

Analysis of the Application of the Instrumented Indentation Test for Aluminum and Its Alloys

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Abstract. This paper considers the specific features of instrumented indentation test as applied to aluminum and aluminum alloys. Particular attention is paid to the pile-up/sink-in effects, strain hardening, surface roughness, thickness of the investigated layer, and indenter geometry. Published results on pure aluminum, aluminum alloys, aluminum coatings and joints, as well as studies aimed at improving the processing of indentation load–displacement curves $P(h)$, are analyzed. The paper also presents an experimental study of AMg2 aluminum alloy (AA5052). At the load of 20 mN, the mean indentation hardness and indentation elastic modulus for the polished surface were approximately 0.959 and 75.8 GPa, respectively, whereas for the unpolished surface they were 0.865 and 72.5 GPa. The most pronounced effect of roughness was not so much a systematic shift in the mean value as an increase in the scatter of the results, particularly for hardness. The experimental results are compared with published data and discussed in terms of the applicability of instrumented indentation to the characterization of aluminum and its alloys.

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REFERENCES

1. E.S. Gorlanov, L.I. Leontev. Directions in the technological development of aluminium pots. *Journal of Mining Institute*, 2024, vol. 266, pp. 246–259.

2. A.M. Shchipachev, A.I. Alekhin, O.G. Perveytalov, E.E. Yakovleva, D.A. Branish. Diagnosis of embrittlement of pipe steels using the instrumental indentation method. *Science & Technologies: Oil and Oil Products Pipeline Transportation*, 2024, vol. 14, no. 6, pp. 536–547.
3. K.Yu. Shakhnazarov, A.R. Rafikov. The influence of hardening heat treatment modes on the crack propagation resistance of 5H2SMF die steel. *Frontier Materials & Technologies*, 2025, no. 2, pp. 95–101.
4. X. Zhang, C. Zhang. Inconsistent nanoindentation test hardness using different Berkovich indenters. *Journal of Materials Research and Technology*, 2023, vol. 25, pp. 6198–6208.
5. P. Jindal, M. Goyal, N. Kumar. Mechanical characterization of multiwalled carbon nanotubes-polycarbonate composites. *Materials & Design*, 2014, vol. 54, pp. 864–868.
6. G. Maculotti, J. Kholkhujaev, G. Genta, M. Galetto. Direct calibration of indenter tip geometry by optical surface topography measuring instruments. *Journal of Materials Research*, 2023, vol. 38, no. 13, pp. 3336–3348.
7. J. Degenhardt, X. Hu, M. Zackaria, F. Menelao, R. Tutsch, G. Dai. Accurate AFM calibration of indenter geometry for instrumented indentation. *Nanomanufacturing and Metrology*, 2025, vol. 8, no. 1, art. no. 15.
8. C.O.W. Trost, S. Zak, S. Schaffer, C. Saringer, L. Exl, M.J. Cordill. Bridging fidelities to predict nanoindentation tip radii using interpretable deep learning models. *JOM*, 2022, vol. 74, no. 6, pp. 2195–2205.
9. A. Burleigh, M.L. Lau, M. Burrill, D.T. Olive, J.G. Gigax, N. Li, T.A. Saleh, F. Pellemoine, S. Bidhar, M. Long, K. Ammigan, J. Terry. Artificial intelligence based analysis of nanoindentation load–displacement data using a genetic algorithm. *Applied Surface Science*, 2023, vol. 612, art. no. 155734.
10. Z. Su, Z. Zhu, Y. Zhang, H. Zhang. Analysis of microstructure and mechanical properties of AZ31B magnesium alloy/AA6061 aluminum alloy welded joint by ultrasonic welding. *Materials Research*, 2021, vol. 24, no. 2, art. no. e20200488.
11. B. Sahoo, J. Paul, A. Sharma. Mechanical and tribological behaviour of surface-graphitised Al-1100 alloy. *Lubricants*, 2024, vol. 12, no. 4, art. no. 139.
12. S.V. Matrenin, A.V. Mostovshchikov, Yu.A. Mirovoy, A.O. Chudinova. Research of structure and physical and mechanical properties of ceramics based on aluminum and zirconium oxynitrides. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 2022, vol. 333, no. 2, pp. 184–192.
13. F. Ishrak, M. Lastovich, A. Malakar, R.S. Haridas, A.J. Bhattacharjee, H. Qiao, M. Clary, J. Tracy, N. Balke, H.P. Lisabeth, R. Mishra, M. Efe, B. Gwalani. Aluminum/SmCo₅ composites for structural and magnetic applications. *Journal of Materials Science*, 2024, vol. 59, no. 36, pp. 16981–16992.
