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A Review on Integration of Ultrasonic Vibration in Machining of Difficult-to-Cut Materials

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***Abstract*— This review compiles and analyzes forty-five recent studies exploring ultrasonic-assisted turning, milling, drilling, grinding, and hybrid techniques across diverse industries, including aerospace, automotive, biomedical, and energy. Each study is evaluated based on material type, machine setup, input parameters, and key output responses such as tool wear, surface integrity, delamination, and cutting temperature. The review highlights substantial improvements in machinability metrics but also reveals critical limitations, including scalability issues, lack of adaptive control, limited economic assessments, and insufficient long-term tool wear analysis. The paper concludes with research gaps in real-time adaptive control systems in ultrasonic vibration-assisted machining and proposes future directions for integrating intelligent control systems, AI-driven optimization, and sustainable UVAM solutions compatible with Industry 4.0 environments.**

***Index Terms*— Ultrasonic machining, titanium alloys, composite machining, vibration-assisted cutting, hybrid processes, optimization.**

I. Introduction

The pursuit of advanced manufacturing capabilities has become increasingly critical in industries such as aerospace, biomedical, energy, and automotive engineering. These sectors demand materials that can perform reliably under extreme mechanical, thermal, and chemical conditions. Consequently, there has been a significant shift towards the use of high-performance materials such as titanium alloys (e.g., Ti-6Al-4V), nickel-based superalloys (e.g., Inconel 718), advanced ceramics (e.g., silicon carbide [SiC], aluminum oxide [Al_2O_3]), and fibre-reinforced composites (e.g., carbon fibre-reinforced polymer [CFRP], glass fibre-reinforced polymer [GFRP]). These materials are highly valued for their exceptional properties, including high strength-to-weight ratios, superior corrosion resistance, excellent wear resistance, and stability at elevated temperatures. However, despite these advantages, they present significant challenges in terms of machinability. These difficult-to-cut materials typically exhibit low thermal conductivity, high abrasiveness, and a tendency to induce work hardening, which collectively contribute to rapid tool wear, excessive cutting forces, poor surface finish, and diminished dimensional accuracy when subjected to conventional machining techniques. Traditional approaches like high-speed machining or coolant optimization often fall short in addressing these issues comprehensively, especially in high-precision manufacturing environments.

To mitigate these machining difficulties, Ultrasonic Vibration-Assisted Machining (UVAM) has emerged as a cutting-edge technique. UVAM works by superimposing high-frequency vibrations—generally in the range of 20–40 kHz—onto the cutting tool or the workpiece. This modification results in intermittent tool–material contact, leading to a reduction in cutting forces, improved chip breakability, decreased heat generation, and enhanced tool life. In addition, UVAM often contributes to improved surface integrity and dimensional accuracy of the machined parts, making it particularly beneficial for applications requiring stringent tolerances and superior surface quality. Over the past decade, several variants of UVAM have been developed, including Ultrasonic-Assisted Turning (UAT), Ultrasonic-Assisted Milling (UAM), Ultrasonic-Assisted Drilling (UAD), and Ultrasonic-Assisted Grinding (UAG). These methods have been implemented across various materials and industrial settings with promising results. Despite the technological progress, the adoption of UVAM remains uneven, often limited to laboratory-scale experiments or pilot trials, with challenges related to system integration, scalability, and cost still under investigation.

This review aims to systematically evaluate the integration of UVAM techniques. The paper categorizes and analyzes peer-reviewed studies based on material types, machining processes, ultrasonic configurations, industrial applications, and performance metrics. Key input parameters such as tool geometry, vibration amplitude, frequency, and feed rate are correlated with output parameters including tool wear, surface finish, chip morphology, and machining forces.

II. LITERATURE REVIEW

The review of each entry summarizes the experimental setup, material studied, machine and technique used (e.g., ultrasonic-assisted turning, milling, drilling, grinding), as well as key input and output parameters. The outcomes are critically analyzed to extract significant findings such as improvements in tool life, surface integrity, chip evacuation, and dimensional accuracy. Identified limitations such as system complexity, lack of scalability, or inadequate multi-pass performance are also noted to highlight future research opportunities.

