Influence of Al_2O_3 content on the mechanical properties of sintered Al-10Cu-xAl_2O_3 composites

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Abstract: *This study investigates the influence of Al_2O_3 content on the mechanical properties of sintered Al-10Cu-xAl_2O_3 (x = 2.5, 5, and 7.5 wt.%) composite materials, produced via powder metallurgy and subjected to quasi-static and dynamic compressive loadings. Quasi-static tests were performed at a constant strain rate of 0.003 s^{-1}, while dynamic tests were conducted at strain rates corresponding to impact velocities of approximately 10 m/s and 20 m/s. The results indicate that a higher Al_2O_3 content enhances the mechanical properties of the composite under both quasi-static and dynamic compression. The most significant improvements were observed under high strain rate impact loading, highlighting the potential of sintered Al-10Cu-xAl_2O_3 for applications in dynamic environments.*
Keywords*: SINTERED AL-10CU-XAL_2O_3 COMPOSITES, POWDER METALLURGY, AL_2O_3 CONTENT, COMPRESSIVE STRENGTH*

1. Introduction

Aluminium and its alloys are proven as prospective base materials for manufacturing light metal matrix composites (MMC) and powder metallurgy is a suitable technique for their production [1-4]. To further improve its properties, primary alloying elements are added to aluminium powder. Copper is believed to be the most significant due to its ability to cause higher densification and age hardening in Al-Cu alloys [2,3,5]. It is known by the literature that Al-Cu composite materials, manufactured by powder metallurgy method are widely used in the automotive and aerospace industries for cost-saving lightweight functional components [3,4,6]. The reinforcement is done mainly by ceramic particles including SiC, B4C, TiC, WC and Al_2O_3 [1-4,7-13]. Among them, Al_2O_3 is generally used to improve the hardness, strength and wear behaviour of aluminium alloy matrix [3,4].

Some research has already been published with 2.5, 5 and 10 wt % Al_2O_3 reinforcement [10] and improvement in tensile and compressive strength of hot extruded MMC materials reinforced by alumina particles up to 5 wt.% is found. The influence of the percentage of the Al_2O_3 reinforcement, the H/D ratio of the compacted samples and the compaction pressure on the physical and mechanical properties of the composites were also investigated using different methodologies [3,4]. The experimental data showed that the best yield and compression strength are obtained at 10% Al_2O_3, 700 MPa, and 1.25 H/D, while the maximum fracture strain is achieved at 700 MPa, 1.25 H/D, and 0% Al_2O_3 [4]. Higher Al_2O_3 content decreases relative density by increasing volumetric voids and segregation between the higher amount of reinforcement and Al-4Cu matrix, but has a positive effect on the hardness of the composites [3]. Despite the serious research that has been conducted on the mechanical characteristics of aluminium-based composites, the distinct mechanical evaluation of Al-10Cu-xAl_2O_3 composites, produced through powder metallurgy, under low and high-strain compressive loading continues to be insufficiently investigated. Current research aims to fill this knowledge gap by studying the performance of Al-10Cu-xAl_2O_3 composites under distinct loading regimes.

This study aims to evaluate the influence of Al_2O_3 content on the mechanical properties of sintered Al-10Cu-xAl_2O_3 (x = 2.5, 5, and 7.5 wt%) composite materials, produced via powder metallurgy and subjected to quasi-static and dynamic compressive loadings.

2. Materials and methods

Aluminium-based alloys were produced using aluminium, copper and Al_2O_3 powders with a particle size of ≤325 mesh. All powders were first mixed in the desired proportions and then subjected to high-energy ball milling with a ball-to-powder ratio of 6:1. The milling process continued for 5 hours at a rotation speed of 500 rpm to achieve a uniform distribution of Cu and Al_2O_3 particles within the Al matrix. After the ball milling process, the powder mixtures were compacted in a cylindrical steel die with a diameter of 16 mm using a hydraulic press. The resulting green bodies were sintered at 530°C for 3 hours. After sintering, the samples were cooled slowly in the furnace to minimise thermal stresses and to secure uniform microstructural development. The specimens for determining the mechanical properties are cylindrical with a diameter and height of 10x15 mm for quasi-static testing and 5 x 5 mm for dynamic testing. A universal servo-hydraulic testing machine Zwick Roell HA250 was used for quasi-static compression tests at a constant low strain rate of 0.003 s^{-1}. A modified Split Hopkinson Pressure Bar (SHPB) apparatus for impact testing of light materials [14], was used for the dynamic compression tests at high strain rates of about ~1500 s^{-1} and ~3200 s^{-1}, corresponding to impact speeds of about 10 m/s and 20 m/s.