14. S. Talangkun, D. Mingmuang. Characterization and mechanical properties of AA1100 aluminium alloy coated on a metakaolin substrate produced by the spot friction surfacing process. *Engineering and Applied Science Research*, 2022, vol. 49, no. 4, pp. 603–611.
15. J. Christudasjustus, C.S. Witharamage, G. Walunj, T. Borkar, R.K. Gupta. The influence of spark plasma sintering temperatures on the microstructure, hardness, and elastic modulus of the nanocrystalline Al-xV alloys produced by high-energy ball milling. *Journal of Materials Science & Technology*, 2022, vol. 122, pp. 68–76.
16. S. Yu, G. Zhao, H. Hou, L. Zheng, Y. Guan. Grain size dependent unloading anelastic behavior and multi-scale model of AA6061 aluminum alloy. *Journal of Materials Research and Technology*, 2026, vol. 42, pp. 6205–6227.
17. M. Maj, Y. Beygelzimer, S. Musiał, S. Kucharski, O. Davydenko, H. Petryk. Gradient microstructure and nanohardness in the plastic boundary layer of an AA5083 aluminum alloy processed by local high-pressure torsion. *Journal of Materials Science*, 2026, vol. 61, no. 33, pp. 25070–25086.
18. E. Giarmas, E. Tzimtzimis, D. Tzetzis. The influence of ageing conditions and liquid nitrogen cooling of extrusion dies on nanoindentation creep in 6060 aluminium alloy. *The International Journal of Advanced Manufacturing Technology*, 2025, vol. 137, no. 11–12, pp. 6187–6205.

19. H. Holz, B. Merle. Novel nanoindentation strain rate sweep method for continuously investigating the strain rate sensitivity of materials at the nanoscale. *Materials & Design*, 2023, vol. 236, art. no. 112471.
20. A.A. Shibkov, M.A. Zheltov, M.F. Gasanov, A.E. Zolotov. Acoustic emission during intermittent creep in an aluminum–magnesium alloy. *Physics of Metals and Metallography*, 2018, vol. 119, no. 1, pp. 76–82.
21. W.C. Oliver, G.M. Pharr. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of Materials Research*, 1992, vol. 7, no. 6, pp. 1564–1583.
22. W.C. Oliver, G.M. Pharr. Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology. *Journal of Materials Research*, 2004, vol. 19, no. 1, pp. 3–20.
23. A. Bolshakov, W.C. Oliver, G.M. Pharr. Finite element studies of the influence of pile-up on the analysis of nanoindentation data. *MRS Proceedings*, 1996, vol. 436, pp. 141–146.
24. T.Y. Tsui, W.C. Oliver, G.M. Pharr. Nanoindentation of soft films on hard substrates: The importance of pile-up. *MRS Proceedings*, 1996, vol. 436, pp. 207–212.
25. S. Soare, S.J. Bull, A.G. O’Neil, N. Wright, A. Horsfall, J.M.M. dos Santos. Nanoindentation assessment of aluminium metallisation; the effect of creep and pile-up. *Surface and Coatings Technology*, 2004, vol. 177–178, pp. 497–503.
26. M.K. Khan, S.V. Hainsworth, M.E. Fitzpatrick, L. Edwards. Application of the work of indentation approach for the characterization of aluminium 2024-T351 and Al cladding by nanoindentation. *Journal of Materials Science*, 2009, vol. 44, no. 4, pp. 1006–1015.
27. R.K. Nutor, N.K. Adomako, Y.Z. Fang. Using the Hollomon model to predict strain-hardening in metals. *American Journal of Materials Synthesis and Processing*, 2017, vol. 2, no. 1, pp. 1–4.
28. A. Voronin. Analysis of the reasons for specific deformation behavior of topocomposite of the AlN-D16T system during instrumental indentation. *East European Scientific Journal*, 2021, vol. 2, no. 10(74), pp. 42–52.
29. M. Wang, G. Zhang, T. Liu, W. Wang. Determination of elastoplastic properties of 2024 aluminum alloy using deep learning and instrumented nanoindentation experiment. *Acta Mechanica Sinica*, 2023, vol. 36, no. 2, pp. 327–339.
30. B. Yin, X. Xue, M. Zhang, T. Deng, J. Li, B. Tang. Parameter identification and pileup behavior of TiAl alloy through nanoindentation and crystal plasticity simulation. *Journal of Alloys and Compounds*, 2023, vol. 948, art. no. 169743.
