Supplementary Information

For the sample synthesis, nano-sized powders of $Mg(OH)_2$, SiO_2 and $CaCO_3$ were used as starting materials. The powders were well mixed and reacted at 1000ºC and 960ºC for 3h to obtain mineral powders of forsterite plus 20 vol% and 30 vol% Ca-bearing pyroxene (Cpx), respectively. We applied a vacuum sintering technique for 0.5 h at 1280ºC and 3h at 1310ºC for 20 vol% and 30 vol% pyoroxene samples, respectively, resulting in the aggregates with > 99.9 % density. Average grain sizes are 410 nm in 20 vol% pyroxene sample and 550 nm in 30 vol% pyroxene sample. Compression and tension experiments were conducted on 5 mm diameter ×10 mm long right-cylindrical samples and dog-bone shaped samples of a gauge length of 12 mm, a width of 2 mm, and a thickness of 2 mm, respectively, using an INSTRON 5567, 5580 and Shimadzu AG-20kNX apparatuses with an attached furnace with heating elements of Kanthal Super to heat the sample. Testing temperatures were established by raising the temperature at 650ºC/h. All tests were conducted at constant displacement rate. Torsion experiment was conducted on 10 mm diameter ×3 mm thick aggregate using gas-medium deformation apparatus fitted with a torsional actuator. Testing temperatures were established by raising the temperature at 50ºC/min. Displacement-torque data were recorded throughout the experiments. Sample hardening during experiments was observed for all the samples, which is attributed to continuous "dynamic" grain growth (Hiraga et al. 2010b). After the experiments, polished sections parallel to the deformation axis for axially deformed samples and perpendicular to shear plane for torsion samples were prepared. The polished surfaces were thermally etched (i.e., grooving) at temperatures at least 100°C below the temperatures applied during deformation to ensure negligible grain growth during the thermal etching, which was confirmed by comparing to the microstructure of samples after chemical etching with dilute HCl + HNO_3. Since the torsion experiment was conducted at lower temperature, thermal grooving was not used on the sample from this experiment to avoid any microstructural modification such as grain growth during thermal grooving. As a result, grain and interphase boundaries were not as well exposed as the boundaries in the thermally etched samples, prohibiting detailed analysis of grain shapes (Fig. 1F). We analyzed the polished and etched surfaces with scanning electron microscopy (SEM)/Back Scattered Electron imaging (BSE), which can distinguish the different phases and grain shapes to a fine scale (Figs. 1A-F). More than 500 Px grains were measured to analyze the number frequency in Px clusters and average and maximum numbers of grains in the clusters in the samples of initial, KS-13 and -17 (Fig. 2 and Supplementary Table DR1).

Table DR1. Experimental conditions and results. "initial" represents the starting material of KS-13 and -17 samples. Average grain sizes are reported for the bulk sample without distinguishing forsterite and pyroxene. d_{fin}: grain size observed after the experiments; σ and τ: stress; strain: true strain; # of measured grains: number of measured Px grains for the aggregation frequency analyses in Fig. 2; ave. aggregation: average number of Px grains in the clusters; max. aggregation: maximum numbers of Px grains in the clusters.

Experiment no.	Experiment	T (K)	Experimental duration	dfin (μm)	strain rate (s^{-1})	σ or τ (MPa)	strain	# of measured grains	ave.aggregatation	max. aggregatation
initial	-	1553	1800	0.41	0.0E+00	0.0	0.0	592	1.7	10
KS-13	tension	1603	48000	1.22	9.7E-06	17.7	0.6	548	1.8	8
KS-17	tension	1603	48060	1.40	1.4E-05	37.4	1.5	729	2.5	14
KF-125	compression	1603	7213	0.84	4.3E-05	8.3	0.7		-	
PI-0629	torsion	1423	28400	-	8.0E-05	97	4.1		-	
					1.6E-04	151				
					5.6E-05	76				
					1.6E-04	151				
					2.2E-04	173				
					1.6E-04	152				
tD1	tension	1573	12180	0.82	9.0E-05	21.7	0.8			