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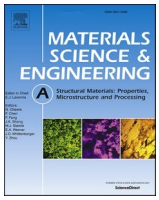

Acoustfic softenfing – finvestfigatfion of the voflume effect and fintroductfion of ampflfitude strafin parameter

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A R T I C L E I N F O

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Ampflfitude strafin
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A B S T R A C T

Acoustfic softenfing fis a phenomenon where metafls exhfibfit a flower fflow stress when excfited by a vfibratfion at ufltrasonfic frequencfies. Thfis softenfing effect has been wefll documented fin the flfiterature, however, there are two areas that requfire further fin-depth anaflysfis. The ffirst reflates to the wfide range of reported softenfing responses for the same aflfloy. The second reflates to the use of coeffficfients and compensatfion factors when modeflfing the acoustfic softenfing phenomenon fin a compflex formfing processes. Thfis study finvestfigates the changes fin softenfing response when aflterfing specfimen dfimensfions fin ufltrasonfic assfisted compressfion tests. Aflumfinum aflfloys (AA) 2024-O and AA7075-O were machfined to dfifferent dfimensfions and compressed wfith ufltrasonfic assfistance, to finvestfigate the reflatfionshfip between specfimen voflume and softenfing response. An finverse reflatfionshfip between softenfing magnfitude and sampfle voflume was found. When reflatfing thfis to acoustfic energy densfity and stress, the vaflues are finvarfiant because the standard acoustfic equatfions cannot account for changes fin specfimen hefight. The ampflfitude strafin parameter, ampflfitude dfivfided by the current specfimen hefight, fis fintroduced, and shown to account for changes fin specfimen dfimensfions. In addfitfion, the softenfing effect dfimfinfishes reflatfive to the state of strafin. The resuflts suggest acoustfic softenfing fis a functfion of the ampflfitude strafin parameter and strafin hfistory.

1. Introduction

Acoustfic softenfing fis a phenomenon fin whfich materfiafl exhfibfits a flower fflow stress when a vfibratfion, typficaflfly above 20 kHz, fis appflfied. An earfly study from Bflaha and Langenecker showed that the shear stress fin zfinc sfingfle crystafls decreased durfing ufltrasonfic excfitatfion [1]. Thfis proved to be a sfignfifficant ffindfing as the requfired energy finput was flower than the requfirement for thermafl softenfing for an equfivaflent fflow stress reductfion. The proposed drfivfing mechanfism fis a flocaflfizatfion of acoustfic energy at defect sfites, such as dfisflocatfions, whfich flowers the crfitficafl energy requfired for sflfip. Some researchers have suggested thfis effect to be drfiven by materfiafl heatfing or sfimpfly the average stress durfing the unfloadfing phase of the vfibratfion, termed stress superposfitfion; however, mufltfipfle studfies have shown that sampfle heatfing does not reach hot formfing temperatures [2–6] and the stress superposfitfion cannot fuflfly account for the reductfion fin fflow stress [3,4].

Sfince thfis finfifiafl ffindfing, acoustfic softenfing has been demonstrated fin a varfiety of metafls and thefir aflfloys fincfludfing aflumfinum, copper, magnesfium, tfitanfium, and steefl [6–10]. The ufltrasonfic vfibratfion fis often appflfied durfing the pflastfic regfime for a short duratfion or ffinfite amount of strafin and the change fin fflow stress can be represented by:

$$\sigma_f = \frac{\sigma_{UA}}{\sigma_{Control}} \tag{1}$$

$$\Delta\sigma = \frac{\sigma_{Control} \quad \sigma_{UA}}{\sigma_{Control}} \bullet 100 \tag{2}$$

where the softenfing fractfion, σ_f, fis the ratfio of the fflow stress for the ufltrasonfic assfisted (UA) sampfle dfivfided by the fflow stress of the quasfi-statfic floaded or controfl sampfle. $\Delta\sigma$ fis the softenfing magnfitude whfich fis the percent change fin stress reflatfive to the controfl sampfle. Acoustfic varfiabfles such as acoustfic energy densfity, fintensfity, and stress have been used to correflate $\Delta\sigma$ and are represented by these equatfions:

$$E = \frac{\sigma_{acoustic}\omega\lambda}{c} = \rho\omega^2\lambda^2 \left[\frac{J}{m^3}\right] \tag{3}$$

$$I = \rho c\omega^2\lambda^2 \left[\frac{W}{m^2}\right] \tag{4}$$

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$$\sigma = \omega\lambda \sqrt{\rho E_{mod}} \ [MPa] \quad (5)$$

E, I, σ are the acoustic energy, intensity, and stress terms respectively. ρ is the density of the sample, ω is the angular frequency of the ultrasonic horn, λ is the applied amplitude, c is the maximum speed of sound in the sample, and E_{mod} is the elastic modulus of the workpiece. The acoustic stress and acoustic energy correlate to amplitude and amplitude squared, respectively.

