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POLSKA AKADEMIA NAUK

Arch. Metall. Mater. **63** (2018), 2, 773-779

DOI: 10.24425/122403

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DISCUSSIONS AND COMMENTS ON THE PAPER
E.S. Dzidowski, 2013, "The Effect of Secondary Metalworking Processes on Susceptibility of Aircraft to Catastrophic Failures and Prevention Methods", Archives of Metallurgy and Materials, 58 (4), pp. 1207-1212)

1. Introduction

The paper *'The effect of secondary metalworking processes on susceptibility of aircraft to catastrophic failures and prevention methods'* [1] emphasizes that fatigue is the main failure mode for metallic aircraft structures. This is corroborated by Figure 1 [2,3] and other sources [4-6].

However, the paper contains some remarkable statements reflecting upon the main topics in it:

(1) Paper abstract: *"The causes of plane crashes, stemming from the subcritical growth of fatigue cracks, are examined. It is found that the crashes occurred mainly because of the negligence of the defects arising in the course of secondary metalworking processes. It is shown that it is possible to prevent such damage, i.e. voids, wedge cracks, grain boundary cracks, adiabatic shear bands and flow localization, through the use of processing maps....."*

(2) Paper section 1: *"There are many indications that the knowledge of the causes of such damage and their criticality and the ways of preventing it is not common. This observation mainly applies to aircraft parts manufacturers who may have difficulties in optimizing the plastic forming of atypical materials such as novel titanium alloys."*

(3) Paper section 2: *"The problem......can be solved provided that the aircraft parts subcontractors (often haphazardly selected) are made aware of the problem and understand its causes."*

The discussions and comments in the following sections of the present document are directed to the foregoing statements and their validities.

2. Causes of Fatigue-Related Aircraft Accidents

Two sources of information on the nucleation sites and causes for fatigue-related accidents in metallic aircraft structures are the compilations by Campbell and Lahey [4] and Tiffany et al. [6]. Figure 2 shows the extensive Campbell and Lahey data, highlighting the nucleation sites (defects) present after secondary metalworking. Such defects represent 1.3% and 2.4% of the totals for fixed wing and rotary wing aircraft, respectively. Even if the categories 'Manufacturing defect or tool mark' and 'Surface or subsurface flaw' are combined (which is at least partly unjustified), then the numbers still represent only 7.3% and 9.6% of the respective totals.

Failure modes	Percentages of failures	
	Aircraft structures	Engineering industry
Corrosion	3-16	29
Fatigue	55-61	25
Brittle fracture	–	16
Overload	14-18	11
High temperature corrosion	2	7
SCC/CF/HE	7-8	6
Creep	1	3
Wear/abrasion/erosion	6-7	3

*SCC: stress corrosion cracking; CF: corrosion fatigue; HE: hydrogen embrittlement

Fig. 1. Failure modes in aircraft structures compared with general engineering: after Refs [2,3]

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Nucleation sites	Numbers of accidents	
	Fixed wing	Rotary wing
Bolt, stud or screw	108	32
Fastener hole or other hole	72	12
Fillet, radius or sharp notch	57	22
Weld	53	3
Corrosion	43	19
Thread (other than bolt or stud)	32	4
Manufacturing defect or tool mark	27	9
Scratch, nick or dent	26	2
Fretting	13	10
Surface or subsurface flaw	6	3
Improper heat-treatment	4	2
Maintenance-induced crack	4	–
Work-hardened area	2	–
Wear	2	7

Fig. 2. Fatigue nucleation sites for aircraft accidents resulting from fatigue [4]

Fatigue causes	Numbers of accidents	
	Airframes	Engine discs
Unanticipated high local stresses (*possibly* combined with *final* manufacturing defects)	11	–
Manufacturing defect or tool mark	3	2
Material defect	2	1
Maintenance deficiencies	6	–
Abnormally high fan speed		1

Fig. 3. Fatigue causes for some aircraft accidents [6]

The less extensive data from Tiffany et al. [6] yield the results summarised in Figure 3. Material defects represent 9.1% of the total for airframes and 25% for the engine discs (though this is obviously biased by the low total number). Notwithstanding the limited numbers of data, it is clear that the main causes of airframe fatigue were unanticipated high local stresses. Also, the material defect data in Figure 3 are significant in the context of improvements in airframe and engine disc structural integrity and safety, as will be discussed in subsections 2.1 and 2.2.