31. W.J. Poole, J.D. Embury, D.J. Lloyd. Work hardening in aluminium alloys. In: R. Lumley (Ed.). *Fundamentals of Aluminium Metallurgy: Production, Processing and Applications*. Woodhead Publishing, Cambridge, 2010, pp. 307–344.
32. A.D. Khalimonenko, Yu.R. Shmakova, O.N. Admakina, V.G. KufaeV. High-speed face milling features of deformable aluminum alloys. *Tsvetnye Metally*, 2024, no. 6, pp. 81–88.
33. M.A. Admakina, O.N. Admakina, D.Yu. Timofeev, A.D. Khalimonenko. Deformation processes during high-speed milling of aluminum alloys. *Tsvetnye Metally*, 2025, no. 3, pp. 75–80.
34. Y. Xia, M. Bigerelle, J. Marteau, P. Mazeran, S. Bouvier, A. Iost. Effect of surface roughness in the determination of the mechanical properties of material using nanoindentation test. *Scanning*, 2014, vol. 36, no. 1, pp. 134–149.
35. W.-G. Jiang, J.-J. Su, X.-Q. Feng. Effect of surface roughness on nanoindentation test of thin films. *Engineering Fracture Mechanics*, 2008, vol. 75, no. 17, pp. 4965–4972.
36. X. Zhou, Z. Jiang, H. Wang, R. Yu. Investigation on methods for dealing with pile-up errors in evaluating the mechanical properties of thin metal films at sub-micron scale on hard substrates by nanoindentation technique. *Materials Science and Engineering: A*, 2008, vol. 488, no. 1–2, pp. 318–332.
37. K.I. Doronin, K.V. Gogolinskiy, A.S. Umanskii. Influence of strain hardening on the results of calculating the material mechanical properties via the instrumented indentation test. *International Review on Modelling and Simulations (IREMOS)*, 2025, vol. 18, no. 5, pp. 340–349.
38. F.B. Kværndrup, C. Engelbrekt, Ö.C. KücükYildiz, M.A.J. Somers, T.L. Christiansen, G. Winther. Area determination with pile-up and sink-in in nanoindentation of oxygen containing titanium. *Materials Today Communications*, 2022, vol. 30, art. no. 103218.

39. M. Khokhlov, D. Ishchenko, J. Khokhlova. Peculiarities of forming diffusion bimetallic joints of aluminum foam with a monolithic magnesium alloy. *Journal of Magnesium and Alloys*, 2016, vol. 4, no. 4, pp. 326–329.
40. F. Fadaeifard, M.R. Pakmanesh, M.S. Esfahani, K.A. Matori, D. Chicot. Nanoindentation analysis of friction stir welded 6061-T6 Al alloy in as-weld and post weld heat treatment. *Physics of Metals and Metallography*, 2019, vol. 120, no. 5, pp. 483–491.
41. A.A. Shushkov, P.V. Bykov, V.L. Vorob'ev, A.V. Vakhrushev, V.Ya. Bayankin. Analysis of mechanical characteristics of surface layers of nickel with a sputtered aluminum film after ion-beam mixing. *Chemical Physics and Mesoscopy*, 2021, vol. 23, no. 1, pp. 46–56.
42. A.A. Shibkov, A.E. Zolotov, A.A. Denisov, M.F. Gasanov. Formation of deformation bands during impact indentation of an Al–6Mg alloy. *Physics of Metals and Metallography*, 2023, vol. 124, no. 4, pp. 402–408.
43. M.M. Lyakhovitsky, V.V. Roshchupkin, M.A. Pokrasin, N.A. Minina. Size effects in continuous nanoindentation. *Strengthening Technologies and Coatings*, 2020, vol. 16, no. 2(182), pp. 93–96. [in Russian]
44. M.A. Skotnikova, A.A. Popov, G.V. Ivanova, G.V. Tsvetkova. Investigation of surface properties of alloys using indentation instruments. *Journal of Instrument Engineering*, 2020, vol. 63, no. 5, pp. 460–466.
45. D.M. Matyunin, A.Yu. Marchenkov, R.Yu. Agafonov, V.V. Danilin, M.A. Karimbekov, M.V. Goryachkina, P.V. Volkov, D.A. Zhgut. On correlation of tensile ultimate strength for samples with Brinell hardness of ferrous and non-ferrous structural materials. *Technology of Metals*, 2021, no. 4, pp. 34–41.