Since amplitude is the main variable in ultrasonic assisted experiments, it is common to correlate the softening response to amplitude or amplitude to the power of a constant. The reported literature has been quite mixed in this correlation. Deshpande et al. performed ultrasonic assisted compression (UAC) on aluminum wire and found correlations to amplitude squared [11]. Wang et al. [12] observed a linear relationship to amplitude in ultrasonic assistance to tensile tests (UAT) of copper foils. Yao et al. [13] found UAC on commercially pure aluminum to correlate linearly to the amplitude. Siddiq et al. [14] introduced $U_{soft} = (1 - d \bullet I)^{e_{ut}}$, where U_{soft} is the softening term, I is the acoustic intensity (Eq. (4)), d and e_{ut} are experimentally fitted constants; they used this equation to modify the finite element (FE) flip resistance in crystal plasticity modeling of ultrasonic consolidation. Siddiq et al. [15] later modeled other processes that used that same aluminum material but had to change the value of e_{ut} from 1 to 2.

In addition, the magnitude of softening reported for the same alloy can vary significantly. Several UAC examples on commercially pure aluminum are taken from literature. Daud et al. [3] observed a softening effect of 38% when using an amplitude of 10 μm. Zhou et al. [7] achieved 37% softening with just a 4 μm amplitude. Yao et al. [13] found a softening effect of 35% with only a 2 μm vibration amplitude. Possible reasons for these differences include the state of strain of the sample at which the excitation was applied and differences in material microstructure. Siu et al. [16] incorporated plastic strain using cold rolling and characterized the softening in UA micro indentation experiments; they observed a non-monotonic response for aluminum specimens. The three cited examples [3,7,13], apply ultrasonic vibration between strains of 0.15–0.20 and evaluates the softening at the very beginning. The strain states are fairly close for this sample set and likely contributes minorly to the variability. There are a few reports of grain size and texture impacting the softening response. Ahmadi et al. [17] conducted ultrasonic assisted equal channel angular press on commercially pure aluminum with grain sizes ranging from 109 μm to 1 μm and discovered a direct correlation between softening and grain size. In contrary, Wang et al. [8] suggested an inverse relationship between grain size and softening in UAT of copper foils. Kang et al. [18] found that the sample texture has a direct relationship in differences of softening response when tensile testing copper sheet parallel or perpendicular to the rolled direction. Although microstructural differences can be a plausible explanation, a key difference in the cited studies is the size of the compression specimens. Daud's, Zhou's, and Yao's compression specimens had heights of 8 mm, 4 mm, and 2 mm respectively.

Aside from fundamental compression and tension experiments, acoustic softening has been tested on a variety of practical manufacturing processes. Vahdati et al. [19] included a vibrating tool in single-point incremental forming of straight grooves. Their results showed greater strains were achieved due to acoustic softening and lower surface roughness. Cheng et al. [20] applied vibrations to two-point incremental forming, which uses a half-die as support. The forming force decreased by 18% and thickness reductions were measured to be greater than the applied amplitude of 3.2 μm. Aziz and Lucas [21] demonstrated using ultrasonic vibrations in the press forming and showed a reduction of 22% with an applied amplitude of 20 μm. Thus, there are a variety of applications demonstrated to benefit from flow stress reductions. However, the strategies on how to accurately model and predict the response require further work. Sedaghat et al. [22] presented a phenomenological model to simulate the expected forming in compression, punch forming, and incremental forming. To do so, they used Kocks-Mecking's dislocation evolution model where they lowered the activation energy for dislocations to overcome barriers. However, it was necessary to introduce two fitting constants for the punch and incremental forming simulations: effective coefficient and active volume parameter. The first coefficient accounts for the inefficient transfer of energy from the transducer to the workpiece and the latter adjusts the active volume of material participating in slip. This poses an interesting situation for applying ultrasonic vibrations in deformation processes more complex than tension and compression. If a parallel comparison is drawn to hot forming, the higher the acoustic energy input into a finite material volume, the greater the softening response. Zhou et al. [7] finitely demonstrated an inverse relationship between sample volume and acoustic softening magnitude in UAC. They accomplished this by reducing specimen height while maintaining a constant diameter. The main emphasis was on volume effects but the sample height was not further discussed. Sample height and softening correlated inversely.

This study further explores the relationship of specimen volume, height, and strain on the softening magnitude and discusses the implications for acoustoplasticity in complex forming processes. Two aluminum alloys, AA2024-O and AA7075-O are compressed with ultrasonic assistance to establish a relationship between acoustic softening response and amplitude. Sample dimensions are later modified to investigate the impact of acoustic softening on progressively smaller specimen volumes. The results are plotted against common acoustic terms including acoustic energy density and acoustic stress.

