Advanced design rules for optimal dynamic properties of additive manufactured products

amadam additive manufacturing

ADVANCED DESIGN RULES
FOR OPTIMAL DYNAMIC PROPERTIES
of additive manufactured products

Fracture mechanics of additive manufactured crack-like notches by digital image correlation

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PROJECT SUPPORTED BY European Commission

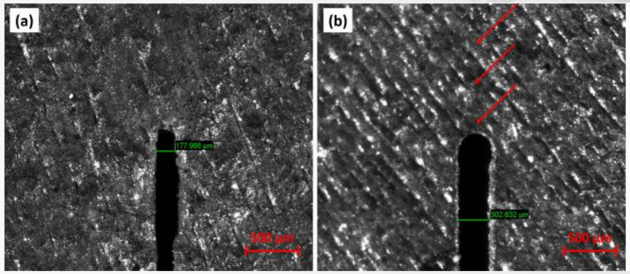
Summary

- A_Madam Project
- Crack-like notches
  - – Are they actual cracks? What about pre-cracking?

  DIC monitored experimental tests on IACB specimens
  - – Different mixed modes
    - Metal
    - Plastics

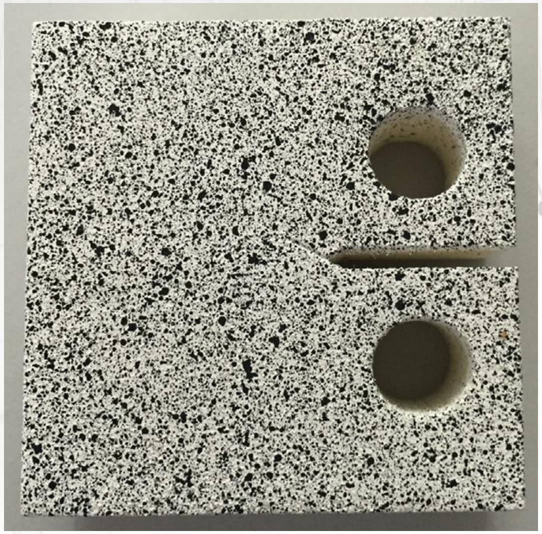
Crack-like notches

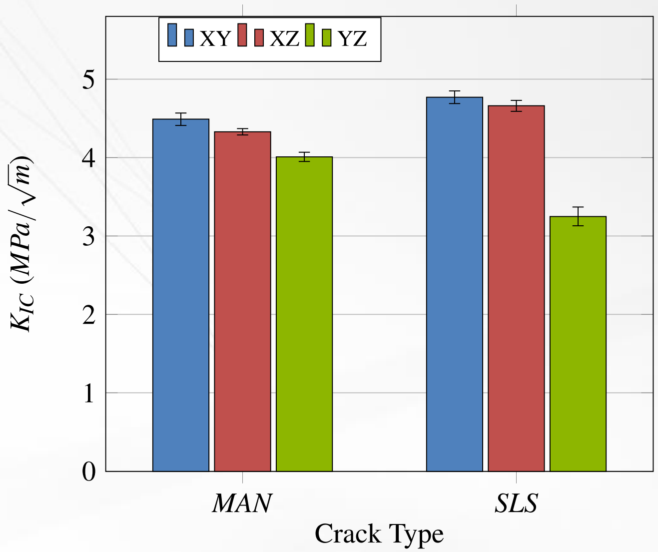
- by AM it is possible to produce crack-like notches, but not real cracks.
- The minimum radius of curvature depends on the technology (around 90 micrometers).
- The possibility to make this crack grow by fatigue pre-cracking is linked to the component geometry and loading.
- Moreover, it would be tricky to make the crack propagate exactly in the desired direction.



Previous work on CT specimens

- Pure Mode I, comparison with blade induced cracks.

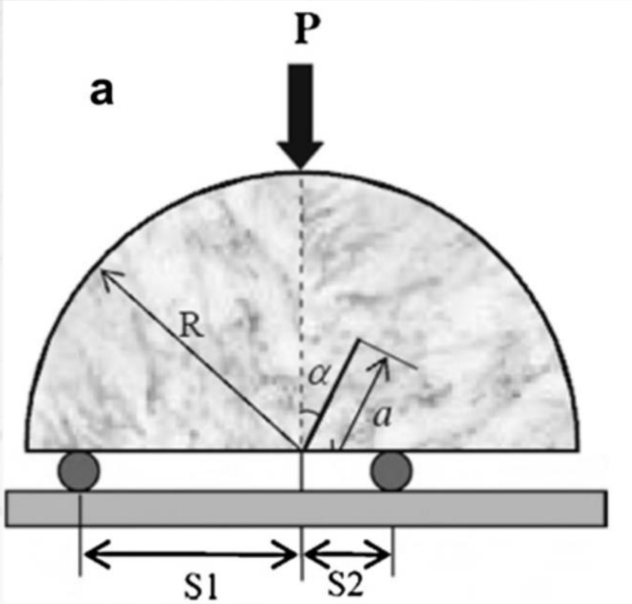




- T. Brugo et al. Fracture *mechanics of laser sintered cracked polyamide for a new method to induce cracks by additive manufacturing.* Polymer Testing, 2016

