Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

Collisional history of asteroid Itokawa

F. Jourdan[1*], N.E. Timms[2], E. Eroglu[1], C. Mayers[1], A. Frew[1], P.A. Bland[2], G.S. Collins[3], T.M. Davison[3], M. Abe[4], and T. Yada[4]

[1]*Western Australian Argon Isotope Facility, Department of Applied Geology & JdL Centre, Curtin University, Perth, WA 6845, Australia*

[2]*Department of Applied Geology, Curtin University, Perth WA 6845, Australia*

[3]*Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, UK*

[4]*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan*

*E-mail: f.jourdan@curtin.edu.au

ABSTRACT

In situ extraterrestrial samples returned for study (e.g., from the Moon) are crucial in understanding the origin and evolution of the Solar System as, contrary to meteorites, they provide a known geological context for the samples and their analyses. Asteroid 25143 Itokawa is a rubble pile asteroid consisting of reaccumulated fragments from a catastrophically disrupted monolithic parent asteroid, and from which regolith dust particles have been recovered by the Hayabusa space probe. We analyzed two dust particles using Electron Backscatter Diffraction (EBSD) and $^{40}Ar/^{39}Ar$ dating techniques. One of the grains showing signs of 15–25 GPa impact shock pressure, yielded a $^{40}Ar/^{39}Ar$ plateau age of 2.3 ± 0.1 Ga. We develop a novel temperature-pressure-porosity model, coupled with diffusion models to show that the relatively low pressure and high temperature involved in the impact process can be reconciled only if the asteroid was already made of porous material at ~2.3 Ga and thus, if asteroid Itokawa was already formed,

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

thereby providing a minimum age for catastrophic asteroid breakup. A second particle shows no sign of deformation indicating shock pressure of < 10 GPa and a calculated maximum temperature of ~200 °C. This low temperature estimate is compatible with a lack of isotopic resetting for this particle. This suggests that the breakup of Itokawa's parent was a relatively low-temperature process at the scale of the asteroid, and occurred on a pre-shattered parent body.

INTRODUCTION

One of the main goals of the Hayabusa mission was to recover samples from asteroid 25143 Itokawa, a 535 × 295 × 209 m body, and return them to the Earth (Abe et al., 2006; Nakamura et al., 2011). In June 2010, the sample catcher was recovered revealing at least 1500 regolith particles, with the majority of them being significantly smaller than a hundred micrometres (Nakamura et al., 2011; Tsuchiyama, 2014). The Itokawa particles are thus the first and only extraterrestrial samples ever recovered from a known asteroid.

Petrographic inspection (Fig. 1; SI Materials and Methods), elemental and oxygen isotope analyses revealed that particles from Itokawa are mostly made of olivine, low- and high-Ca equilibrated pyroxene and albitic plagioclase, suggesting high temperature metamorphism of grades 5 and 6, and that those particles are LL5 and LL6 equilibrated chondrites (Nakamura et al., 2011; Nakashima et al., 2013). Equilibrium temperature calculations showed that these minerals experienced a peak metamorphic temperature of ~800 °C during the formation of the parent asteroid (Nakamura et al., 2011). Particles are either unshocked or show a variety of shock signatures from lightly- to moderately-shocked (Nakamura et al., 2011) due to subsequent impact events. Because the internal metamorphic temperatures are too high for a small Itokawa-size body, and, because of its clear rubble pile structure (Tsuchiyama, 2014), it has been suggested that the first-generation parent body of Itokawa must have been initially as large as a few tens of

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

kilometers, and has subsequently been destroyed by an impact (Nakamura et al., 2011). The resulting fragments then reaccumulated to form a rubble pile asteroid (Michel and Richardson, 2013). An $^{40}Ar/^{39}Ar$ age of ~1.3 Ga was obtained by Park et al. (2015) which was unfortunately derived from analyzing an uncharacterized mixture of three grains, each likely to have its own time-temperature history, making any interpretation difficult.