3. Results and discussion

When it comes to analysis of the mechanical response of certain material it is always helpful to be aware of its structure and possible changes during fabrication. According to the Al−Cu phase diagram, Al_2Cu, AlCu, Al_3Cu_4, Al_2Cu_3, and Al_4Cu_9 could be formed in the Al−Cu system through solid-state phase transformation [15,16,17] among which stable phases are AlCu, Al_2Cu, and Al_4Cu_9 [18]. Al_2Cu phase evolves among the first due to its lowest formation energy [16,17] and usually the increasing of Cu content results in the formation of only Al_2Cu in the fabricated composites [15] because the thermal processing time is long enough to convert AlCu to Al_2Cu. Thus, the structure of the matrix material is believed to be consistent with aluminium grains with dissolved copper surrounded by copper precipitated in the form of the Al_2Cu phase at the aluminium grain boundaries [1, 2].

In addition, alumina leads to grain refinement. If the harder alumina particles are reasonably distributed, they could increase the dislocation density of the matrix and the load is transferred from the matrix to the reinforcement/second phases. The Al_2O_3 particles distort the crystal lattice of the Al-Cu matrix, hinder the mobility of dislocations and thus strengthen the alloy [3]. The Al_2Cu phase and alumina particles are believed to be the main reason for the enhanced mechanical properties of the tested Al-10Cu-xAl_2O_3 composites

Quasi-static compression test results are presented in Fig. 1, showing the stress-strain curves for three types of powder-metallurgy-derived Al-10Cu-xAl_2O_3 materials with different Al_2O_3 content. The graphs show similar behaviour under quasi-static compression, starting with the stage of elastic compression up to the proportional limit and yielding, strain hardening with ductile deformation and non-uniform deformation at compressive strength with shear bands beginning to develop [19,20]. A decrease in the load-bearing capacity of the compacted composites occurs because of the deformation within the shear bands, followed by complete failure due to the separation of bonded particles along the shear bands [20].