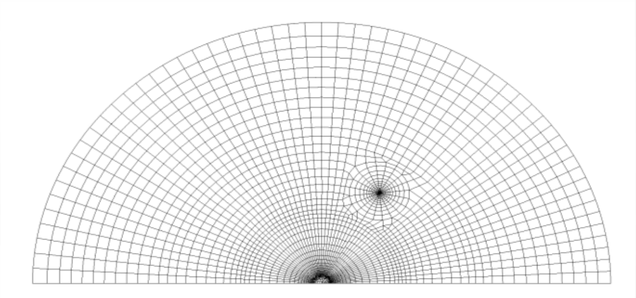
IASCB Specimens

- A Variety of mixed modes is attainable
- Suitable for brittle plastics, pre-cracking issues for metals.
- Shape functions (Y_1 and Y_2) FEM calculation is needed.

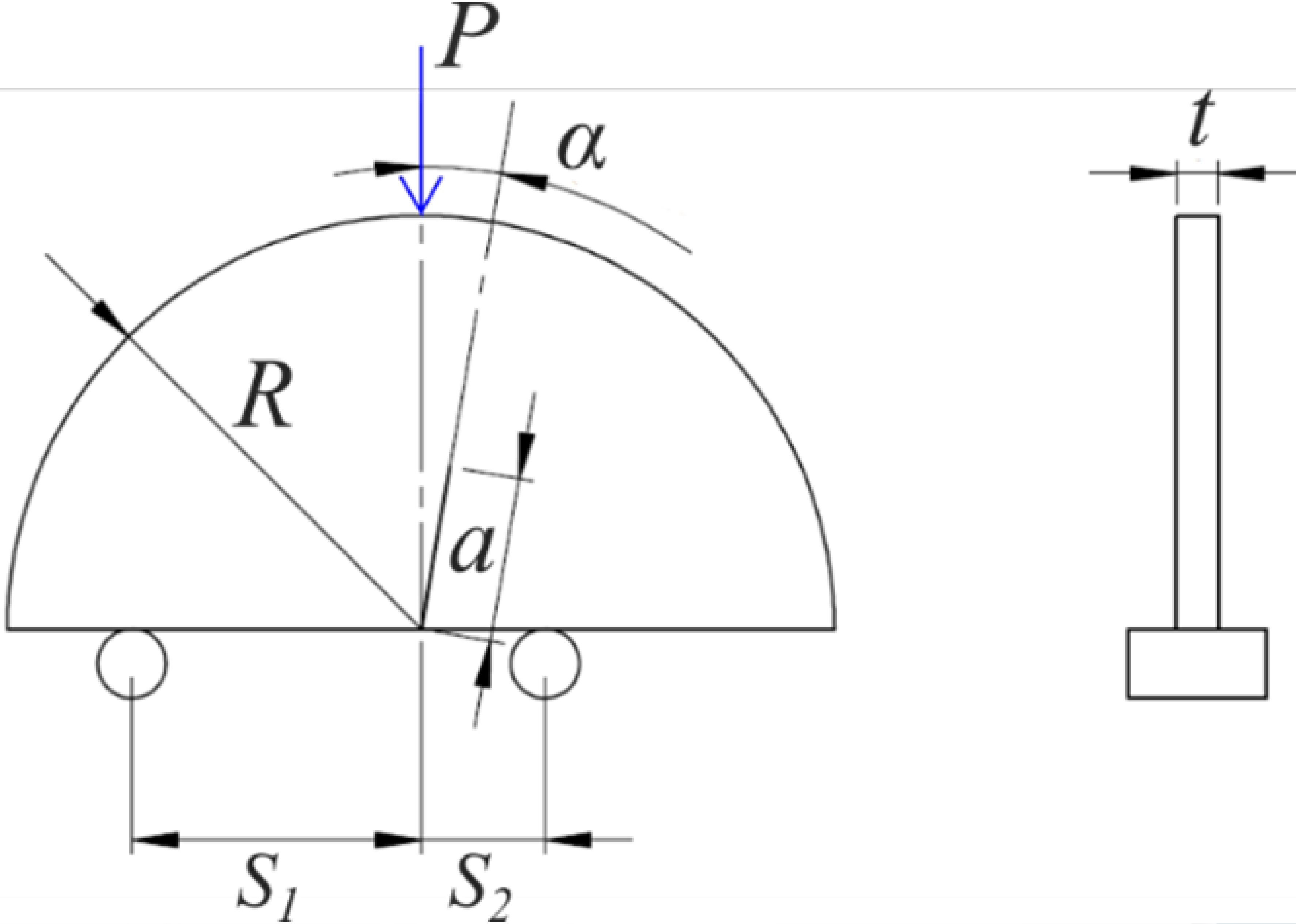


$$K_I = \frac{P}{2Rt}\sqrt{\pi a}Y_I(a/R, S1/R, S2/R, \alpha)$$

$$K_{II} = \frac{P}{2Rt}\sqrt{\pi a}Y_{II}(a/R, S1/R, S2/R, \alpha)$$



- H. Saghafi et al. , *Evaluating fracture behavior of brittle polymeric materials using an IASCB specimen*, Polymer Testing (2013)



displacement field rather than to the strain one

Materials and Production devices

- EOSINT M 280 selective laser sintering (SLS) machine
- EOS Maraging steel MS1

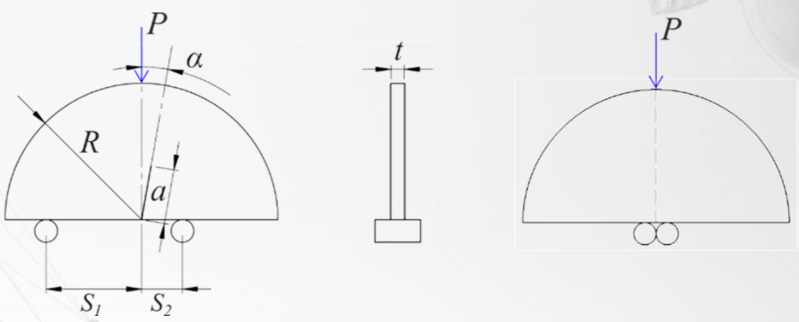
Property	Value
Sintered Density	8.0–8.1 g/cm^3
Elastic Modulus	180 ± 20 GPa
Yield Strength	min. 1862 MPa
Tensile Strength	min. 1930 MPa
Hardness	typ. 50–56 HRC
Ductility (Notched Charpy Impact Test)	11 ± 4 J

- EOS Formiga P100 (SLS) machine
- Fine polyamide PA 2200 powder (Plastic Design & Service)

Property	Value
Flexural Young's modulus	2.1 ± 0.1 GPa
Flexural Yield strength–	55 ± 3 MPa
Flexural strength	68 ± 2 MPa

Experimental testing plans and DIC setup

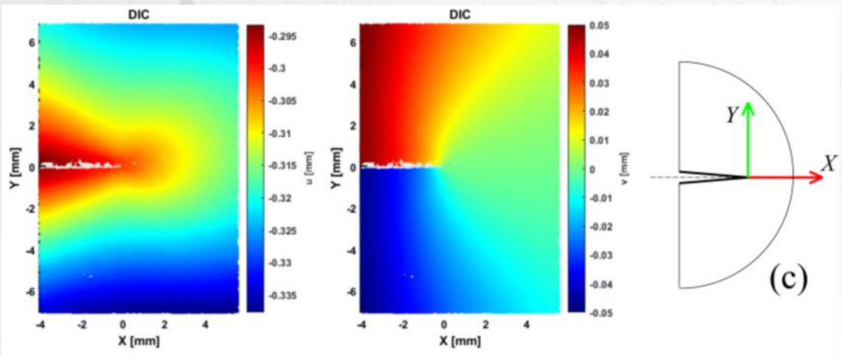
- 2D measurement setup
  - no large displacements
  - errors duo to lens imperfections can be neglected for localized displacements
  - 2D setup gives more flexibility with field of view (FOV) sizes, since the number of pixels in the camera is constant but just by changing the lens settings and distance from the object it is possible to adjust the 2D FOV practically to any desired size
  - Care must be taken with 2D setups since the camera chip needs to be perfectly parallel to the specimen surface
  - the specimen should have negligible out of plane displacement and rotations during the test since there is no possibility to compensate for out of plane rigid body motion,
  - In 3D setups, the surface must be smooth enough not to cause problems to DIC when viewed from different sides for big magnifications
- The images were acquired by exploiting the GOM Snap 2D free software and processed by GOM Correlate (GOM GmbH, Braunschweig, Germany)
- A black speckle pattern was spray-painted
- 19 pixels facet size, 16 pixels point distance, 8 facets spatial filter (median) and 3 time-step temporary filters (median).
- Optimal compromise between the spatial resolution and the precision of the displacement field measurement around the crack tip.