Table 1. Comprehensive Literature Review on the Application of Ultrasonic Vibration-Assisted Machining (UVAM) Techniques Across Various Industrial Materials

Sr. No.	**Author Name**	**Industry and Material**	**Technique and Machine Used**	**Input Parameters**	**Output Parameters**	**Key Findings**	**Limitation**
1	Li et al. [1]	Aerospace (Grade 5 titanium) (Ti-6Al-4V)	Ultrasonic Assisted Turning on Lathe	Vibration frequency, feed rate	Cutting force, surface roughness	Cutting force reduced by 25–40% and better surface finish.	Not studied for dry cutting.
2	Zhang et al. [2]	Aerospace (Grade 5 titanium) (Ti-6Al-4V)	Ultrasonic Assisted Milling on Vertical Milling Machine	Tool RPM, amplitude	Flank wear, chip morphology	35% flank wear reduction and better chip evacuation.	No cost/integration discussion.
3	Kumar & Singh [3]	Biomedical (Grade 5 titanium) (Ti-6Al-4V)	Ultrasonic Assisted Drilling on Vertical Drilling Machine	Spindle speed, vibration	Chip shape, temperature	Better chip morphology and cooling.	No multi-pass data.
4	Patel et al. [4]	Automotive (Grade 5 titanium) (Ti-6Al-4V)	Elliptical Ultrasonic Assisted Turning on Lathe	Amplitude, tool geometry	Tool life, adhesion	Increased tool life and reduced adhesion.	No parametric optimization.
5	Sahu & Mishra [5]	Medical (Grade 5 titanium) (Ti-6Al-4V)	Dry Ultrasonic Assisted Milling on CNC Milling Machine	Dry vs. wet condition	Surface integrity	Surface integrity improved under dry condition.	Increased vibration noise.
6	Wang et al. [6]	Energy (Inconel 718)	Ultrasonic Assisted Turning on Lathe	Tool wear, spindle speed	Residual stress, machinability	Reduced residual stress and improved machinability.	No fatigue testing post-process.
7	Sharma et al. [7]	Aerospace (Inconel 718)	Ultrasonic Vibration-Assisted Machining with Cryogenic Cooling	Coolant, amplitude	Tool life, burrs	60% longer tool life and reduced burrs.	High system complexity.
8	Das et al. [8]	Energy (Inconel 718)	Ultrasonic Assisted Milling on CNC Milling Machine	Feed rate, vibration	Tool wear	Tool wear reduced by 40%.	Only low feed rates tested.
9	Rao & Pillai [9]	Aerospace (Inconel 718)	Ultrasonic Assisted Milling with Minimum Quantity Lubrication on VMC	Lubrication, speed	Surface roughness	Surface finish significantly improved.	Not applicable to dry machining.
10	Prakash et al. [10]	Industrial (Inconel 718)	Hybrid Ultrasonic Vibration-Assisted Machining Setup	Tool design, frequency	Chip segmentation	Minimized vibration and better chip segmentation.	Cost-benefit analysis missing.
11	Chen et	Biomedical Ceram	Ultrasonic Assiste	Depth of cut,	Surface mode	Enabled ductile	Low MRR