2.1. Material defect influences on airframe structural integrity

The airframe material defects listed in Figure 3 refer to two materials and aircraft types [6]:

(1) A propeller nacelle magnesium casting failure on the experimental Curtis Wright X-19 aircraft, which crashed during a flight test in mid-1965. The manufacturing defect was a sand inclusion. This accident is significant because it is a dramatic demonstration of the inadvisability of using sand castings in airframe structures. For many years much effort has been put into obtaining premium quality investment castings, but these are generally not regarded as competitive with wrought products, particularly for critical components. This is reflected in the use of 'Casting Factors', i.e. extra safety factors on design allowables, and also a recent FAA opinion [7] that airframe castings should be removed from officially validated MMPDS handbook data [8].

(2) Failure of the high-strength D6ac steel left wing pivot fitting of the U.S. Air Force (USAF) General Dynamics F-111A #67-0049 aircraft during a practice bombing run on December 22nd, 1969. The failure was the result of an approximately semi-elliptical surface defect 23.4 mm X 5.9 mm in the lower plate of the pivot fitting, see Figure 4. As Tiffany *et al.* [6] stated, this manufacturing defect *"is arguably the most infamous crack in aviation history"*. This statement presumably refers to the large size of the defect, which should have been detected before the aircraft entered service.

On a more positive note, this failure, and early fatigue cracking in Lockheed C-5A wing boxes [10], resulted in the USAF abandoning the fatigue Safe-Life policy and introducing the USAF Damage tolerance (DT) approach in 1974-1975 [11,12].