Type	α (deg)	S_2 (mm)	S_1 (mm)	n	Mode	M^e
SM	0	42	42	3	Mode I	1
AM	0	42	42	3	Mode I	1
AM	10	42	42	3	Mixed I-II	0.77
AM	10	42	18	3	Mixed I-II	0.48
AM	10	42	10.2	3	Mode II	0.12

Modelling for Maraging Steel

- Interpolation of the results by the Williams formulation.



$$u_I = \sum_{n=1}^{\infty} \frac{r^{\frac{n}{2}}}{2\mu} a_n \left\{ \left[\kappa + \frac{n}{2} + (-1)^n \right] cos \frac{n\theta}{2} - \frac{n}{2} cos \frac{(n-4)\theta}{2} \right\}$$

$$v_I = \sum_{n=1}^{\infty} \frac{r^{\frac{n}{2}}}{2\mu} a_n \left\{ \left[\kappa - \frac{n}{2} - (-1)^n \right] sin \frac{n\theta}{2} + \frac{n}{2} sin \frac{(n-4)\theta}{2} \right\}$$

$$u_{II} = -\sum_{n=1}^{\infty} \frac{r^{\frac{n}{2}}}{2\mu} b_n \left\{ \left[\kappa + \frac{n}{2} - (-1)^n \right] sin \frac{n\theta}{2} - \frac{n}{2} cos \frac{(n-4)\theta}{2} \right\}$$

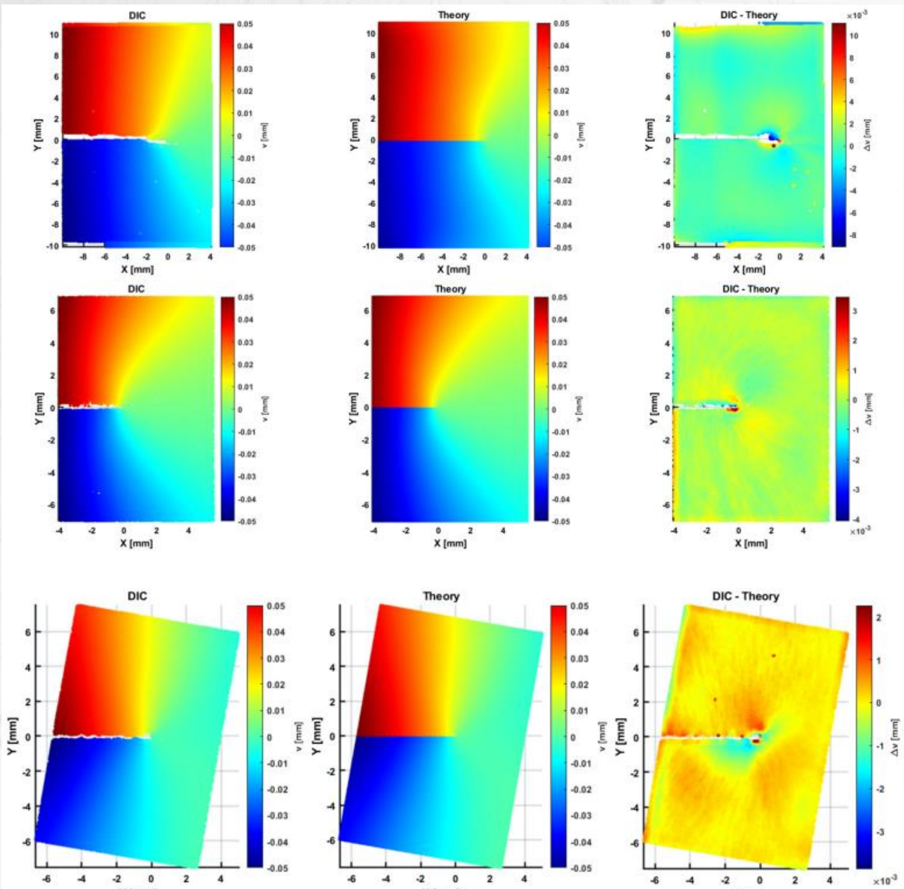
$$v_{II} = \sum_{n=1}^{\infty} \frac{r^{\frac{n}{2}}}{2\mu} b_n \left\{ \left[\kappa - \frac{n}{2} + (-1)^n \right] cos \frac{n\theta}{2} + \frac{n}{2} cos \frac{(n-4)\theta}{2} \right\}$$