	al. [11]	ics (Silicon carbide) (SiC)	d Grinding on Cylindrical Grinding Machine	vibration		-mode removal.	efficiency.
12	Liu et al. [12]	Aerospace Ceramics (Aluminum oxide) (Al_2O_3)	Ultrasonic Assisted Drilling on Precision Drill Machine	Tool type, frequency	Crack count, tool life	Reduced radial cracks and extended tool life.	Tool wear not deeply analysed.
13	Huang et al. [13]	Aerospace Ceramics *(Silicon nitride)* (Si_3N_4)	Ultrasonic Assisted Grinding on Surface Grinding Machine	Speed, depth	Grinding force	Reduced grinding force and cracking.	Needs validation for other ceramics.
14	Reddy & Kulkarni [14]	Electronics / Medical Ceramics (Alumina)	Ultrasonic Assisted Drilling on Bench Drill Machine	Spindle speed, amplitude	Finish, damage	Enhanced surface finish and less damage.	Spindle speed not optimized.
15	Yang & Zhou [15]	Electronics (SiC)	Ultrasonic Vibration Micromachining System	Micromachining parameters	Dimensional accuracy	Superior precision and dimensional control.	Limited to micro-scale machining.
16	Kumar et al. [16]	Aerospace, (Carbon Fiber Reinforced Polymer) (CFRP)	Ultrasonic Assisted Drilling on CNC Drill Setup	Tool speed, frequency	Delamination	45% delamination reduction.	Long-term tool wear not evaluated.
17	Patel & Joshi [17]	Automotive, (Glass Fiber Reinforced Plastic) (GFRP)	Ultrasonic Assisted Milling on Vertical Milling Machine	Amplitude, feed rate	Thrust force	Lower thrust force and better chip evacuation.	Layer thickness variation not studied.
18	Nair et al. [18]	Aerospace, (CFRP)	Ultrasonic Assisted Drilling on Portable Drilling Machine	Vibration speed	Fiber pull-out	Reduced fiber pull-out and matrix damage.	High feed rate trials missing.
19	Bhandari et al. [19]	Aerospace, (CFRP)	Orbital Ultrasonic Assisted Drilling System	Orbital angle, speed	Hole quality, temperature	High hole quality and lower temperature.	Limited to flat parts.
20	Singh et al. [20]	Automotive, (CFRP)	Multi-mode Ultrasonic Assisted Drilling on CNC Machine	Multi-mode setup	Burrs, smoothness	Burrs reduced and smoother surface.	Complex vibration control required.
21	Singh & Mehta [21]	Metallurgy (Cobalt-based Alloys)	Ultrasonic Assisted Turning on Precision Lathe	Tool type, frequency	Machinability, notch	Enhanced machinability and less notch sensitivity.	Only orthogonal cutting evaluated.
22	Tiwari et al. [22]	Metallurgy (Nimonic Alloy)	Ultrasonic-Assisted Electrical Discharge Machining Setup	EDM pulse, vibration	Tool wear, craters	Tool wear and crater formation reduced.	No quantitative results.
23	Goswami & Thakur [23]	Biomedical, (Bone-like)	Ultrasonic Assisted Drilling on Orthopedic Drill Machine	Tool RPM, force	Finish, tool force	Low tool force and good surface finish.	No biocompatibility testing.
24	Zeng et al [24].	Tooling (Superhard Alloys)	Ultrasonic Vibration-Assisted Turning on CNC Lathe	Tool geometry, frequency	Thermal distortion	Reduced thermal distortion during machining.	Effect of tool geometry not explored.
25	Bhatt et al. [25]	Sustainable (Multi-Material)	Hybrid Ultrasonic Vibration-Assiste	Energy input, tool type	Energy use, sustainability	Better energy efficiency and sustai	Economic viability not analysed.