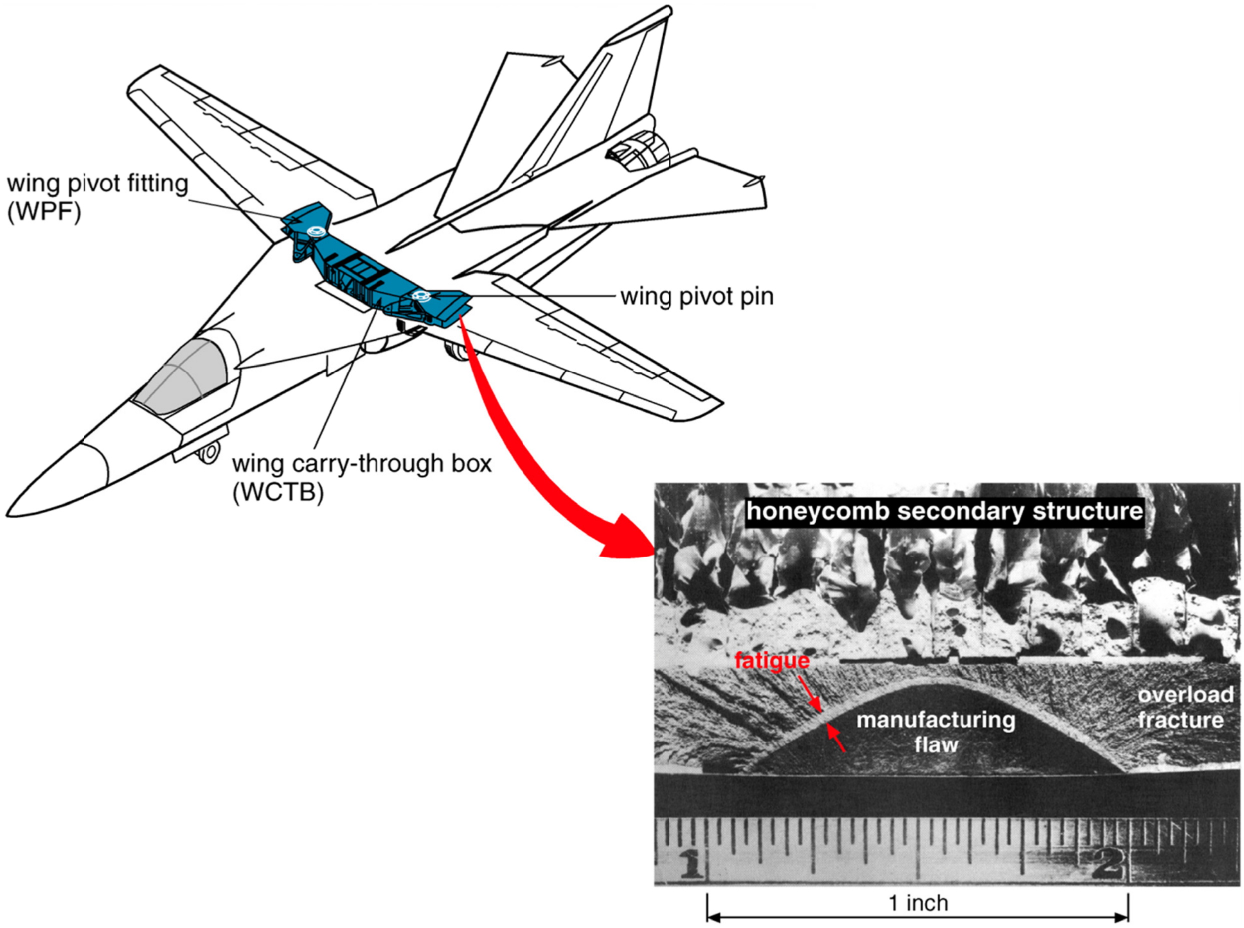


Fig. 4. Origin of F-111A wing pivot failure: a large manufacturing defect [9]

The F-111A accident represents a 'milestone' in the history of military airframe structural integrity requirements [9]. However, there are at least five other 'milestones', concerning both military and civil aircraft and their structural integrity requirements, see Figures 5 and 6. Furthermore there were ten 'milestone' accidents: 4 B-47s, 1 F-111A, 1 MB326H, 2 Comets, 1 Boeing 707 and 1 Boeing 737. These have recently been reviewed [9], and the evidence is that only one – the F-111A accident – was caused by a material defect.

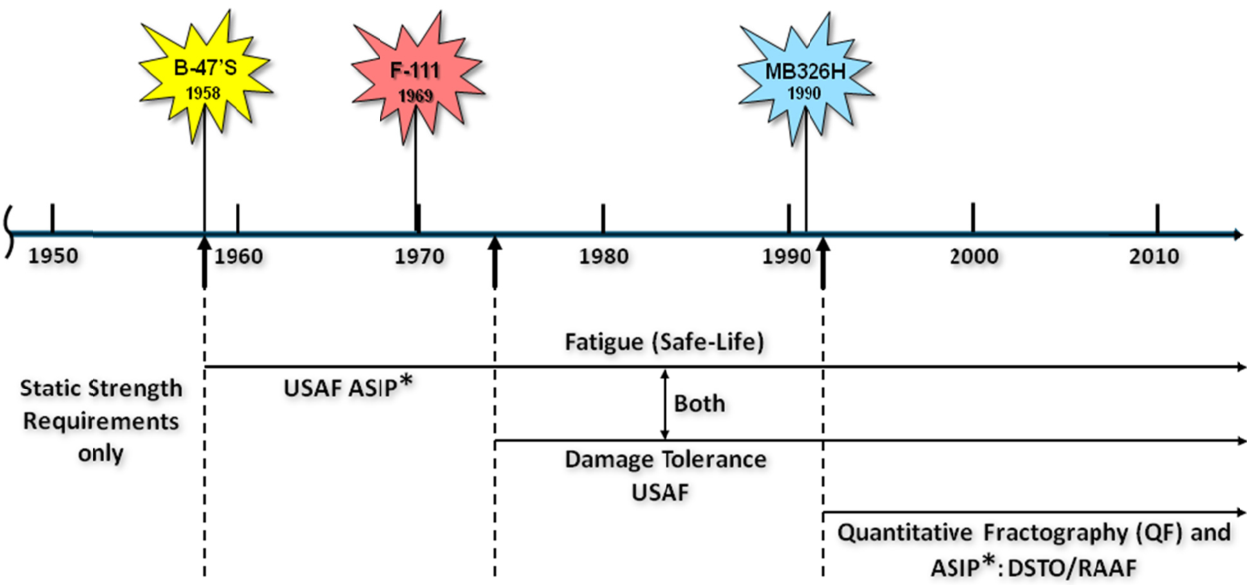


Fig. 5. 'Milestone' military aircraft (airframe) accidents and the evolution of military aircraft fatigue requirements [13,14] and techniques [15]: *ASIP = Aircraft Structural Integrity Program(mes)