When and how did the collision that resulted in the breakup of Itokawa's parent body occur? In this study, we investigate the deformation (shock) state of the RA-QD02–0030 and RA-QD02–0013 highly-equilibrated particles (Nakamura et al., 2011); hereafter #0030 and #0013) which are two plagioclase + olivine + pyroxene composite grains of 165 μm and 91 μm in diameter, respectively and with #0013 containing K-feldspar exolutions (full petrographic descriptions are given in SI Materials and Methods). We used electron backscatter diffraction (EBSD), alongside the first *single-grain* $^{40}Ar/^{39}Ar$ age dating analyses of extra-terrestrial dust particles. These results give us some insight on the time-temperature (±shock) history of each of those particles. To make sense of those data, we then developed a pressure-temperature-porosity model that supports a low-energy impact process for the disruption of Itokawa's parent body, and used an argon diffusion model to provide a minimum age for this event.

RESULTS

EBSD analyses show that the minerals from particle #0030 appear as irregularly shaped and sized grains, with no crystallographic preferred orientations, common 120° triple junctions and negligible intra-grain lattice strain, indicative of high-temperature textural equilibration (Fig. 1; SI Materials and Methods). Absence of glass, high-pressure polymorphs, mosaicism, planar deformation features (PDFs) and extensive crack damage seems to indicate that this particle did not experience significant shock. The presence of a few cracks (Fig. 1) might suggest a S1-S2

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

shock condition placing an upper limit of 5–10 GPa (Schmitt, 2000). In contrast, particle #0013 shows clear signs of deformation. Although no glass, high-pressure polymorphs, or PDFs were observed, EBSD analyses showed that a large olivine crystal is strained and has up to 6° variation in orientation (Fig. 1). The likely cause for such features in an asteroid particle is shock. Signs of misorientation in olivine provide a minimum shock pressure estimate of 10–15 GPa when compared with artificial shock experiment observations (Schmitt, 2000). A maximum pressure value of 25 GPa can be estimated, above which, experiments show that plagioclase turns to diaplectic glass and above 30 GPa, pyroxene shows signs of mosaicism (Schmitt, 2000), which are not observed.

Particle #0030 had the smallest argon yield of the two particles and this was clearly at the limit of the technique and yielded plateau ages of 5.4 ± 1.6 Ga and 4.6 ± 1.8 Ga depending on the blank correction applied (2σ; Figure 2; SI Materials and Methods). These results suggest that the formation age of the high temperature, equilibrated fabric of this particle is in fact very old. Although the current data do not allow one to exactly calculate its formation age, the important point is that the apparent old age is in agreement with the very low shock nature of particle #0030, where no age resetting is expected. Particle #0013 yielded a well-defined plateau age of 2289 ± 139 Ma (2σ; MSWD = 0.31, P = 1.0; Fig. 2). Two separate spikes of ^{39}Ar released (Fig. 2) are associated with the argon released first from the ca. 5 μm sized K-feldspar, and subsequently from the 25 μm albite crystals, because albite has a higher activation energy than K-feldspar (Cassata and Renne, 2013). A full plateau indicates that all of the radiogenic gas that had accumulated before the impact involving the chondritic grain has been completely reset in both phases during a thermal event at ~2.3 Ga. These data represent the first precise ^{40}Ar/^{39}Ar plateau age ever obtained from a single-grain dust particle recovered in situ from an asteroid.

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

DISCUSSION

Petrographic observations showed that most Itokawa dust particles experienced only very low levels of shock (Nakamura et al., 2011), which a priori suggests low post-shock temperatures. Shock heating in an asteroid collision is a strong function of initial porosity (Davison et al., 2010). The energy expended compacting pore space is retained as waste heat, which dramatically increases the post-shock temperature resulting from a given shock pressure excursion, even for low to moderate shock events (Davison et al., 2016). To better understand the significance of our data, we (1) used solid-state volume diffusion models to test the maximum time-temperature conditions required to reproduce the $^{40}Ar/^{39}Ar$ age spectra for particle #0030 (Fig. 3a) and (2), developed a novel shock-heating model based on the numerical approach described by Davison et al. (2010) using forsterite as an analogue for the composition of Itokawa to calculate the post-shock temperature as a function of peak-shock pressure and porosity (Fig. 4). We ran our model for pressure values up to 70 GPa and initial porosity up to 40% and starting from a pre-shock temperature of 0 °C, (Fig. 4). We have calculated that pre-shock ambient temperature of *buried* particles could vary between ca. 65 °C to –110 °C for a variety of orbits (0.5–1.7 AU), but this would affect our porosity estimate by less than 5% (Fig. 4).