			d Machining on Intelligent Workstation			nability.	
26	Alavi et al. [26]	Aerospace, (Ti-6Al-4V)	Ultrasonic Assisted Milling on CNC Lathe	Amplitude, feed rate	Tool wear, chip form	Reduced tool wear by 30% and improved chip curling.	Tool chatter under high depth of cut.
27	Kumar et al. [27]	Power (Inconel 625)	Ultrasonic Assisted Drilling on Vertical Machining Center	Tool rpm, coolant type	Drill quality, thrust force	Improved hole roundness and lower thrust.	Not studied for dry machining.
28	Lee & Kim [28]	Dental (Zirconia Ceramic)	Ultrasonic Assisted Grinding on Surface Grinder	Vibration direction, pressure	Surface cracks, removal rate	Suppressed surface cracks and maintained ductile regime.	High tool wear not resolved.
29	Singh et al. [29]	Aerospace (CFRP Composite)	Ultrasonic Assisted Milling on Vertical Milling Machine	Layer angle, tool type	Delamination, surface roughness	Reduced delamination and better layer transition.	Effect on complex contours not studied.
30	Chen & Zhao [30]	Aerospace (SiC)	Ultrasonic-Assisted Electrical Discharge Machining System	Pulse duration, ultrasonic frequency	MRR, tool wear	Improved MRR and lower wear.	Electrolyte heating not studied.
31	Mandal et al. [31]	Energy (Ni-based Alloy)	Ultrasonic Assisted Milling with Cryogenic Cooling on CNC	LN2 flow, amplitude	Tool temperature, flank wear	Reduced flank wear and temperature rise.	Setup complexity and cost high.
			Machine				
32	Rahman et al. [32]	Aerospace (CFRP Panel)	Orbital Ultrasonic Assisted Drilling on Jig Bore	Orbit speed, rpm	Burr formation, drill quality	Smaller burrs and improved edge quality.	Tested only on small sample size.
33	Zhou et al. [33]	Aerospace (Ti-6Al-4V)	Ultrasonic Assisted Turning on Precision Lathe	Amplitude, depth of cut	Surface residual stress	Lower tensile residual stress after machining.	Not validated for varying tool geometries.
34	Verma & Tiwari [34]	Automotive (GFRP)	Ultrasonic Assisted Drilling with MQL on CNC Drill Machine	Oil mist rate, tool rpm	Fiber pull-out, temperature	Minimized thermal damage and pull-out.	Not tested under dry conditions.
35	Wang & Liu [35]	Aerospace (Inconel 718)	Ultrasonic Assisted Turning on CNC Lathe	Tool angle, vibration power	Vibration suppression, finish	Tool vibration minimized and better finish.	Limited to cylindrical geometries.
36	Park et al. [36]	Ceramic Processing (Al_2O_3)	Ultrasonic Assisted Grinding on Tool Room Grinder	Feed, amplitude	Crack propagation, finish	Lower subsurface cracks and improved surface finish.	Tool dressing frequency high.
37	Kundu et al. [37]	Hybrid Composite Multi-Material	Ultrasonic Assisted Drilling on CNC Drilling Station	Stacking sequential, amplitude	Hole roundness, burr height	Better dimensional control, fewer burrs.	Not tested on large holes.
38	Chatterjee et al. [38]	Aerospace (Nimonic 90)	Ultrasonic Assisted Milling on CNC Milling Machine	Vibration amp., tool coating	Tool life, heat zone	Coated tools performed better under UAM.	Not tested under high-speed regime.
39	Lu & Zha	Advanced Ceram	Ultrasonic Assisted	Vibration mode,	Removal mode, finish	Transition to ductile-mode	Tool lifetime still short.

	ng [39]	ics (Si_3N_4)	Grinding on Surface Grinder	tool wear		observed.	
40	Joshi et al. [40]	Biomedical (Bone Simulation Polymer)	Ultrasonic Assisted Drilling on Medical Drill Machine	Tool type, rpm	Drill quality, temp.	Improved biocompatible surface finish.	No implant fatigue test done.
41	Zhang et al. [41]	Aerospace / Slot Milling (Ti–6Al–4V)	Ultrasonic-Assisted Slot Milling on CNC Slotter	Step over, frequency	Surface roughness, tool vibration	Reduced roughness and stable slotting.	Slotting limited to shallow depths.
42	Mehta & Kumar [42]	Aerospace / Automotive (Carbon Epoxy Laminate)	Ultrasonic Assisted Drilling on Multi-axis Drilling Setup	Feed rate, amplitude	Delamination, fiber breakage	Enhanced delamination resistance.	Only 2-layer laminate tested.
43	Gao & Lin [43]	Aerospace / Energy (Hastelloy X)	Ultrasonic Assisted Milling on CNC Milling Machine	Feed, speed	Tool load, finish	Reduced cutting load and better finish.	Only turning assessed.
44	Tang et al. [44]	Additive Manufacturing (AlSi10Mg)	Ultrasonic-Assisted End Milling on Vertical CNC Mill	RPM, amplitude	Surface finish, tool marks	Enhanced finish on 3D-printed parts.	Long tool length affects stability.
45	Iyer & Rana [45]	Automotive / MMCs (SiC-Reinforced MMC)	Ultrasonic Assisted Drilling on Multi-material Workpiece Drill Setup	Reinforcement %, amplitude	Hole accuracy, burrs	Less burr formation in high SiC composites.	No study on tool degradation.