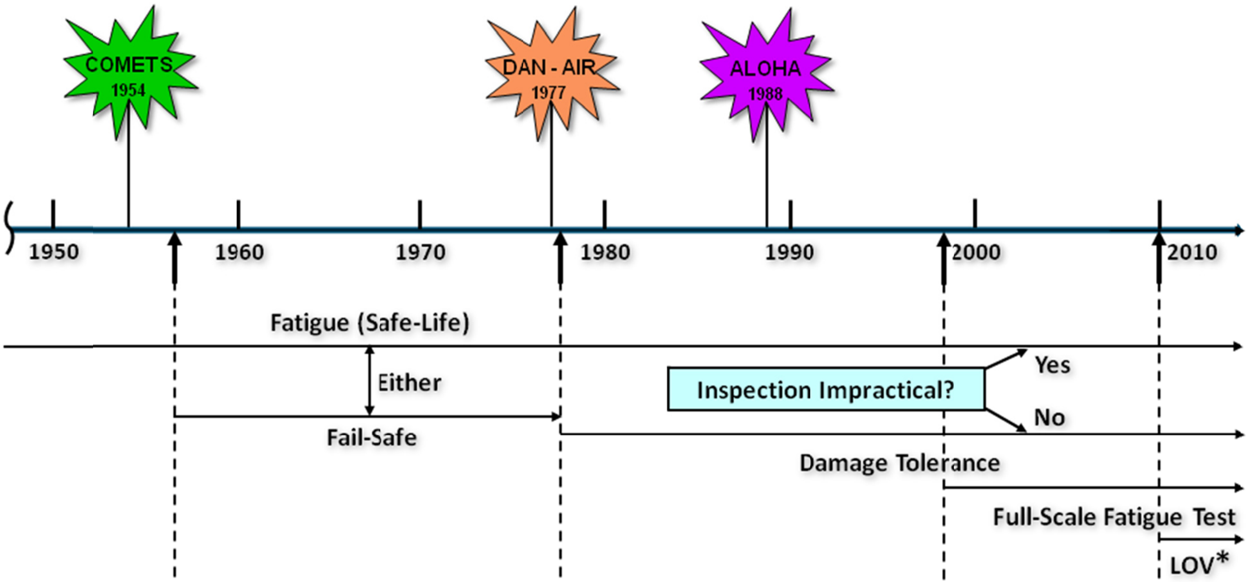
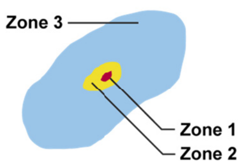
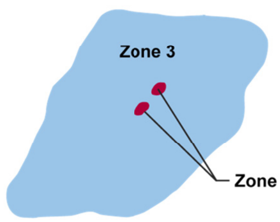
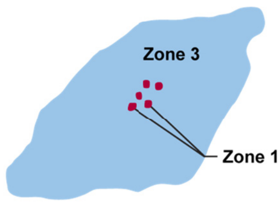
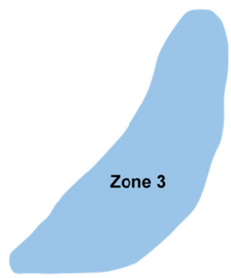


Fig. 6. 'Milestone' civil aircraft (airframe) accidents and the evolution of civil aircraft fatigue requirements [13,16]: *LOV = Limit Of Validity

2.2. Material defect influences on engine disc structural integrity

The engine disc material defect listed in Figure 3 refers to fatigue failure of a forged titanium alloy Ti-6Al-4V stage 1 fan disc in the tail engine of a McDonnell Douglas DC-10 aircraft, resulting in loss of the aircraft and many fatalities [6].

The failure began from a Type I defect in the forged disc [6], see Figure 7. The resulting accident caused the FAA to set up a "Titanium Rotating Components Review Team" [17] which visited six engine manufacturers and obtained information on 25 discs that had cracked or failed in service: 22 of these discs enabled the material defect classification in Figure 7.