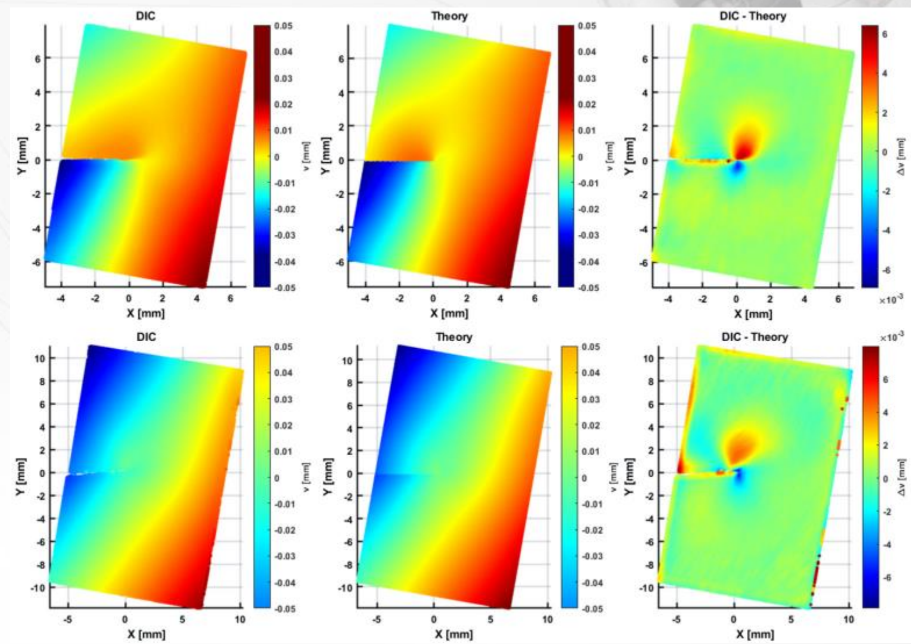
$$u = u_I + u_{II} \qquad K_I = a_1 \sqrt{2\pi}$$

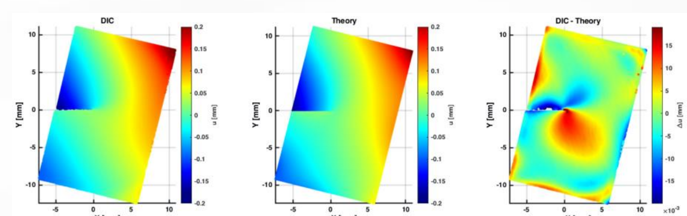
$$v = v_I + v_{II} \qquad K_{II} = -b_1 \sqrt{2\pi}$$

I. Campione et al. *Investigation by Digital Image Correlation of Mixed-Mode I and II Fracture Behavior of Metallic IASCB Specimens with Additive Manufactured Crack-Like Notch,* Metals (2020)

Results for Maraging steel (displacements)





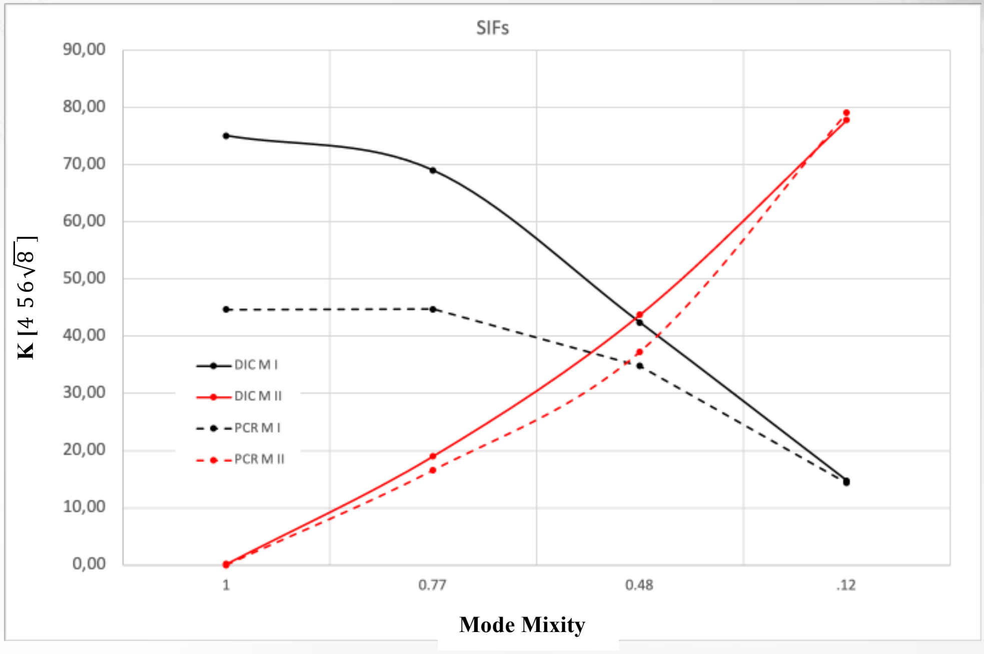


Results for Maraging steel (SIFS)