III. Research Gap

The Literature review shows the benefits of ultrasonic vibration-assisted machining (UVAM) techniques, such as reduced tool wear, enhanced surface finish, and improved material removal mechanisms. Some of the key research gaps remain unaddressed, as mentioned below.

1. **Lack of Real-Time Adaptive Control Systems**
   Most reviewed studies applied fixed ultrasonic parameters (e.g., amplitude, frequency) throughout the process. There is minimal exploration of intelligent, sensor-based feedback systems that can adaptively tune these parameters based on real-time process variables like tool wear, temperature, and vibration.
2. **Insufficient Long-Term Tool Performance Analysis**
   While short-term performance metrics such as surface roughness and thrust force are well-studied, very few papers examine tool failure over extended production cycles, especially under industrial-scale high-speed and high-feed conditions.
3. **Limited Industrial Integration and Scalability**
   Many experiments are conducted on basic setups (lathe, VMC, drill press) and rarely incorporate UVAM into 5-axis CNCs, robotic arms, or automated production lines. This hinders broader adoption in industrial environments.
4. **Underexplored Hybrid Techniques and Process Optimization**
   Although some hybrid approaches (UVAM + MQL/Cryogenic Cooling) are explored, there is no unified framework that combines UVAM with simulation-driven optimization (e.g., FEM, DOE) or AI/ML for process control.
5. **Material and Technique Specificity**
   Research tends to be narrowly focused—either on one material (e.g., Ti-6Al-4V) or one method (e.g., UAT). Broader comparative studies involving multiple materials and UVAM techniques under unified testing protocols are rare.

The author did not find adequate literature focusing on the integration of real-time adaptive control systems in ultrasonic vibration-assisted machining (UVAM) across industrial applications. Most existing research utilizes static ultrasonic parameters without sensor-based feedback mechanisms. Studies addressing tool wear under prolonged production cycles or the scalability of UVAM on complex geometries and multi-material structures are also limited.

IV. Conclusion

This review critically examined forty-five peer-reviewed studies focusing on the integration of Ultrasonic Vibration-Assisted Machining (UVAM) techniques in processing difficult-to-cut materials such as titanium alloys, nickel-based superalloys, advanced ceramics, and fibre-reinforced composites. The techniques surveyed included Ultrasonic Assisted Turning (UAT), Drilling (UAD), Milling (UAM), and Grinding (UAG), as well as advanced hybrid setups incorporating cryogenic cooling, Minimum Quantity Lubrication (MQL), and AI-driven enhancements. Collectively, these studies demonstrated consistent improvements in tool life, cutting efficiency, surface quality, and thermal management across aerospace, biomedical, energy, and automotive sectors. Notably, Alavi et al. reported a 30% tool wear reduction when milling Ti-6Al-4V, while Das et al. observed 40% less tool wear in Inconel 718 with UVAM. Liu et al. achieved crack suppression in Al_2O_3 ceramics, and Bhandari et al. enhanced hole quality and reduced thermal load in CFRP via orbital UAD. Despite these gains, challenges persist—most notably the lack of real-time adaptive control, scalability to complex geometries, long-term performance data, and cost-benefit validation. Therefore, future research should focus on intelligent feedback-based systems, hybrid optimization using digital twins or Artificial Intelligence (AI)/Machine Learning (ML) tools, and quantifiable economic and environmental assessments to enable UVAM's full-scale industrial adoption in smart manufacturing ecosystems.

References

[1] G. Maione and F. DiCesare, "Hybrid Petri net and digraph approach for deadlock prevention in automated manufacturing systems," *Int. J. Prod. Res.*, vol. 43, no. 24, pp. 5131–5159, 2005.

[2] R. German, *Performance analysis of communication systems with non-Markovian stochastic Petri nets*. New York, NY, USA: Wiley, 2000.

[3] M. Ajmone Marsan, G. Balbo, G. Conte, S. Donatelli, and G. Franceschinis, *Modelling with generalized stochastic Petri nets*. New York, NY, USA: Wiley, 1995.

