in peak intensity found for both materials. Mechanically activated TTCP, which was hydrolyzed at room temperature to form HA and CaO, was used as a control material and showed no significant enthalpy peaks except for those related to formation of TTCP at  $1300^{\circ}\text{C}$ .

XRD patterns of the 24 h-milled TTCP heated to various temperatures are displayed in Fig. 2. The phase compositions according to Rietveld refinement analyses of XRD patterns are presented in Fig. 3(a) (TTCP raw material) and 3(b) (TTCP, 24 h milled). Even at  $200^{\circ}\text{C}$ , the formation of crystalline HA could be observed in the mechanically activated material (6 wt%), which increased to more than 90 wt% at  $600^{\circ}\text{C}$ . Simultaneously, diffraction peaks for TTCP decreased in intensity and a second crystalline phase of CaO could be detected from  $600^{\circ}\text{C}$  with a maximum of nearly 7 wt% at  $1200^{\circ}\text{C}$ . Reconversion to TTCP in the mechanically activated sample commenced  $\sim 1300^{\circ}\text{C}$  and the material consisted almost completely of crystalline TTCP at  $1500^{\circ}\text{C}$ . In contrast, the crystalline TTCP raw material showed different phase compositions during heating to  $1500^{\circ}\text{C}$ . In this case, HA formation started at  $600^{\circ}\text{C}$  and increased linearly to nearly 80 wt% at  $1100^{\circ}\text{C}$ ; in addition, crystalline CaO content increased to 9 wt% and TTCP content



**Fig. 2.** X-ray diffraction patterns of 24 h wet-milled tetracalcium phosphate (TTCP) after reheating to temperatures between  $300^{\circ}$  and  $1500^{\circ}\text{C}$ ; \*, HA and apatitic phases; +, TTCP; x, CaO diffraction peak.

decreased to 11 wt%. Interestingly, reconversion to TTCP in the crystalline raw material started  $\sim 100^{\circ}\text{C}$  lower than for the mechanically activated TTCP and a nearly complete reconversion to TTCP was almost completely achieved at  $1400^{\circ}\text{C}$ .

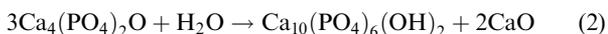


**Fig. 3.** Phase composition of crystalline TTCP raw material (a) and 24 h-milled TTCP (b) after reheating to temperatures between  $300^{\circ}$  and  $1500^{\circ}\text{C}$  according to Rietveld refinement analysis.

In order to determine whether significant quantities of CaO had formed at low temperatures that were insufficiently crystalline to be detected using XRD data, powdered 24 h-milled TTCP not heat treated and heat treated at various temperatures from 400° to 900°C was immersed in water and the pH was measured. For a saturated solution of unheated TTCP, a pH of 10.2 was measured. Although CaO was not detected at 400°C in XRD patterns, the pH of the saturated solution was 10.8 and a slight increase to 11.6 was observed at heat treatment temperature 900°C.

#### IV. Discussion

TTCP is not thermodynamically stable at temperatures < 1300°C, depending on water partial pressure; yet, it may be prepared at room temperature by rapid quenching following high temperature synthesis.<sup>8</sup> Monoclinic TTCP has an epitaxial relationship to the hexagonal apatite lattice as shown by Dickens *et al.*,<sup>9</sup> whereby every 2/3 of TTCP  $d_{010}$  has many structural similarities with  $d_{100}$  of the apatite lattice. This structural similarity may explain why solid-state decomposition of the TTCP phase to HA and CaO is accompanied by almost no enthalpy changes. When thermal decomposition of crystalline TTCP to HA and CaO occurred between 600° and 1000°C (Fig. 3(a)), no significant peaks were detectable from DSC measurements (Fig. 1). In contrast, the DSC measurements of mechanically activated TTCP (Fig. 1) showed two distinct strong exothermic peaks at 400° and 750°C, corresponding to enthalpy changes of -44.73 kJ/mol (370°–480°C) and -171.4 kJ/mol (630°–930°C) after peak integration. This exothermic behavior is thought to be the result of the energy input during ball milling; the application of shear and compressive stress to the TTCP particles during the impact of the milling balls resulted, besides crushing the particles, in the formation of defects within the TTCP lattice and it probably disrupted the apatite-like layers within the TTCP structure. It is known from the literature that this mechanical energy input can reach up to several hundred kJ/mol for ceramic and metallic materials during prolonged ball milling.<sup>6</sup> As can be seen in Eq. (2), the decomposition of TTCP to CaO is accompanied by the formation of HA.