Our model suggests that the low level of pressure experienced by particle #0030 (max. ≤ 10 GPa) corresponds to a maximum temperature of ca. 200 °C for a target rock with a porosity of 10% (Fig. 3), the latter value being similar to most chondrites and expected for a post-compaction (pre-breakup) 4.5 Ga old chondritic asteroid (Consolmagno et al., 2008). Our diffusion models suggest that such a low (and brief) spike in temperature would not be sufficient to reset the K/Ar isotopic clock in feldspar which can withstand temperature spikes up to 500°C

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

before being noticeably affected (Fig. 3a). This is in agreement with (but does not rely upon) the apparent lack of isotopic resetting shown by the $^{40}Ar/^{39}Ar$ age of particle #0030 (Fig. 2). This suggests that the final disruption (breakup) of the proto-Itokawa asteroid was globally a relatively low-temperature process, with some areas not heated above 200 °C. This is in excellent agreement with breakup models of structurally weakened monolith asteroids (Michel et al., 2004a, b) where asteroids have been suggested to be pre-shattered by continuous battering by small impacts and more prone to breakup, even by a final low-energy impact.

EBSD and $^{40}Ar/^{39}Ar$ analyses of particle #0013 suggest a localized impact event with sufficient energy to fully reset the K/Ar system in plagioclase and K-feldspar at ~2.3 Ga. To estimate the heating conditions (minimum temperature coupled with cooling duration) that can reproduce the reset $^{40}Ar/^{39}Ar$ age spectrum of particle #0013, we calculated the post-impact cooling duration of a chondrite boulder of 25 m radius (similar to size of the biggest boulders at the surface of Itokawa; Tsuchiyama, 2014) from peak post-shock temperatures of 900 °C to below 200 °C following the approach of Humayun and Koeberl (2004), and considering that particle #0013 is buried in the boulder at an unknown depth. We iteratively coupled these results with our solid-state diffusion model discussed above (Fig. 3; SI Materials and Methods for details). Our models show that a post-shock temperature greater than ~900 °C associated with a cooling duration of 12.5 days are necessary to fully reset the K/Ar system. For the low (≤ 10%) porosity material expected to be found in Itokawa's monolithic parent body prior to breakup (Consolmagno et al., 2008; Michel and Richardson, 2013), a post-shock temperature of 900 °C would imply shock levels >50 GPa (Fig. 4), which is inconsistent with petrographic observations. However, our pressure-temperature-porosity model suggests that impact shock pressure of 15–25 GPa can produce post-shock temperatures of 900 °C, provided that the target

material had an initial porosity of at least 20%–30% (Fig. 4). Such a high porosity level is more likely compatible with the average porosity of a rubble pile asteroid (~40% for Itokawa; Tsuchiyama, 2014).

Therefore, those results imply that the high-porosity rubble pile structure seen today already existed at ~2.3 Ga, which provides a *minimum* age for the breakup event of the monolithic proto-Itokawa parent body and the formation of the rubble-pile Itokawa. The two particles then resided at least few meters in the regolith layer until they surfaced less than 10 million years ago as indicated by cosmogenic nuclides obtained on several other particles (Nagao et al., 2011).

CONCLUSIONS

In this study, petrographic and EBSD observations, $^{40}Ar/^{39}Ar$ analyses, pressure-temperature-porosity models and solid-state argon diffusion models provide coherent constraints and suggest that the breakup of Itokawa's monolithic parent body (formed at 4.5 Ga) occurred more than 2.3 billion years ago and was a relatively low temperature process caused by a moderate sized impact occurring on a pre-shattered parent body.

ACKNOWLEDGMENTS

We thank an anonymous reviewer, D. Nakashima and K. Min for their constructive reviews, and editor D. Brown.

REFERENCES CITED

Abe, M., et al., 2006, Near-infrared spectral results of asteroid Itokawa from the Hayabusa spacecraft: Science, v. 312, p. 1334–1338.

Benz, W., Cameron, A.G.W., and Melosh, H.J., 1989, The origin of the Moon and the single-impact hypothesis III: Icarus, v. 81, p. 113–131, doi:10.1016/0019-1035(89)90129-2.