	Type I Defects		Type II Defects	
	Category 1	Category 2	Category 3	Category 4
Metallurgical observations (typical)	• Nitrogen stabilized hard alpha zone (zone 2) encasing large spongy-appearing void (zone 1) • Alpha case surrounded by enlarged or blocky alpha grains or platelets (zone 3)  	• Small or no voids (zone 1) • No hard alpha zone • Large area of nitrogen stabilized enlarged and elongated alpha grains or platelets (zone 3)  	• Microvoids (zone 1) • Low or no elevated nitrogen or oxygen concentration • Large area of aluminium stabilized enlarged and elongated alpha grains or platelets (zone 3)  	• Pure elemental segregation of Ti or Al (zone3) 
Zone hardness*	• Zone 2 = RC 65-80 • Zone 3 = RC 55-70	RC 45-65	RC 35-45	RC 12
Zone shape	All Zones Ellipsoid Shaped as Per the Direction of Work			
Most probable cause	Burnt titanium sponge (source material for ingot production)	Contaminated weldment or contaminated revert material entering ingot	Inclusion drop-in during ingot production	Improperly melted/homogenized alloy or a solidification pipe
Defects in 22 in-service discs	41%	41%	14%	4%
Increasing difficulty to detect by ultrasonic testing →				

* RC = Rockwell hardness "C" scale

Fig. 7. Classification of material defects causing fatigue failures in forged titanium alloy engine discs [17,18]

The Review Team investigation resulted in many changes to titanium alloy processing controls in the titanium industry. These process controls are well-recognised in both developed and developing countries [19-21]. It is also important to note that (i) these types of material defects occurred during primary processing, not secondary metalworking, and (ii) titanium disc failures have been rare: the 25 discs investigated by the Review Team represent a very small number compared to the thousands of discs in service up to the time of the review (1990).

3. Aircraft parts manufacturer and subcontractor competences

In Ref. [1] it was suggested that (i) aircraft parts manufacturers may be unaware of the causes of cracks and their prevention during secondary metalworking processes, and (ii) aircraft parts subcontractors are often haphazardly selected: see the second and third quotations in section 1 of the present document.

These suggestions do little justice to the rigour with which both manufacturers and subcontractors are selected and certified, e.g. Refs. [22,23] which describe the procedures instituted in India for existing and novel materials. A schematic is given in Figure 8.

Finally, Figure 9 is one of several processing maps developed for a novel aluminium-lithium (Al-Li) alloy, as part of a general treatise on the mechanical working of these alloys [24]. Figure 9 gives a 'snapshot' impression of Indian research efforts to ensure that cracks and other undesired phenomena do not occur during secondary metalworking. Such efforts, also for other materials, provide support to the indigenous aerospace materials manufacturers.

4. Conclusions

(1) Material defects from secondary metal working processes are not the main causes of aircraft (airframe) fatigue-related accidents (crashes). Data from the literature [4,6] indicate that such defects are responsible for no more than 10% of these accidents. A similar conclusion can be drawn from the 'milestone' accidents that have had major influences on the evolution of airframe structural integrity requirements [9,13,14,16].

(2) Suggestions that (i) aircraft parts manufacturers may be unaware of the causes of cracks and their prevention during secondary metalworking processes, and (ii) aircraft parts subcontractors are often haphazardly selected, are unjustified. Examples supporting this conclusion have been taken from Refs. [22-24].