46. E.I. Pryakhin, D.A. Pribytkova. The influence of the quality of surface preparation of pipes for heating networks on their corrosion resistance during operation in underground conditions. *Chernye Metally*, 2023, no. 11, pp. 97–102.
47. V.V. Maksarov, D.D. Maksimov, M.S. Sinyukov. Quality control of complex contour surfaces in aluminium alloy items during magnetic abrasive finishing. *Tsvetnye Metally*, 2023, no. 4, pp. 96–102.
48. V.V. Maksarov, A.O. Minin, V.P. Zakharova. Ensuring surface quality in AlMn alloy items during high-frequency wave impact boring. *Tsvetnye Metally*, 2023, no. 4, pp. 90–95.
49. E.J. Frankberg, A. Lambai, J. Zhang, J. Kalikka, S. Khakalo, B. Paladino, M. Cabrioli, N.G. Mathews, T. Salminen, M. Hokka, J. Akola, A. Kuronen, E. Levänen, F. Di Fonzo, G. Mohanty. Exceptional microscale plasticity in amorphous aluminum oxide at room temperature. *Advanced Materials*, 2023, vol. 35, no. 46, art. no. 2303142.
50. V.Yu. Bazhin, N.A. Gordevnin. Microstructural features of Al–Yb master alloys produced by aluminothermic reduction of ytterbium fluoride. *Tsvetnye Metally*, 2023, no. 8, pp. 50–56.
51. S. Shi, N. Lam, Y. Cui, G. Lu, E. Gad, L. Zhang. Indentation modelling of aluminium cladding panels subjected to hailstone impact. *International Journal of Impact Engineering*, 2023, vol. 179, art. no. 104638.
52. P. Blaško, J. Petřík, M. Šolc, M. Mihalíková, L. Girmanová, A. Pribulová, P. Futáš, J. Furman, K.-C. Marzena. The effect of aluminum deformation conditions on microhardness and indentation size effect characteristics. *Crystals*, 2025, vol. 15, no. 3, art. no. 252.
53. Y. Bai, C. Liu. Estimation of mechanical properties of aluminum alloy based on indentation curve and projection area of contact zone. *Metals*, 2024, vol. 14, no. 5, art. no. 576.
54. T. Bond, A. Badmos, R.A. Ahmed, J.D. Obayemi, A. Salifu, N. Rahbar, W.O. Soboyejo. Indentation size effects in aluminum and titanium alloys. *Materials Science and Engineering: A*, 2022, vol. 839, art. no. 142542.
55. T.A. Kuznetsova, S.A. Chizhik, A.L. Khudoley. Deformation structuring of aluminum films upon microindentation. *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*, 2014, vol. 8, no. 6, pp. 1275–1285.
56. A. Voronin. Analysis of the reasons for specific deformation behavior of topocomposite of the AlN-D16T system during instrumental indentation. *East European Scientific Journal*, 2021, vol. 2, no. 10(74), pp. 42–52.
57. P.L. Podkur, I.S. Volchikov, M.Kh. Gadzhiev, A.E. Muslimov, V.M. Kanevsky, M.V. Ilyichev. The relationship between the particle size distribution of aluminum powder and the structural-

- phase composition and properties of the $\text{Al}_2\text{O}_3\text{--AlN}$ coating formed under the influence of electric arc nitrogen plasma. *Structural Diagnostics of Materials*, 2024, no. 3–4 (123–124), pp. 60–67.
58. S.V. Matrenin, A.V. Mostovshchikov, Yu.A. Mirovoy, A.O. Chudinova. Research of structure and physical and mechanical properties of ceramics based on aluminum and zirconium oxynitrides. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 2022, vol. 333, no. 2, pp. 184–192.
 59. G.G. Popov, V.I. Bolobov, A.O. Oparina, A.O. Shvets. Effect of hydrogenation on hardness of metallic materials used in oil and gas industry. *International Journal of Engineering*, 2025, vol. 38, no. 2, pp. 295–303.
 60. A.M. Shchipachev, A.I. Alekhin. Determining the endurance limit of oil and gas steels based on software-assisted indentation testing results. *International Journal of Engineering*, 2026, vol. 39, no. 3, pp. 668–676.
 61. V.M. Matyunin, A.Yu. Marchenkov, P.V. Volkov, M.A. Karimbekov, A.A. Pankina. Influence of scale factor on modulus of elasticity determined by instrumental indentation. *Technology of Metals*, 2023, no. 6, pp. 37–45.