Specimen Configuration	By Critical Fracture Load (PCR)		By Crack Tip Displacement Field (DIC)		DIC vs. PCR	
	K_I (MPa $\sqrt{m}$)	K_{II} (MPa $\sqrt{m}$)	K_I (MPa $\sqrt{m}$)	K_{II} (MPa $\sqrt{m}$)	ΔK_I (%)	ΔK_{II} (%)
SM-0-42-42-1	32.1	0.0	58.3	1.2	81	-
SM-0-42-42-2	30.4	0.0	56.1	2.9	85	-
SM-0-42-42-3	33.7	0.0	60.5	2.3	80	-
AM-0-42-42-1	42.5	0.0	73.5	0.2	73	-
AM-0-42-42-2	44.9	0.0	76.4	0.1	70	-
AM-0-42-42-3	46.6	0.0	75.2	0.2	61	-
AM-10-42-42-1	44.4	16.5	70.5	20.5	59	25
AM-10-42-42-2	44.6	16.5	66.2	18.3	49	11
AM-10-42-42-3	45.1	16.7	70.2	18.3	56	10
AM-10-42-18-1	33.7	36.1	43.7	42.2	30	17
AM-10-42-18-2	36.3	38.8	39.2	43.4	8	12
AM-10-42-18-3	34.4	36.9	44.2	45.7	28	24
AM-10-42-10.2-1	15.3	83.5	14.9	77.1	−2	−8
AM-10-42-10.2-2	13.6	74.2	14.4	75.5	5	2
AM-10-42-10.2-3	14.2	79.4	14.9	80.8	5	2

Discussion for Maraging steel

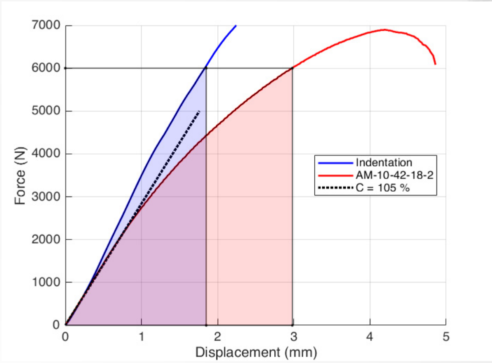
- The discrepancy in Mode I cannot be provoked by the small plastic zone at the crack-tip (for not more than 5%)
- The K_I depends on the three-dimensional stress state at the crack tip.
- The DIC based technique evaluates the SIF from the displacement field measured on the outer surface, which is in-plane stress condition.
- This phenomenon becomes less important reducing the Mode Mixity until Mode II is reached.
- AM Crack-like notches show a 25% higher K_I than the actual cracks

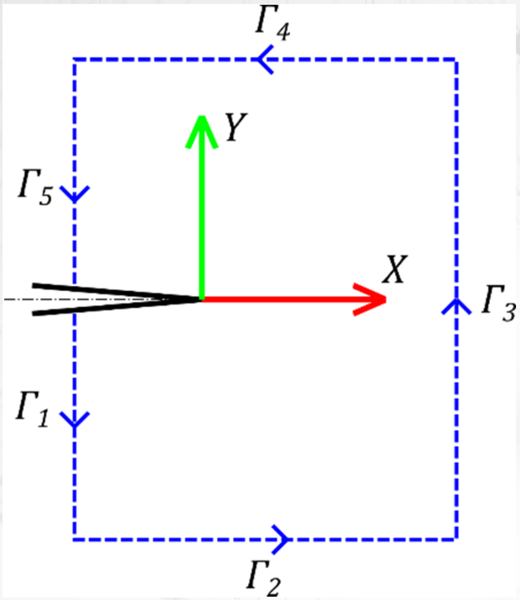


Modelling for Polyamide

- Calculation of the J-integral
  - from the Load-Displacement curve by means of FEM,
  - directly from DIC

$$J = \eta \frac{U}{t\,(R-a)}$$





$$J = \int_{\Gamma} \left(W dy - t_i \frac{\partial u_i}{\partial x} ds \right)$$