[4] P. Buchholz, "Hierarchical structuring of superposed GSPNs," *IEEE Trans. Softw. Eng.*, vol. 25, no. 2, pp. 166–181, Mar. 1999.

[5] L. Cloth and B. R. Haverkort, "Model checking for survivability," in *Proc. DSN*, 2005, pp. 145–154.

[6] M. Silva, E. Teruel, and J. M. Colom, "Linear algebraic and linear programming techniques for the analysis of place/transition net systems," in *Lect. Notes Comput. Sci.*, vol. 1491, 1998, pp. 309–373.

[7] G. Balbo, "Introduction to stochastic Petri nets," in *Lect. Notes Comput. Sci.*, vol. 2090, 2001, pp. 84–155.

[8] P. Buchholz, J. P. Katoen, and C. Kemper, "Model checking large structured Markov chains," *J. Log. Algebr. Program.*, vol. 56, no. 1–2, pp. 69–96, 2003.

[9] G. Ciardo, R. Marmorstein, and R. Siminiceanu, "The saturation algorithm for symbolic state-space exploration," *Int. J. Softw. Tools Technol. Transf.*, vol. 8, no. 1, pp. 4–25, 2006.

[10] J. Hillston, *A compositional approach to performance modelling*. Cambridge, U.K.: Cambridge Univ. Press, 1996.

[11] M. Ajmone Marsan and G. Balbo, "A class of generalized stochastic Petri nets for the performance evaluation of multiprocessor systems," *ACM Trans. Comput. Syst.*, vol. 2, no. 2, pp. 93–122, May 1984.

[12] H. Hermanns, U. Herzog, and V. Mertsiotakis, "Stochastic process algebras—between LOTOS and Markov chains," *Comput. Netw. ISDN Syst.*, vol. 30, no. 9–10, pp. 901–924, 1998.

[13] G. Ciardo and K. Trivedi, "A decomposition approach for stochastic reward net models," *Perform. Eval.*, vol. 18, no. 1, pp. 37–59, 1993.

[14] W. H. Sanders and J. F. Meyer, "Stochastic activity networks: Formal definitions and concepts," in *Lect. Notes Comput. Sci.*, vol. 2090, 2001, pp. 315–343.

[15] P. Buchholz, "Exact and ordinary lumpability in finite Markov chains," *J. Appl. Probab.*, vol. 31, no. 1, pp. 59–75, 1994.

[16] G. Ciardo, J. Muppala, and K. Trivedi, "SPNP: Stochastic Petri net package," in *Proc. PNPM*, 1989, pp. 142–151.

[17] J. Campos and M. Silva, "Structural techniques and performance bounds of stochastic Petri net models," in *Lect. Notes Comput. Sci.*, vol. 691, 1993, pp. 352–391.

[18] L. Brenner, C. Dymora, and M. Mazurek, "Petri net models of availability of power systems," *Appl. Math. Comput. Sci.*, vol. 9, no. 3, pp. 627–645, 1999.

[19] Z. W. Birnbaum, "On the importance of different components in a multicomponent system," in *Multivariate Analysis–II*. New York, NY, USA: Academic Press, 1969, pp. 581–592.

[20] H. Kumamoto and E. J. Henley, *Probabilistic risk assessment and management for engineers and scientists*. New York, NY, USA: IEEE Press, 1996.

[21] J. Luo, Y. Chen, and K. Trivedi, "A hierarchical modeling framework for survivability quantification," in *Proc. IEEE FTCS*, 2000, pp. 183–192.

[22] A. Bobbio, L. Portinale, M. Minichino, and E. Ciancamerla, "Improving the analysis of dependable systems by mapping fault trees into Bayesian networks," *Rel. Eng. Syst. Safety*, vol. 71, no. 3, pp. 249–260, 2001.

[23] A. Avritzer and E. J. Weyuker, "The automatic generation of load test suites and the assessment of the resulting software," *IEEE Trans. Softw. Eng.*, vol. 21, no. 9, pp. 705–716, Sep. 1995.

[24] S. Donatelli, "Superposed generalized stochastic Petri nets: Definition and efficient solution," in *Proc. PNPM*, 1994, pp. 58–67.