164 Cassata, W.S., and Renne, P.R., 2013, Systematic variations of argon diffusion in feldspars and
165 implications for thermochronometry: Geochimica et Cosmochimica Acta, v. 112, p. 251–
166 287, doi:10.1016/j.gca.2013.02.030.
167 Consolmagno, G., Britt, D., and Macke, R., 2008, The significance of meteorite density and
168 porosity: Chemie der Erde-Geochemistry, v. 68, p. 1–29, doi:10.1016/j.chemer.2008.01.003.
169 Crank, J., and Gupta, R.S., 1975, Isotherm Migration Method in 2 Dimensions: International
170 Journal of Heat and Mass Transfer, v. 18, p. 1101–1107, doi:10.1016/0017-9310(75)90228-
171 8.
172 Davison, T.M., Collins, G.S., and Ciesla, F.J., 2010, Numerical modelling of heating in porous
173 planetesimal collisions: Icarus, v. 208, p. 468–481, doi:10.1016/j.icarus.2010.01.034.
174 Davison T. M., Collins G. S., and Bland P. A. 2016. Mesoscale Modeling of Impact Compaction
175 of Primitive Solar System Solids. *The Astrophysical Journal* 821:68.
176 Humayun, M., and Koeberl, C., 2004, Potassium isotopic composition of Australasian tektites:
177 Meteoritics & Planetary Science, v. 39, p. 1509–1516, doi:10.1111/j.1945-
178 5100.2004.tb00125.x.
179 McDougall, I., and Harrison, T.M., 1999, Geochronology and thermochronology by the
180 40Ar/39Ar method: Oxford, New York, Oxford University Press, 269 p.
181 Michel, P., Benz, W., and Richardson, D.C., 2004a, Catastrophic disruption of asteroids and
182 family formation: A review of numerical simulations including both fragmentation and
183 gravitational reaccumulations: Planetary and Space Science, v. 52, p. 1109–1117,
184 doi:10.1016/j.pss.2004.07.008.
185 -, 2004b, Catastrophic disruption of pre-shattered parent bodies: Icarus, v. 168, p. 420–432,
186 doi:10.1016/j.icarus.2003.12.011.

Michel, P., and Richardson, D.C., 2013, Collision and gravitational reaccumulation: Possible formation mechanism of the asteroid Itokawa: Astronomy and Astrophysics, v. 554, p. L1–L4, doi:10.1051/0004-6361/201321657.

Nagao, K., Okazaki, R., Nakamura, T., Miura, Y.N., Osawa, T., Bajo, K.-i., Matsuda, S., Ebihara, M., Ireland, T.R., and Kitajima, F., 2011, Irradiation history of Itokawa regolith material deduced from noble gases in the Hayabusa samples: Science, v. 333, p. 1128–1131, doi:10.1126/science.1207785.

Nakamura, T., et al., 2011, Itokawa dust particles: A direct link between S-type asteroids and ordinary chondrites: Science, v. 333, p. 1113–1116, doi:10.1126/science.1207758.

Nakashima, D., Kita, N.T., Ushikubo, T., Noguchi, T., Nakamura, T., and Valley, J.W., 2013, Oxygen three-isotope ratios of silicate particles returned from asteroid Itokawa by the Hayabusa spacecraft: A strong link with equilibrated LL chondrites: Earth and Planetary Science Letters, v. 379, p. 127–136, doi:10.1016/j.epsl.2013.08.009.

Park, J., Turrin, B.D., Herzog, G.F., Lindsay, F.N., Delaney, J.S., Swisher, C.C., Uesugi, M., Karouji, Y., Yada, T., and Abe, M., 2015, 40Ar/39Ar age of material returned from asteroid 25143 Itokawa: Meteoritics & Planetary Science, v. 50, p. 2087–2098, doi:10.1111/maps.12564.

Schmitt, R.T., 2000, Shock experiments with the H6 chondrite Kernouve: Pressure calibration of microscopic shock effects: Meteoritics & Planetary Science, v. 35, p. 545–560, doi:10.1111/j.1945-5100.2000.tb01435.x.

Tsuchiyama, A., 2014, Asteroid Itokawa a source of ordinary chondrites and a laboratory for surface processes: Elements, v. 10, p. 45–50, doi:10.2113/gselements.10.1.45.