$$f\Delta l = W\Delta y - t_i \frac{\Delta u_i}{\Delta x} \Delta s$$

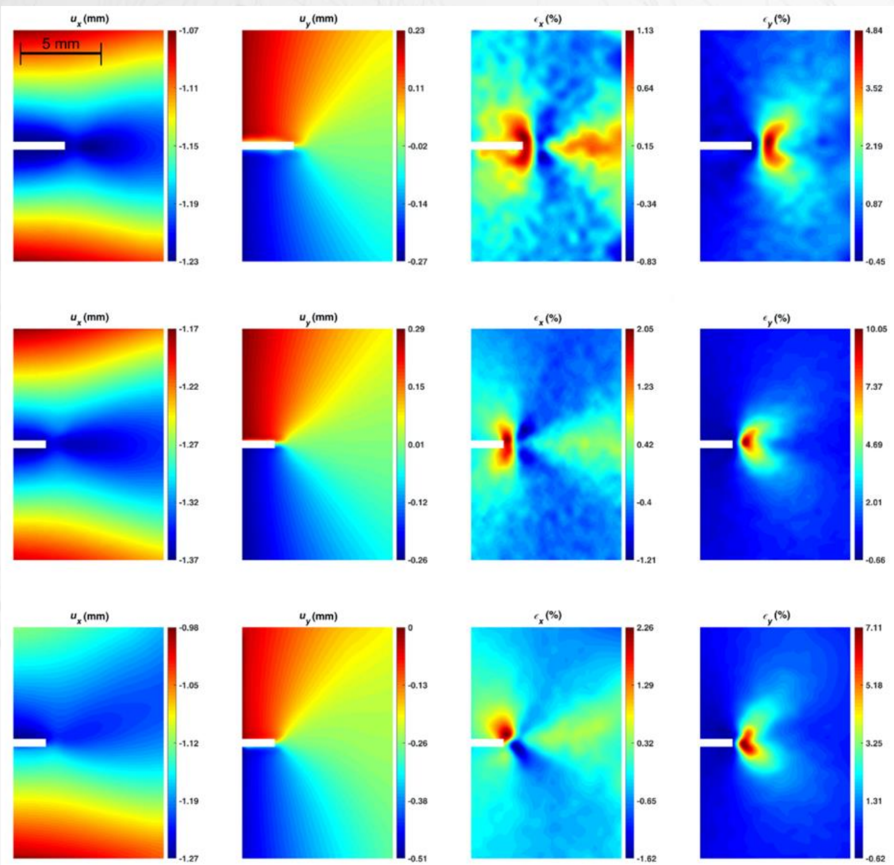
$$\frac{\varepsilon_e}{\varepsilon_0} = \frac{\sigma_e}{\sigma_0} + \alpha \left(\frac{\sigma_e}{\sigma_0} \right)^n$$

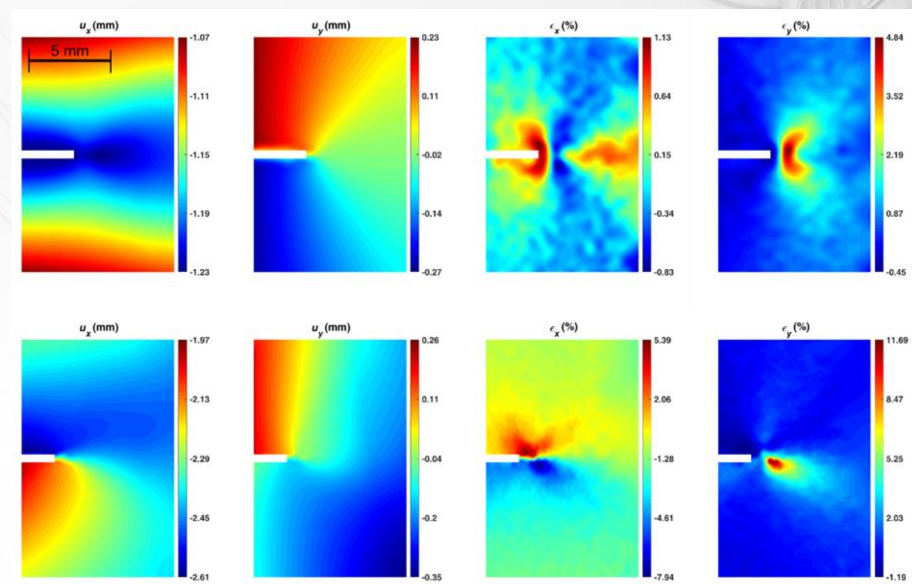
$$f\Delta l = W\Delta y - \left[\frac{\Delta u_x}{\Delta x} (n_x \sigma_x + n_y \tau_{xy}) + \frac{\Delta u_y}{\Delta x} (n_y \sigma_y + n_x \tau_{xy}) \right] \Delta s$$

$$W = \frac{1}{E} \left[\frac{1}{2} {\sigma_e}^2 + \frac{1}{2} (1 - 2\nu)(\sigma_x \sigma_y - {\tau_{xy}}^2) + \frac{\alpha n}{n+1} {\sigma_e}^2 \left(\frac{\sigma_e}{\sigma_0} \right)^{n-1} \right]$$

- T. Brugo et al. *Investigation by Digital Image Correlation of Mixed-Mode I and II Fracture Behavior of Polymeric IASCB Specimens with Additive Manufactured Crack-Like Notch*, Materials (2021)

Results for Polyamide (displacements and strain)