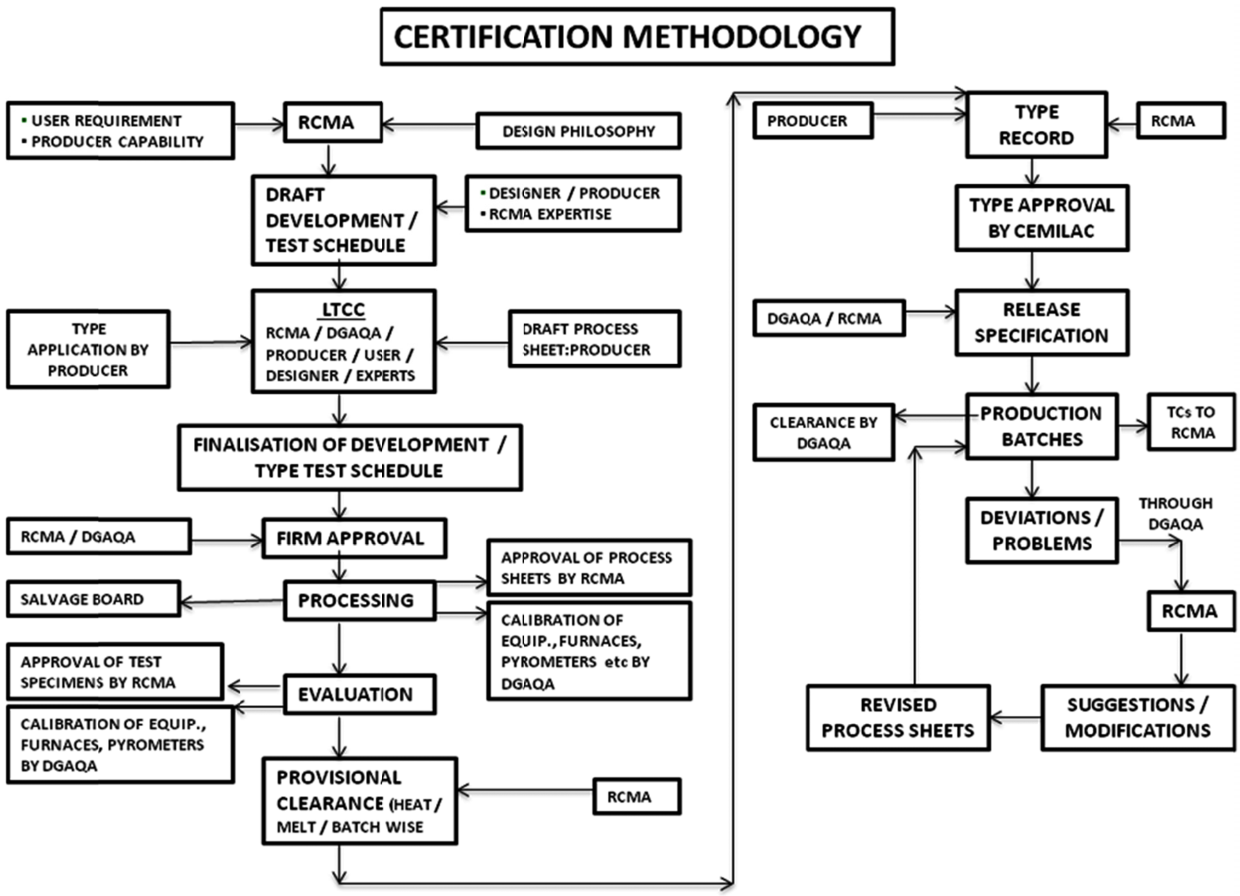


Fig. 8. Indian certification methodology for aerospace materials [22,23]