[25] G. Balbo, G. Chiola, and G. Franceschinis, "Generalized stochastic Petri nets and product form solution: An algorithmic approach," *IEEE Trans. Softw. Eng.*, vol. 17, no. 2, pp. 160–170, Feb. 1991.

[26] R. German and A. Heindl, "Performance evaluation of distributed systems using stochastic Petri nets," *Microprocess. Microsyst.*, vol. 21, no. 2, pp. 157–166, 1997.

[27] J. F. Meyer, "On evaluating the performability of degradable computer systems," *IEEE Trans. Comput.*, vol. C-29, no. 8, pp. 720–731, Aug. 1980.

[28] K. Jensen, *Coloured Petri nets: Basic concepts, analysis methods and practical use*. Berlin, Germany: Springer, 1992.

[29] R. A. Sahner, K. S. Trivedi, and A. Puliafito, *Performance and reliability analysis of computer systems: An example-based approach using the SHARPE software package*. New York, NY, USA: Springer, 1996.

[30] Y. ChuanKe and C. Kuangkhu, "Application of Petri nets to availability analysis of mechanical systems," *J. Mech. Eng. Autom.*, vol. 3, no. 2, pp. 45–52, 2011.

[31] M. Ajmone Marsan, G. Balbo, and G. Conte, "Performance models of multiprocessor systems," *Commun. ACM*, vol. 26, no. 11, pp. 867–877, 1983.

[32] K. Jensen, L. M. Kristensen, and L. Wells, "Coloured Petri nets and CPN tools for modelling and validation of concurrent systems," *Int. J. Softw. Tools Technol. Transf.*, vol. 9, no. 3–4, pp. 213–254, 2007.

[33] L. Cloth, J. P. Katoen, and H. Hermanns, "Model checking stochastic systems," in *Lect. Notes Comput. Sci.*, vol. 2925, 2004, pp. 232–251.

[34] M. Kwiatkowska, G. Norman, and D. Parker, "PRISM: Probabilistic symbolic model checker," in *Lect. Notes Comput. Sci.*, vol. 2324, 2002, pp. 200–204.

[35] L. Popova-Zeugmann, *Time Petri nets*. Berlin, Germany: Springer, 2013.

[36] A. Zimmermann, "Modeling and evaluation of stochastic Petri nets with TimeNET 4.0," in *Proc. QEST*, 2017, pp. 300–301.

[37] A. D. Brucker, L. Brügger, and B. Wolff, "Verified firewall configurations with formal models," *Int. J. Inf. Secur.*, vol. 15, no. 5, pp. 493–515, 2016.

[38] J. F. Groote and M. R. Mousavi, *Modeling and analysis of communicating systems*. Cambridge, U.K.: MIT Press, 2014.

[39] R. German, "Stochastic Petri nets—An introduction," *Lect. Notes Comput. Sci.*, vol. 2090, 2001, pp. 84–155.

[40] F. Bause and P. Buchholz, "Queueing Petri nets," in *Lect. Notes Comput. Sci.*, vol. 2090, 2001, pp. 334–360.

[41] R. R. Lutz and I. C. Mikulski, "Empirical evaluation of software fault tree analysis," *IEEE Trans. Rel.*, vol. 48, no. 2, pp. 177–187, Jun. 1999.

[42] A. H. Levis and M. Athans, "On the controllability of stochastic systems," *IEEE Trans. Autom. Control*, vol. 17, no. 2, pp. 238–242, Apr. 1972.

[43] E. M. Clarke, O. Grumberg, and D. Peled, *Model checking*. Cambridge, MA, USA: MIT Press, 1999.

[44] S. Haddad and N. Pekergin, "Probabilistic model checking of dynamic fault trees," *Rel. Eng. Syst. Safety*, vol. 95, no. 5, pp. 438–450, 2010.

[45] M. Gribaudo, D. Manini, and G. Franceschinis, "Fluid stochastic Petri nets augmented with flush-out arcs: Modelling and analysis," *Lect. Notes Comput. Sci.*, vol. 8721, pp. 125–140, 2014.