 62. A.V. Ilinskiy, A.V. Fedorov, K.A. Stepanova, I.U. Kinzhagulov, I.O. Krasnov. Study of the dynamic hardness of structural metal materials. *Industrial Laboratory. Diagnostics of Materials*, 2020, vol. 86, no. 1, pp. 57–61.
 63. A.P. Kren, G.A. Lantsman, A.V. Nikiforov, N.K. Tursunov, T.T. Urazbaev. Control of cast iron mechanical properties using microimpact indentation method. *Devices and Methods of Measurements*, 2025, vol. 16, no. 3, pp. 222–234.
 64. A. Kren, M. Delendik, A. Machikhin. Non-destructive evaluation of metal plasticity using a single impact microindentation. *International Journal of Impact Engineering*, 2022, vol. 162, art. no. 104141.
 65. D.S. Gromyka, K.V. Gogolinsky, E.K. Shchiptsova, V.V. Alekhovich. Possibility evaluation of monitoring areas of local plastic deformation during fatigue wear of metal structures using the dynamic instrumented indentation method. *International Journal of Engineering*, 2026, vol. 39, no. 1, pp. 104–111.
 66. L. Qin, H. Li, X. Shi, B.D. Beake, L. Xiao, J.F. Smith, Z. Sun, J. Chen. Investigation on dynamic hardness and high strain rate indentation size effects in aluminium (110) using nano-impact. *Mechanics of Materials*, 2019, vol. 133, pp. 55–62.
 67. H. Yamada, N. Ogasawara, Y. Shimizu, H. Horikawa, H. Kobayashi. Effect of high strain rate on micro-indentation test in pure aluminum. *EPJ Web of Conferences*, 2012, vol. 26, art. no. 01028.
 68. X. Xing, Y. Wang, G. Xiao, S. Yu, Y. Ma, X. Shu, Y. Wu. Rate-dependent indentation size effect on hardness and creep behavior of a titanium metallization film on alumina substrate. *Journal of Materials Research and Technology*, 2021, vol. 15, pp. 4662–4671.
 69. V.M. Matyunin, A.Yu. Marchenkov, R.Yu. Agafonov, N.O. Tsvetkova, M.P. Petrova, G.B. Sviridov. Instrumental indentation as a tool of express control of mechanical properties in aluminum alloys. *Inorganic Materials*, 2026, vol. 62, no. 3, pp. 410–416.
 70. S. Khan, Khadija, M. Junaid, T. Shehbaz, F.N. Khan. Evaluations of nanomechanical and indentation creep of diffusion-bonded aluminum and austenitic stainless steel joint interface. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 2025, vol. 239, no. 7, pp. 1353–1365.
 71. H. Chen, P. Zhao, G. Fu, W. Li, A. Lai, Z. Meng, H. Peng. Cylindrical indentation method for predicting tensile properties of additive manufacturing aluminum alloys. *Advanced Engineering Materials*, 2025, vol. 27, no. 18, art. no. 2500846.
 72. R.R. Ambriz, D. Chicot, N. Benseddiq, G. Mesmacque, S.D. de la Torre. Local mechanical properties of the 6061-T6 aluminium weld using micro-traction and instrumented indentation. *European Journal of Mechanics - A/Solids*, 2011, vol. 30, no. 3, pp. 307–315.
 73. J. Nohava, P. Haušild, D.G. Axelson, G. Bolloré. Mechanical properties of aluminum alloys by instrumented indentation: Case study on Almigo Hard. *Key Engineering Materials*, 2013, vol. 586, pp. 59–62.
 74. Y. Terasaki, T. Mochizuki, J. Kobata, T. Yamamoto, Y. Takigawa. Effect of additional element on local mechanical properties of high purity aluminum alloys by nanoindentation. *Journal of the Japan Institute of Metals and Materials*, 2023, vol. 87, no. 7, art. no. J2023001.

75. M. Liu, Z. Xu, F. Yang. Characterization of cyclic dynamic and creep responses of pure aluminum by instrumented indentation. *SCIENTIA SINICA Physica, Mechanica & Astronomica*, 2023, vol. 53, no. 1, art. no. 214605.
76. A. Musza, D. Ugi, Á. Vida, N.Q. Chinh. Study of anodic film's surface and hardness on A356 aluminum alloys, using scanning electron microscope and in-situ nanoindentation. *Coatings*, 2022, vol. 12, no. 10, art. no. 1528.