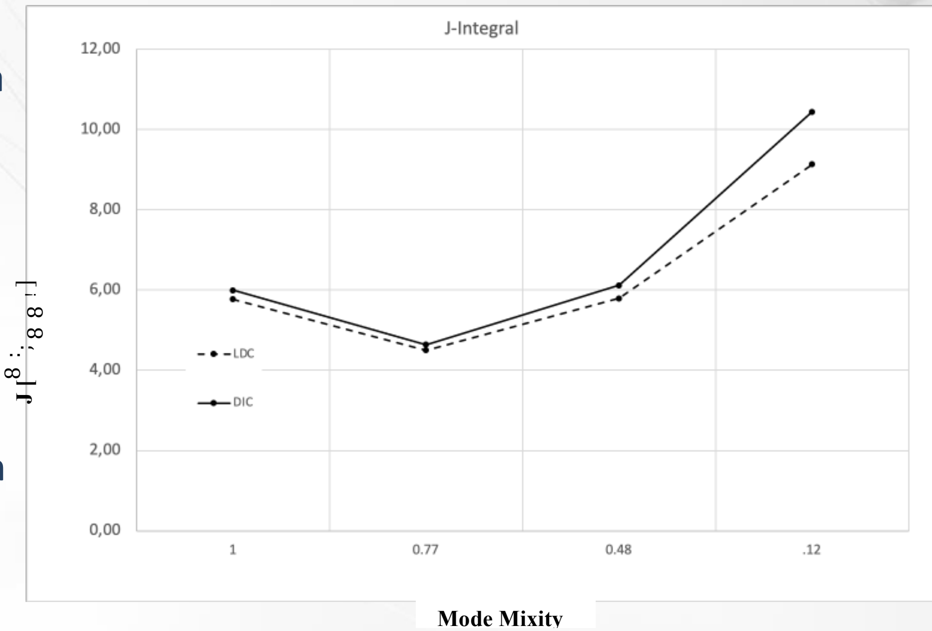


Results for Polyamide (J)

Specimen Configuration	M^e	LDC Method J (mJ/mm^2)	J_{mean}	σ(J)	DIC Method J (mJ/mm^2)	J_{mean}	σ(J)	LDC vs. DIC Δ%
SM-0-42-42-1		5.40			4.95			−8.33
SM-0-42-42-2	1	4.82	5.14	0.29	4.68	4.66	0.30	−2.90
SM-0-42-42-3		5.20			4.36			−16.15
AM-0-42-42-1		5.09			6.42			26.13
AM-0-42-42-2	1	6.12	5.77	0.59	5.52	5.99	0.45	−9.80
AM-0-42-42-3		6.10			6.03			−1.15
AM-10-42-42-1		4.30			4.98			15.81
AM-10-42-42-2	0.77	4.78	4.50	0.25	4.55	4.64	0.30	−4.81
AM-10-42-42-3		4.42			4.40			−0.45
AM-10-42-18-1		5.56			6.16			10.79
AM-10-42-18-2	0.48	5.95	5.79	0.21	6.48	6.12	0.38	8.91
AM-10-42-18-3		5.87			5.72			−2.56
AM-10-42-10.2-1		9.03			9.59			6.20
AM-10-42-10.2-2	0.12	8.26	9.13	0.92	10.50	10.44	0.82	27.12
AM-10-42-10.2-3		10.10			11.23			11.19

Discussion for Polyamide

- The difference between the values computed by the DIC-based method and the conventional LDC method comparable to the experimental errors of each method
- Therefore, the DIC methodology can be considered a valid method to evaluate the J-integral in condition where is not possible to use the conventional LDC method due to complex non know loading conditions
- The J-integral mean value of the notch induced by the AM method is 12.2 % higher than the one obtained by the SM method, but it is within the experimental error
- This can be attributed to a less sharp crack-like notch in the case of AM specimens, which leads to a lower stress concentration in the area near the crack tip, and therefore to a higher apparent fracture toughness value
- J-integral as a function of the mode mixity ratio M curve has a minimum at a mixity ratio equal to 0.77 and then it increases up to pure mode II.



Conclusion

- Two methodologies based on DIC have been shown in detail and compared in the case of IASCB specimens containing additive manufactured crack-like notches.

The main findings are:

- by DIC measurement of the displacement it is possible to evaluate the SIFs using the interpolation of the William’s model.
- by DIC measurement of the displacement and by the derivation of the strain and stresses (using a material constitutive equation) it is possible to evaluate the average J-integral around the crack tip.
- The values obtained by the first method are overestimated in the case of pure Mode 1 with respect to the results obtained from the load-displacement curve.
- The values obtained by the second method are in good agreement with the results obtained from the load-displacement curve.

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Thank you!

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