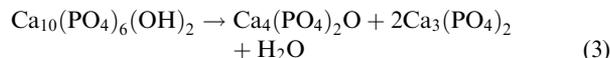
It has been proposed by Ciesla and Rudnicki<sup>10–12</sup> that an intermediate phase of apatite with a Ca/P ratio of more than 1.67 is formed following decomposition of TTCP at temperatures lower than 660°C. At a low temperature, this apatitic phase may be phosphate deficient as a result of the incomplete decomposition. The endothermic peak at 750°C in the DSC pattern of 24 h mechanically activated TTCP may therefore be attributed to a combination of the transformation of this nonstoichiometric apatite phase to stoichiometric HA and crystalline CaO. In order to further confirm that mechanical activation was responsible for decomposition of TTCP at temperatures as low as 200°C, DSC measurements were performed on mechanically activated TTCP that had been hydrolyzed to CaO and HA at room temperature in water.<sup>7</sup> The endothermic peaks thought to be associated with decomposition of TTCP and nonstoichiometric apatite were absent; yet similar thermal behaviour was observed at ~1300°C.

Rietveld refinement data indicated that at 1200°C no detectable TTCP was left in the mechanically activated sample, while the conversion of unmilled TTCP was still incomplete after heat treatment. This difference is thought to be a kinetic effect since it is known<sup>12</sup> that even crystalline TTCP will be completely decomposed to HA and CaO after long-term annealing at 1000°–1200°C. However, in our experiments, we rapidly quenched the materials after reaching this temperature such that the observed higher decomposition rate of the mechanically activated material is more likely a result of a higher reaction speed compared with the crystalline TTCP rather than a thermodynamic effect.

The exothermic peak at ~1300°C is thought to be a result of formation of TTCP from the decomposition products formed at lower temperature, since crystalline TTCP is not stable below 1300°C and was produced initially by quenching from high temperature.

A striking feature of the presented measurements was the reduction in the decomposition temperatures of mechanically activated TTCP compared with crystalline TTCP from ~600° to ~200°C. This is in agreement with previous investigations on the thermal behavior of mechanically activated ilmenite and pyrites,<sup>13,14</sup> where it was also demonstrated that mechanical activation led to a decrease in decomposition temperature. These authors proposed that an increase in lattice distortions caused by mechanical activation enabled decomposition to occur at significantly lower temperatures. Apparent formation of apatite due to undetected epitaxy between TTCP and apatite seemed improbable since the apatitic layers in TTCP have lower  $a$  axes (~0.1 Å) and higher  $c$  axes (~0.1 Å) than HA.<sup>9</sup> Lattice parameters of all apatitic phases formed in both heat-treated unmilled and mechanically activated TTCP were  $a = 9.41 \pm 0.006$  Å and  $c = 6.8841 \pm 0.01$  Å, which are very similar to those expected for HA and non-apatitic planes in TTCP.<sup>9</sup>

Lin *et al.*<sup>15</sup> proposed on the basis of XRD measurements of thermal decomposition of HA in air, that decomposition proceeded according to Eq. (3), forming tricalcium phosphate (TCP) and TTCP.



This could not be observed in the XRD patterns (Fig. 2), in contrast to the experiments of Lin *et al.*, where quenching of HA and reheating of the decomposition products, TTCP and TCP, was investigated. The decomposition of HA to TTCP and TCP would thus appear to occur only while quenching HA. While reheating the decomposition products TTCP and TCP, Lin *et al.* also discovered that TTCP reconverts solely into HA, yielding calcium hydroxide. The decomposition of TTCP to an apatitic phase respectively HA and CaO seems to be a thermodynamically favored process.

The reason for the lower reversion temperature in the originally crystalline TTCP (Figs. 1 and 3(a,b)) could be explained by the incomplete decomposition of crystalline TTCP to HA and CaO. This led to a significant amount of TTCP in the sample before reversion started. The remaining TTCP was likely to act as seed crystals for the following reversion of HA and CaO to TTCP, which therefore led to a lower reaction temperature of 1100°–1200°C compared with 1200°–1300°C for the sample of originally activated TTCP.

The process of reducing thermal decomposition temperature by mechanical activation has clear application in the field of nanotechnology where crystal growth can be avoided by solid-state synthesis at very low temperature, which is important given that nanotexture has a strong effect on biological properties,<sup>16</sup> a phenomenon that is only just beginning to be appreciated. Further study is required to determine the extent to which this processing route can be harnessed to derive new materials with novel biological properties.