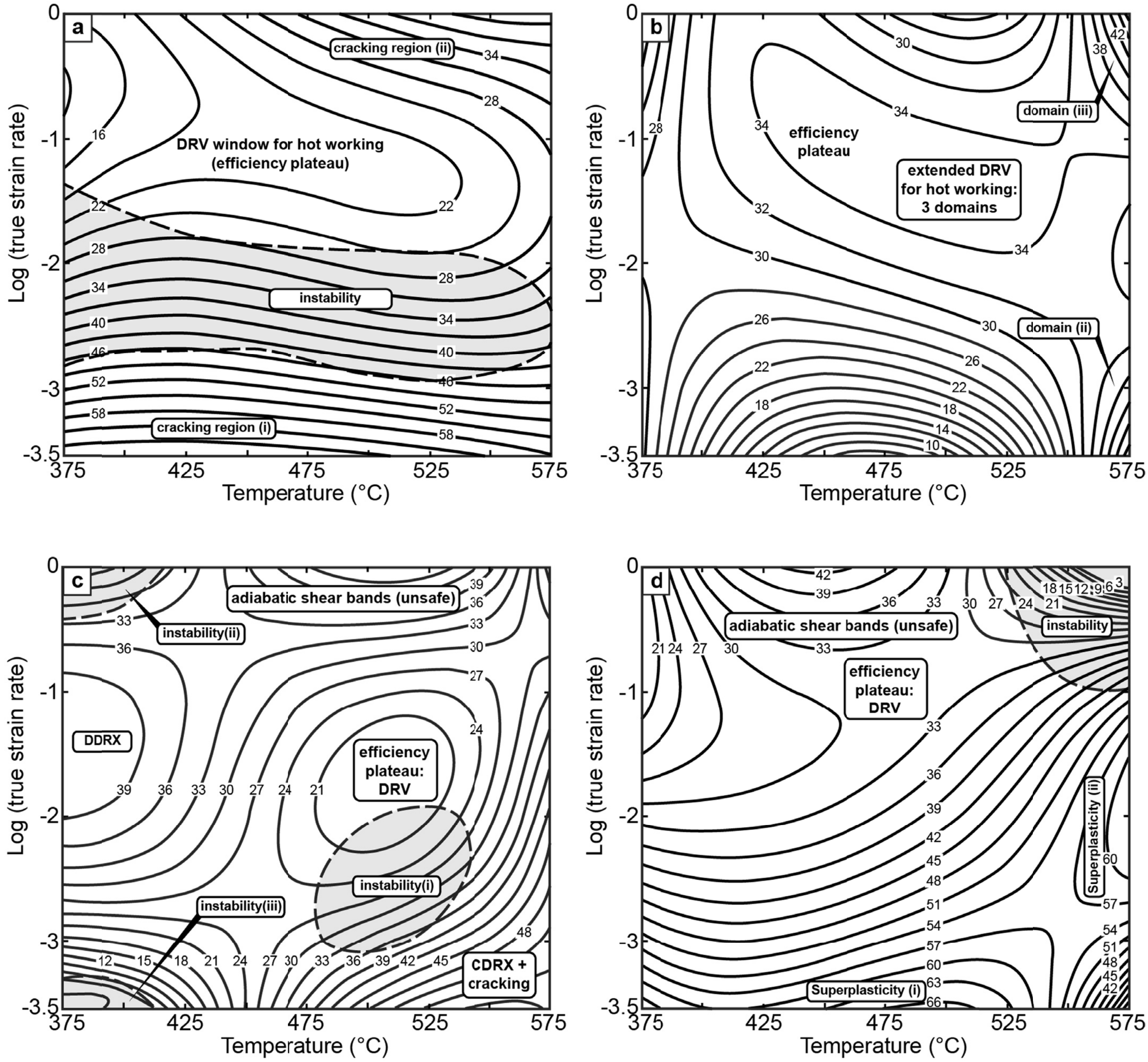


Fig. 9. Processing maps for an Al-Li alloy starting from different initial conditions: a) spray cast; b) HIPed; c) homogenized; d) extruded. DRV: dynamic recovery; CDRX: continuous dynamic recrystallization; DDRX: discontinuous dynamic recrystallization [24]

REFERENCES

[1] E.S. Dzidowski, The effect of secondary metalworking processes on susceptibility of aircraft to catastrophic failures and prevention methods, Archives of Metallurgy and Materials **58** (4), 1207-1212 (2013).

[2] C.R. Brooks, A. Choudhury, Failure Analysis of Engineering Materials, McGraw-Hill, New York, NY 10121, USA 2001.

[3] S.J. Findley, N.D. Harrison, Why aircraft fail, Materials Today **5** (11), 18-25 (2002).

[4] G.S. Campbell, R. Lahey, A survey of serious aircraft accidents involving fatigue fracture, International Journal of Fatigue **6** (1), 25-30 (1984).

[5] R.J.H. Wanhill, Some notable aircraft service failures investigated by the National Aerospace Laboratory (NLR), Structural Integrity and Life **9** (2), 71-87 (2009).

[6] C.F. Tiffany, J.P. Gallagher, C.A. Babish IV, Threats to structural safety, including a compendium of selected structural accidents/incidents, USAF Technical Report ASC-TR-2010-5002, Aeronautical Systems Center Engineering Directorate, Wright-Patterson Air Force Base, OH 45433-7101, USA 2010.

[7] T. Khaled, Casting factors, Report #: ANM-112N-13-05, 14 January 2014, Federal Aviation Administration, Western Pacific Region, Lakewood, CA 90712, USA 2014.

[8] Metallic Materials Properties Development and Standardization (MMPDS) Handbook: updated regularly, e.g. Issue 10, Battelle Memorial Institute, Columbus, OH 43201, USA, (2016).

[9] R. Wanhill, L. Molent, S. Barter, Milestone case histories in aircraft structural integrity, Reference Module in Materials Science and Materials Engineering, Elsevier 2016, doi:10.1016/B978-0-12-803581-8.00847-X.

[10] J.W. Mar, Structural integrity of aging airplanes: a perspective, in: Structural Integrity of Aging Airplanes, Eds. S.N. Atluri, S.G. Sampath and P. Tong, Springer, Berlin, Germany, 241-262 (1991).

[11] Military Specification Airplane Damage Tolerance Requirements, MIL-A-83444, United States Air Force, The Pentagon, Virginia USA, 1974.