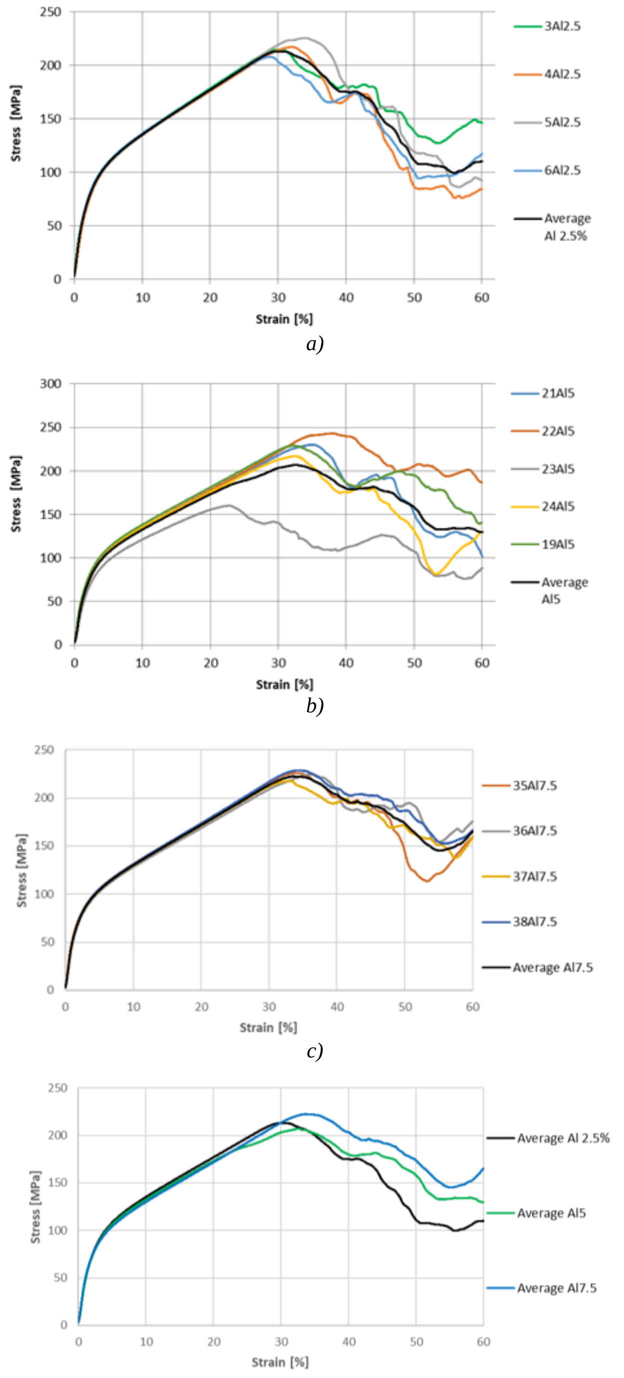

Fig. 1 *Quasi-static tests result at a constant strain rate of 0.003 s^{-1} of: a) sintered Al-10Cu-2.5Al_2O_3 ; b) sintered Al-10Cu-5Al_2O_3 c) sintered Al-10Cu-7.5Al_2O_3 ; d) average curves*

The stress-strain curves are smooth up to about 30% deformation in the tested specimens The yield stress in all the specimens is almost identical and the material continues to strain harden till 30% plastic strain. The first drop of stresses is notable right after 30% strain in alloys with 2,5 wt% Al_2O_3 followed by the ones with 5 wt% Al_2O_3. Before 40% deformation all tested materials have reached their compressive strength with 7,5 wt% Al_2O_3 alloy being at the maximum. The variation graphs of elastic modulus and yield stress (fig. 2a) and compression strength and strain (fig. 2b) are obtained from the experimental data at a constant strain rate of 0.003 s^{-1}. The elastic modulus and the compression strain at the strength point of the Al-10Cu-xAl_2O_3 composites showed an upward trend when a higher content of Al_2O_3 was added. The average yield stress stays almost unaffected by alumina content. The compression strength remained constant up to 5 wt% Al_2O_3 and then raised at a concentration of 7.5 wt% Al_2O_3. It can be concluded that the higher amount of alumina particles demonstrates improvement in the properties of the composites tested under quasi-static loadings.

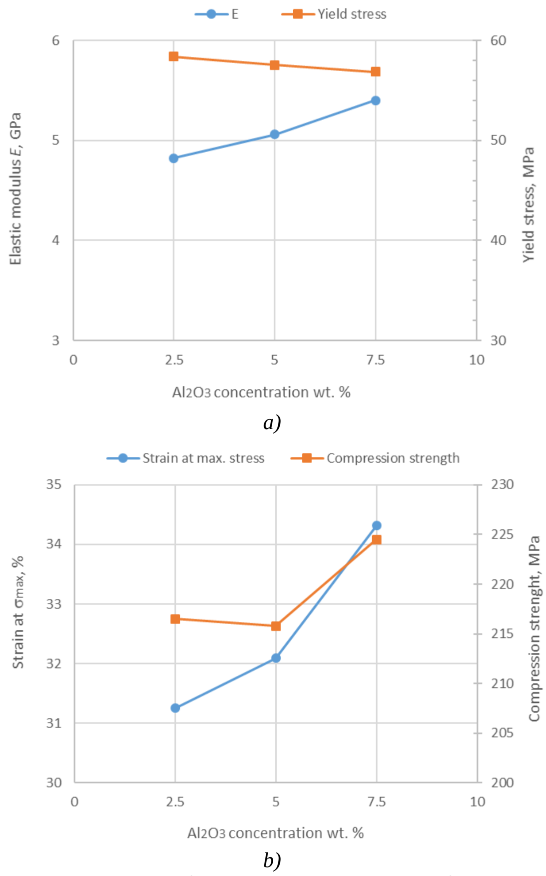

Fig. 2 *Variation curves of the mechanical properties of the composites with different Al_2O_3 content, tested under quasi-static loading: a) elastic modulus and yield stress; b) compression strength and strain*

The mechanical properties under all strain rates of the tested Al-10Cu-xAl_2O_3 composites, as summarised in Table 1.