FIGURE CAPTIONS

Figure 1. Crystallographic orientation maps measured by Electron Back Scatter Diffraction (EBSD). A) particle #0030; B) particle #0013; C) enlarged portion panel B). The particles contain olivine (Ol), low- and high-Ca pyroxene (L-Px, H-Px), plagioclase (Pl), K-feldspar (K-Fd), chromite (Chr), taenite (Tae) and kamacite (Kam). Phases in (A) and (B) are colored using an Euler color scheme. Olivine in (B) and (C) is colored for crystallographic misorientation from a reference point (red cross), and shows up to 6° of lattice strain. Greyscale of feldspar in C reflects crystallinity (pale = stronger EBSD patterns), and reveals planar fractures (white triangles). Detailed procedure and results are provided in the Supplementary Information.

Figure 2. Single-grain laser step-heating $^{40}Ar/^{39}Ar$ age spectra of particles #0030 and #0013 measured on the ARGUS VI mass spectrometer. Note that #0030 yielded plateau ages of ~5.4 ± 1.6 Ga for blank correction #2 or and 4.6 ± 1.8 Ga for blank correction #1 (not shown). The solid line indicates the width of the plateau age (i.e., the steps included in the calculation). Detailed procedure and results are provided in the SI Materials and Methods.

Figure 3. Modeled age spectra based on the diffusion equations of Crank and Gupta (1975) and McDougall and Harrison (1999) for a mixture comprising a 25 μm radius sphere with an albite composition and a 5μm radius sphere with a K-feldspar composition that has been heated at peak temperatures ranging from 500 °C to 900 °C. Cooling from the peak temperature to 200 °C is simulated over 12.5 days (cf. Supplementary information). Blue areas represent age spectrum envelopes from Fig. 2.

Figure 4. Post-shock temperature of forsterite as a function of shock pressure for a range of different initial porosities (ϕ). Shock and release calculations computed using ANEOS (ANalytical Equation Of State) for forsterite (Benz et al., 1989), following the approach described by (Davison et al., 2010). Temperatures above the solidus (dashed lines) are

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39138.1

approximate as latent heat of fusion is neglected. Horizontal lines indicate the upper and lower bounds on heating inferred from K/Ar system resetting.

1GSA Data Repository item 2017xxx, xxxxxxxx, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

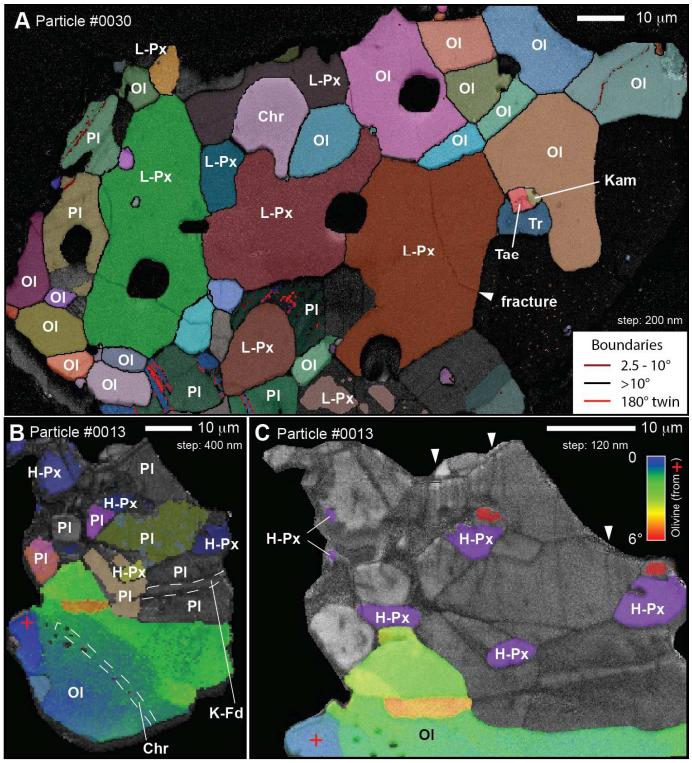

Fig. 1: Jourdan et al.