#### V. Conclusion

Mechanically activated TTCP showed a completely different thermal behavior compared to unactivated, i.e., unmilled highly crystalline, TTCP. The decomposition mechanisms for both TTCPs investigated were the same, but for mechanically activated TTCP compared with crystalline TTCP, the starting temperature of conversion was lowered by an astonishing 400 K and also the conversion rate to HA and CaO was enhanced to almost 100% without annealing. This unequal behavior from a thermal point of view further explained the completely different

patterns of this activated material in the reaction/setting-behavior when it comes to application in the field of medical bone cements.<sup>7</sup>

### References

- <sup>1</sup>H. Monma, M. Goto, H. Nakajima, and H. Hashimoto, "Preparation of Tetracalcium Phosphate," *Gypsum Lime*, **202**, 17 (1986).
- <sup>2</sup>W. E. Brown and E. F. Epstein, "Crystallography of Tetracalcium Phosphate," *J. Res. Natl. Bur. Stand.—A. Phys. Chem.*, **69A** [6] 547–51 (1965).
- <sup>3</sup>W. E. Brown and L. C. Chow, "A New Calcium Phosphate, Water-Setting Cement;" pp. 352–79 in *Cements Research Progress*, Edited by P. W. Brown. The American Ceramic Society, Westerville, OH, 1986.
- <sup>4</sup>L. C. Chow, M. Markovic, and S. Takagi, "Calcium Phosphate Cements;" pp. 215–38 in *Cements Research Progress*, Edited by L. J. Struble. The American Ceramic Society, Westerville, OH, 1987.
- <sup>5</sup>L. C. Chow, "Development of Self-Setting Calcium Phosphate Cements," *J. Ceram. Soc. Jpn.*, **99**, 954–64 (1991).
- <sup>6</sup>E. Gaffet, F. Bernard, J. C. Niepce, F. Charlot, C. Gras, G. Le Caer, J. L. Guichard, P. Delcroix, A. Mocellin, and O. Tillement, "Some Recent Developments in Mechanical Activation and Mechanosynthesis," *J. Mater. Chem.*, **9** [1] 305–14 (1999).
- <sup>7</sup>U. Gbureck, J. E. Barralet, M. Hofmann, and R. Thull, "Mechanical Activation of Tetracalcium Phosphate," *J. Am. Ceram. Soc.*, **87** [2] 311–3 (2004).
- <sup>8</sup>J. C. Elliott, *Structure and Chemistry of the Apatites and Other Calcium Orthophosphates*. Elsevier, Amsterdam, 1994.
- <sup>9</sup>B. Dickens, W. E. Brown, G. J. Kruger, and J. M. Stewart, "Ca<sub>4</sub>(PO<sub>4</sub>)<sub>2</sub>O, Tetracalcium Diphosphate Monoxide, Crystal Structures and Relationships to Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>OH and K<sub>3</sub>Na(SO<sub>4</sub>)<sub>2</sub>," *Acta Crystallogr.*, **B29**, 2046–56 (1973).
- <sup>10</sup>K. Ciesla and R. Rudnicki, "Synthesis and Transformation of Tetracalcium Phosphate in Solid State. Part I. Synthesis of Roentgenographically Pure Tetracalcium Phosphate from Calcium Dibasic Phosphate and Calcite," *Pol. J. Chem.*, **61** [7–12] 719–27 (1987).
- <sup>11</sup>K. Ciesla and R. Rudnicki, "Synthesis and Transformation of Tetracalcium Phosphate in Solid State. Part II. Studies on Synthesis of Tetracalcium Phosphate by the Thermal Analysis Method," *Pol. J. Chem.*, **62** [1–3] 31–9 (1988).
- <sup>12</sup>K. Ciesla and R. Rudnicki, "Synthesis and Transformation of Tetracalcium Phosphate in Solid State. Part IV. Transformations of Ca<sub>4</sub>P<sub>2</sub>O<sub>9</sub> Occurring While Heated in Air Within the Temperature Range from Ambient to 1500°C," *Pol. J. Chem.*, **63** [1–3] 83–91 (1989).
- <sup>13</sup>F. S. Pan, K. Li, A. T. Tang, Y. Wang, J. Zhang, and Z. X. Guo, "Influence of High Energy Ball Milling on the Carbothermic Reduction of Ilmenite," *Adv. Mater. Process. II, Mater. Sci. Forum*, **437–4**, 105–8 (2003).
- <sup>14</sup>H. Hu, Q. Chen, Z. Yin, and P. Zhang, "Thermal Behaviors of Mechanically Activated Pyrites by Thermogravimetry," *Thermochem. Acta*, **398**, 233–40 (2002).
- <sup>15</sup>F. H. Lin, C. J. Liao, K. S. Chen, and J. S. Sun, "Thermal Reconstruction Behaviour of the Quenched Hydroxyapatite Powder During Reheating in Air," *Mater. Sci. Eng. C—Biomimetic Supramolecular Systems*, **13** [1–2], special issue 97–104 (2000).
- <sup>16</sup>M. J. Dalby, S. J. Yarwood, M. O. Riehle, H. J. H. Johnstone, S. Affrossman, and A. S. G. Curtis, "Increasing Fibroblast Response to Materials Using Nanotechnology: Morphological and Genetic Measurements of Cell Response to 13-nm-High Polymer Demixed Islands," *Exp. Cell. Res.*, **276** [1] 1–9 (2002). □

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