Table 1: *Average values of the mechanical properties of tested materials.*

Alumina concentration wt%	2.5% Al_2O_3	5% Al_2O_3	7.5% Al_2O_3
quasi-static compression at the strain rate of 0.003 s^{-1}			
Modulus of elasticity [GPa]	4.8	5.1	5.4
YS(offset=0.2%) [MPa]	58	58	57
Compressive strength [MPa]	217	216	225
Deformation ε [%]	31.3	32.1	34.3
high impact dynamic compression at the strain rate of 1500 s^{-1}			
Modulus of elasticity [GPa]	7.9	9.7	12.9
YS(offset=0.2%) [MPa]	72	82	93
Compressive strength [MPa]	328	323	338
Deformation ε [%]	44.4	45.7	45.8
high impact dynamic compression at the strain rate of 3200 s^{-1}			
Modulus of elasticity [GPa]	7.4	5.3	5.0
YS(offset=0.2%) [MPa]	84	64	71
Compressive strength [MPa]	1399	1365	1614
Deformation ε [%]	83.7	85.1	84.8

The results from dynamic compression tests are shown in Fig. 3 for moderate strain rates of 1500 s^{-1} and Fig. 4 for high strain rates of 3200 s^{-1}. All specimens tested at high strain rates exhibited a distinct elastic stage, followed by strain hardening up to the compression strength, with plenty of fluctuations in stress during the tests under dynamic compression at 10 m/s. The ultimate strength and failure strain increased with the strain rate for all tested materials. There is some difference in the failure mode – at impact speeds of 10m/s the tested alloys generally exhibit plastic failure, while in the ones tested at 20 m/s a mixed mode of splitting and smash failure is observed. The stress-strain relationships revealed superior dynamic mechanical properties at a strain rate of 3200 s^{-1} compared to 1500 s^{-1}, although the yield strength values are quite close.