[12] Military Standard Aircraft Structural Integrity Program, Airplane Requirements, MIL-STD-1530A (11), United States Air Force, The Pentagon, Virginia USA, 1975.

[13] P. Safarian, Fatigue and Damage Tolerance Requirements of Civil Aviation, Lesson 01 – Introduction, Winter 2014, University of Washington, Seattle, WA 98195, USA 2013.

[14] E.S. Wilson, Developments in RAAF aircraft structural integrity, in: Estimation, Enhancement and Control of Aircraft Fatigue Performance, Eds. J.M. Grandage and G.S. Jost, Engineering Materials Advisory Services, Warley, UK **II**, 959-970 (1995).

[15] S.A. Barter, L. Molent, R.J.H. Wanhill, Fatigue life assessment for high performance metallic airframe structures − an innovative practical approach, in: Structural Failure Analysis and Prediction Methods for Aerospace Vehicles and Structures', Ed. S.-Y. Ho, Bentham E-Books, Bentham Science Publishers, Sharjah, UAR, Chapter 1, 1-17 (2010).

[16] R.G. Eastin, W. Sippel, The "WFD rule" − have we come full circle?, USAF Aircraft Structural Integrity Program Conference 2011, November 29-December 1, 2011, San Antonio, TX 78205, USA 2011.

[17] J.G. Costa, R.E. Gonzalez, R.E. Guyotte, D.P. Salvano, T. Swift, R.J. Koenig, Titanium Rotating Components Review Team Report, December 14th 1990, United States of America Federal Aviation Administration, Aircraft Certification Service, Engine and Propeller Directorate, Burlington, MA 08103, USA 1990.

[18] R. Wanhill, S. Barter, Fatigue of Beta Processed and Beta Heat--treated Titanium Alloys, Springer Science+Business Media, Dordrecht, the Netherlands 2012.

[19] C.R.V.S. Nagesh, G.V.S.B. Kumar, B. Saha, A.A. Gokhale, Titanium sponge production and processing for aerospace applications, Chapter 4 in: Aerospace Materials and Material Technologies, Aerospace Materials, Eds. N.E Prasad and R.J.H. Wanhill, Springer Science+Business Media, Singapore, Volume 1: 73-89.

[20] A. Bhattacharjee, B. Saha, J.C. Williams, Titanium alloys: Part 1: physical metallurgy and processing, Chapter 5 in: Aerospace Materials and Material Technologies, Volume 1: Aerospace Materials, Eds. N.E. Prasad and R.J.H. Wanhill, Springer Science+Business Media, Singapore, 91-115 (2017).

[21] M. Chatterjee, A. Patra, R.R. Babu, M.N. Rao, Processing of aerospace metals and alloys: Part 1: special melting technologies, Chapter 1 in: Aerospace Materials and Material Technologies, Aerospace Material Technologies, Eds. N.E. Prasad and R.J.H. Wanhill, Springer Science+Business Media, Singapore, Volume 2: 3-24 (2017).

[22] B. Saha, R.J.H. Wanhill, N.E. Prasad, G. Gouda, K. Tamilmani, Airworthiness certification of metallic materials, Chapter 16 in: Aluminum-Lithium Alloys, Processing, Properties and Applications, Eds. N.E. Prasad, A.A. Gokhale and R.J.H. Wanhill, Butterworth-Heinemann (Elsevier), Oxford, UK, 537-554 (2014).

[23] M.S.K. Rao, P. Rambabu, C.V.S. Murthy, B. Jana, B. Saha, N.E. Prasad, P. Jayapal, K. Tamilmani, Airworthiness certification of metallic and non-metallic materials: The Indian approach and methodologies, Chapter 24 in: Aerospace Materials and Material Technologies, Aerospace Material Technologies, Eds. N.E. Prasad and R.J.H. Wanhill, Springer Science+Business Media, Singapore, Volume 2: 515-540 (2017).

[24] G.J. Reddy, R.J.H. Wanhill, A.A. Gokhale, Mechanical working of aluminum-lithium alloys, Chapter 7 in: Aluminum-Lithium Alloys, Processing, Properties and Applications, Eds. N.E. Prasad, A.A. Gokhale and R.J.H. Wanhill, Butterworth-Heinemann (Elsevier), Oxford, UK, 187-219 (2014).