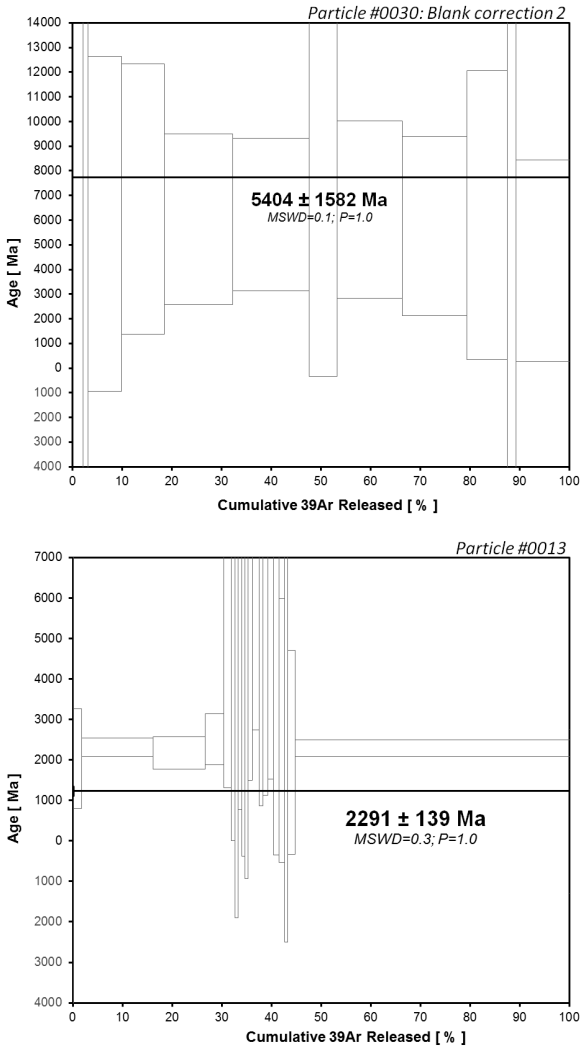

Fig. 2: Jourdan et al.

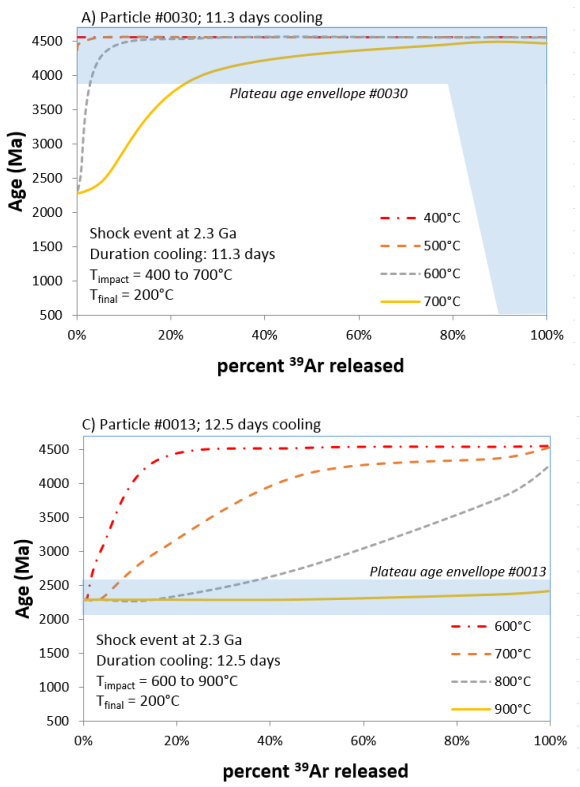

Fig. 3: Jourdan et al.

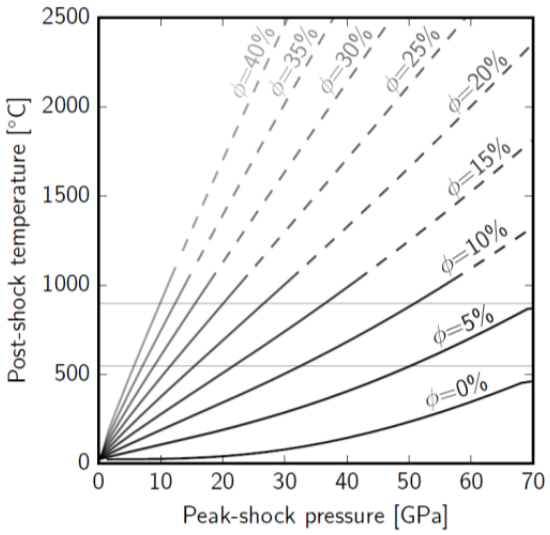

Fig . 4: Jourdan et al.