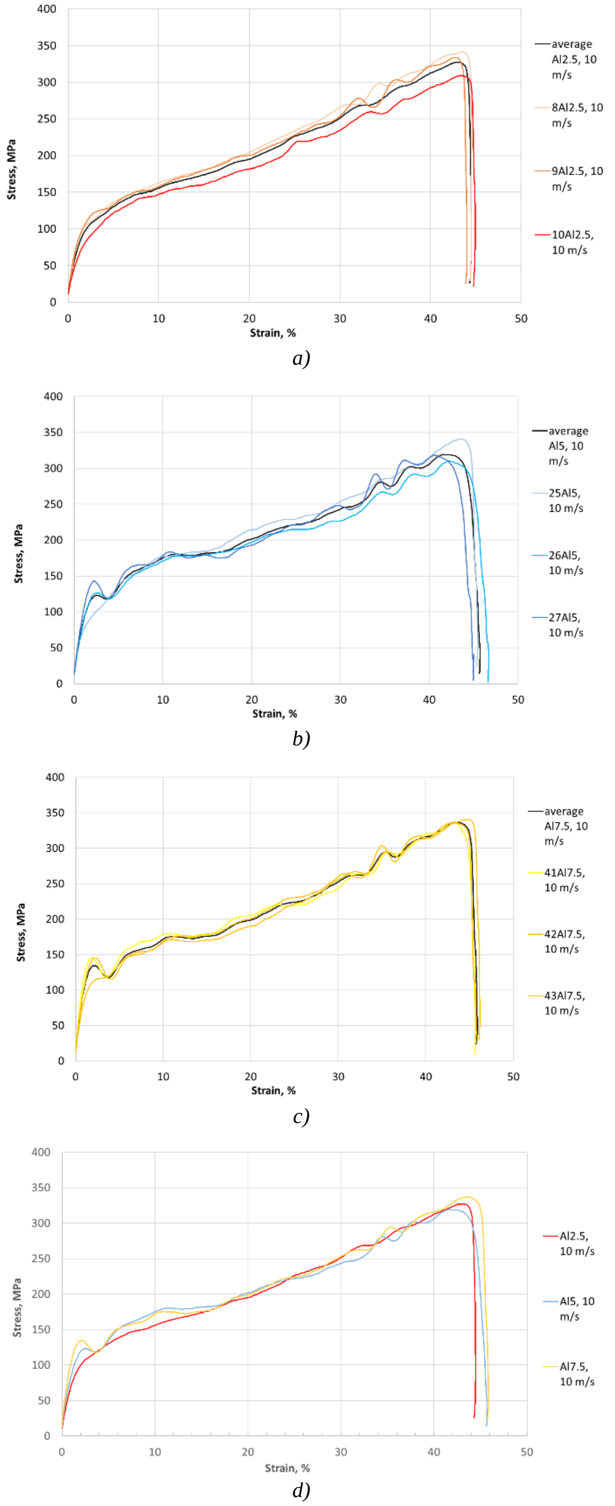

Fig. 3 *SHPB dynamic test results at 10 m/s of: a) sintered Al-10Cu-2.5Al_2O_3 ; b) sintered Al-10Cu-5Al_2O_3 c) sintered Al-10Cu-7.5Al_2O_3 ; d) average curves*

The variation graphs of elastic modulus and yield stress (fig. 5 a, b) and compression strength and strain (fig. 5 c, d) are obtained from the experimental data at a strain rate of 1500 s^{-1} and 3200 s^{-1}. At high strain rates no obvious trend in the properties is observed. It is visible that the strain is not affected by the Al_2O_3 content. The elastic modulus and yield stress are varied in very tight intervals, especially for the strain rate of 3200 s^{-1} and can hardly be attributed to the alumina content. The major positive effect of alumina content is demonstrated in compression strength for 7.5 wt% Al_2O_3, with a slight drop in the values at 5 wt% Al_2O_3.

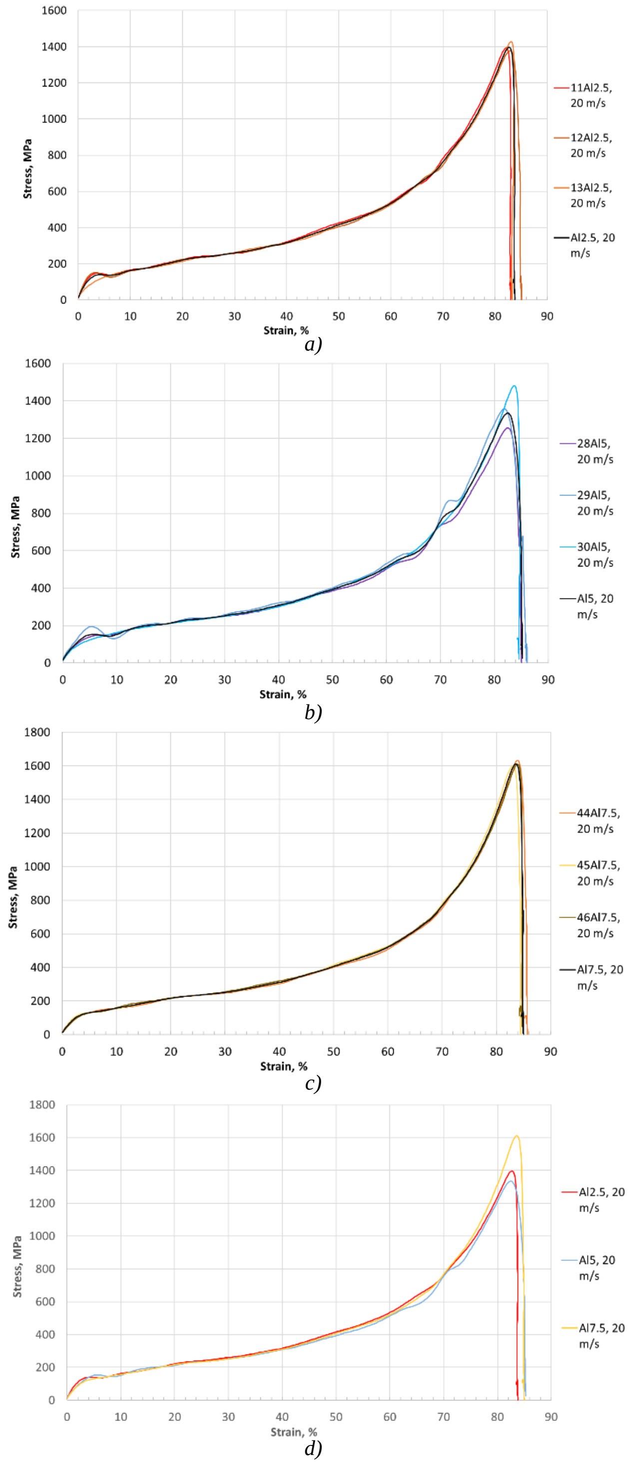

Fig. 4 *SHPB dynamic test results at 20m/s of: a) sintered Al-10Cu-2.5Al_2O_3 ; b) sintered Al-10Cu-5Al_2O_3 c) sintered Al-10Cu-7.5Al_2O_3 ; d) average curves*