77. A. Dhal, S. Thapliyal, S. Gaddam, P. Agrawal, R.S. Mishra. Multiscale hierarchical and heterogeneous mechanical response of additively manufactured novel Al alloy investigated by high-resolution nanoindentation mapping. *Scientific Reports*, 2022, vol. 12, no. 1, art. no. 18344.
78. V. Kumar, U.N. Kempaiah, Shivasharanayyaswamy, S.B. Bopanna. Nanoindentation studies on multiwalled carbon nanotubes/graphene reinforced aluminium alloy 6061 nanocomposites. *Materials Today: Proceedings*, 2021, vol. 45, pp. 202–206.
79. A. Staszczuk, J. Sawicki, Ł. Kołodziejczyk, S. Lipa. Nanoindentation study of intermetallic particles in 2024 aluminium alloy. *Coatings*, 2020, vol. 10, no. 9, art. no. 846.
80. V.B. Bhagwat, A.G. Kadam, D. Rupanwar. Simulation of micro-indentation process of black NiAl coated aluminum substrate using FEM. In: P.M. Pawar, B.P. Ronge, R. Balasubramaniam, S. Seshabhatar (Eds.). *Techno-Societal 2016: Proceedings of the International Conference on Advanced Technologies for Societal Applications*. Springer International Publishing, Cham, 2018, pp. 809–817.
81. T.A. Kuznetsova, S.A. Chizhik, A.L. Khudoley. Deformation structuring of aluminum films upon microindentation. *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*, 2014, vol. 8, no. 6, pp. 1275–1285.
82. M. Cabibbo. Instrumented nanoindentation tests applied to bulk metallic materials: From calibration issue to pile-up phenomena. *Materials*, 2021, vol. 14, no. 21, art. no. 6360.
83. Y.-J. Roh, H. Yang, J.Y. Jeong, H. Cho, S.-H. Lee. Enhancement in mechanical properties of AA5052 sheet for small ship by cold roll-bonding process. *Journal of Welding and Joining*, 2024, vol. 42, no. 5, pp. 550–559.
84. Y. Li, L. Li, J. Nie, Y. Cao, Y. Zhao, Y. Zhu. Microstructural evolution and mechanical properties of a 5052 Al alloy with gradient structures. *Journal of Materials Research*, 2017, vol. 32, no. 23, pp. 4443–4451.
85. A. Useinov, V. Reshetov, I. Maslenikov, A. Rusakov, E. Gladkikh, V. Bepalov, B. Loginov. Study of properties of thin films in dynamic mechanical analysis mode using NanoScan-4D scanning nano-hardness tester. *Nanoindustry Russia*, 2016, no. 1(63), pp. 80–87.
86. International Organisation for Standardization. *Metallic materials — Instrumented indentation test for hardness and materials parameters — Part 1: Test method*. ISO 14577-1:2015. ISO, Geneva, 2015.
87. A. Achuthankutty, R. Saravanan, H. Nagarajan, V. Pasunuri, N.H. Gopal, A. Ramesh, S. Arangot, D.T. Thekkuden. Cryo-rolled AA5052 alloy: Insights into mechanical properties, formability, and microstructure. *Journal of Manufacturing and Materials Processing*, 2024, vol. 8, no. 6, art. no. 284.
88. M. Moradpour, F. Khodabakhshi, S.R. Mohebpour, H. Eskandari, M. Haghshenas. Finite element modeling and experimental validation of CGP classical and new cross routes for severe plastic deformation of an Al-Mg alloy. *Journal of Manufacturing Processes*, 2019, vol. 37, pp. 348–361.
89. W. Li, V. Yakubov, M. Karpenko, A.M. Paradowska. Investigation of thermal–microstructure–hardness relationships in dissimilar AA5052-H32/AA6061-T6 friction stir welded joints. *Materials*, 2026, vol. 19, no. 7, art. no. 1410.
90. D.D. Olodu, S. Igbinoba, M.O. Ozakpolor. Mechanical properties and performance of aluminium alloy AA5052: A comprehensive analysis. *Inspiring Technologies and Innovations*, 2025, vol. 4, no. 2, pp. 44–57.
91. P. Farhadipour, N. Omid, N. Barka, M. Idriss, F. Nadeau, A. El Ouafi. Comparative analysis of the high-temperature tensile properties of laser-welded AA5052 and AA6061 for automotive applications. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2025, vol. 239, no. 12, pp. 4661–4676.
92. H. Zhang, Z. Guo, Z. Yuan. Indentation characteristic strain determined based on metallic material damage. *Archives of Metallurgy and Materials*, 2024, vol. 69, no. 3, pp. 973–980.