The increase in compressive strength is attributed to the Al_2O_3 particles, with best results of Al-10Cu-7.5Al_2O_3 under all strain rates in the investigation. Also, it is noticed that the amount of alumina addition (up to 7,5 wt%) does not affect the plasticity of the composite at a certain strain rate. The difference in deformation is observed only when comparing the results from tests at different strain rates, with the highest results for strain rates 3200 s^{-1}. The compressive strength increases from 200-250 MPa at quasi-static rates (0.003 s^{-1}) to 1400-1600 MPa at high strain rates (3200 s^{-1}) and the strain corresponding to the maximum compressive stress is shifted from about 30-35% to 85%. The reduction in strength, observed in Al-10Cu-5Al_2O_3 is attributed to the presence of a higher amount of unbounded free particles in the Al-Cu matrix than in other tested composites [10]. The slight differences in properties could also be due to the different densification of specimens [19], although this is not obvious from compression tests.

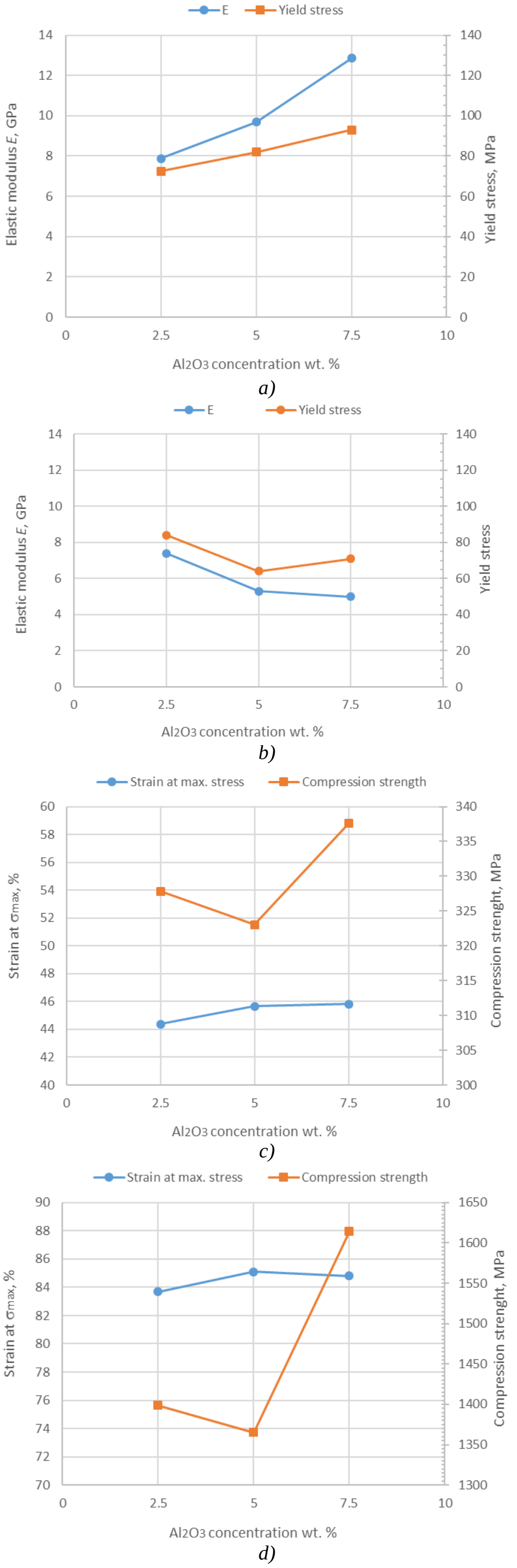

Fig. 5 *Variation curves of the mechanical properties of the composites with different Al_2O_3 content: a) Elastic modulus and yield stress at 1500 s^{-1}; b)Elastic modulus and yield stress at 3200 s^{-1}; c)Strain at maximum stress and compressive strength at 1500 s^{-1}; d) Strain at maximum stress and compressive strength at 3200 s^{-1}.*

4. Conclusions

The current investigation focuses on the influence of Al_2O_3 addition on the mechanical behaviour of Al-10Cu-xAl_2O_3 composites (x = 2.5, 5, and 7.5 wt.%) produced through powder metallurgy under quasi-static and dynamic compressive loading conditions. The major conclusions that could be drawn back are:

1. Al-10Cu-xAl_2O_3 composites with 2.5, 5, and 7.5 wt.% Al_2O_3 were successfully synthesised through the powder metallurgy method.

2. Increased compressive strength up to 1600 MPa and deformation up to 85% at high strain rates (3200 s^{-1}) were experimentally achieved by SHPB testing.

3. The improvement in mechanical properties is attributed to the higher Al_2O_3 content, which enhances strength and deformation capacity under dynamic loading conditions of the tested alloys.

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7. References

1. A. Wąsik, B. Leszczyńska- Madej, P. Noga. The Int. J. of Adv. Man. Tech (2024) **134**:3611–3620
2. A. Wasik, B. Leszczynska-Madej, M.Madej, M. Goły. Materials (2023) 16, 5492.
3. Nassef AE, El-Katatny SM, El_Garaihy WH (2019). Adv Metallurg Mater Eng 2(1):71-80
4. Elkatatny, S.; Alsharekh, M.F.; Alateyah, A.I.; El-Sanabary, S.; Nassef, A.; Kamel, M.; Alawad, M.O.; BaQais, A.; El-Garaihy, W.H.; Kouta, H. Appl. Sci. 2023, 13, 7483.
5. M. N. Khan, S. Narayan, A. Rajeshkannan. AIMS Mat. Sci. (2019) 6(3): 441–453.
6. Gökçe, A.; Findik, F.; Kurt, A.O. Pract. Metallogr. 2017, 54, 533–551.
7. S. Jain, R.S Rana, P. Jain. Int. Res. J. of Eng. and Tech (2016), Vol: 03, Issue: 01
8. M.N. Khan, S. Narayan, A. Rajeshkannan A.K. Jeevanantham. Materials Today: Proceedings 22 (2020) 2499–2508
9. O. Emadinia, M. T. Vieira, M. F. Vieira. Met. 2020, 10, 1416
10. AE Nassef, GA Ebrahim, AA El-Baghdady (2003) J. of Eng. and Appl. Sci. 50: 371-386.
11. El-Kady, O.A.; Yehia, H.M.; Nouh, F.; Ghayad, I.M.; El-Bitar, T.; Daoush,W.M. Materials 2022, 15, 7116
12. Kolev, M.; Drenchev, L.; Petkov, V.; Dimitrova, R. Metals 2023, 13, 131.
13. Kolev, M.; Drenchev, L.; Petkov, V. Metals 2023, 13, 814. https://doi.org/10.3390/met13040814
14. R. Krastev, V. Kavardzhikov, T. Simeonova. Math. Modeling (2024), Vol. 8 pp.27-31.
15. S. LUO, Y. WU, B. CHEN, M. SONG, J. YI, B. GUO, Q. WANG, Y. YANG, W. LI, Z. YU. Trans. Nonferrous Met. Soc. China **32**(2022) 3860−3872
16. R. Ali, F. Ali, A. Zahoor, R. N. Shahida, N. H. Tariq, T. He, M. Shahzad, Z. Asghar, A. Shah, A. Mahmood, H. B. Awais. J. of Alloys and Comp. **889** (2021) 161531
17. D. Kim, K. Kim, H. Kwon. Materials (2021**)**, **14**, 266.
18. R. Malik, P. A. Bajakke, K. K. Saxena, A. Lakshmikanthan, A. S. Deshpande, S. Mabuwa, V. Masomi. Mater. Res. Express 9 (2022) 066507
19. X. Tang, Z. Wang, J. Yin, J. Yi. Adv. in Mat. Sci. and Eng. 2021, Article ID 5518172, 9 pages
20. M. Guden,T, E. Celik, E. Akar, S. Cetiner. Materials Characterization **54** (2005) 399– 408