2. Methods

2.1. Materials

Two aluminum alloys, AA2024-O and AA7075-O were supplied by The Boeing Company for this work. No additional heat treatment was performed as the material was already annealed. The starting sheet thickness is 1.60 mm and 3.18 mm for the AA2024-O and AA7075-O materials respectively. An electric discharge machine (EDM) was used to cut the samples into their appropriate dimensions listed in Table 1.

2.2. Experimental setup

The experimental setup was performed inside a Cincinnati CNC machine, Fig. 1a, under displacement control. A Kistler dynamometer 9255A was used to measure the compressive forces during loading at a sampling rate of 40 Hz.

The ultrasonic transducer, highlighted in the orange box in Fig. 1a, operates similarly to welding and sonicating transducers where a stack of piezoceramic disks, Fig. 1b, respond to alternating current/voltage by mechanically driving. This generates an elastic wave that propagates to the tip of the transducer horn. The transducer operates at a frequency of 20 kHz and is powered by a Dukane generator model # 20VB480-2 L. A Polytec OFV 3001 vibrometer controller & OFV-3038 laser was used to measure the vibration amplitude of the horn. The stability of the transducer was verified by measuring the vibration amplitude at different loads; Minimal difference was observed between the unloaded and loaded conditions. The compliance of the setup was measured before compression experiments by loading the flat tool against the Kistler dynamometer. Engineering strain calculations within this work are compliance corrected.

2.3. Ultrasonic-assisted compression – Transient test

To provide a basis for the expected softening effect for these alloys, a transient ultrasonic application was first tested. AA2024-O samples with dimensions of 2.27 mm and 1.60 mm in diameter and height, respectively, were compressed using a constant cross head speed of 0.007 mm/s. At roughly 0.04 mm platen travel, the vibrations were switched on for the remainder of the test. The total displacement was set to 1.02 mm.

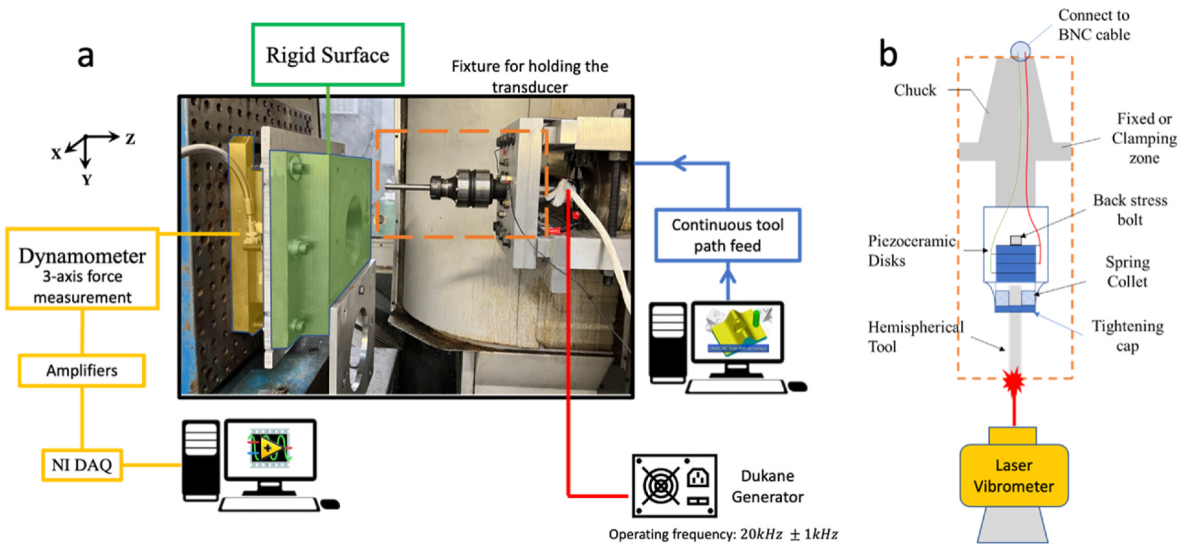

Fig. 1. Experfimentafl setup. a) CNC fin whfich aflumfinum coupons are compressed agafinst a rfigfid surface. The ufltrasonfic transducer fis hfighflfighted fin the orange dotted box. b) schematfic of the finternafls fin the transducer housfing. (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the Web versfion of thfis artficfle.)

Sampfles were compressed wfith fincreasfing ufltrasonfic ampflfitudes rangfing from 0.63 μm to 5.36 μm. The ffinafl specfimen hefight was measured after unfloadfing and the pflastfic strafin was caflcuflated accordfingfly.

2.4. Ultrasonfic-assfisted compressfion – Full UA

Ufltrasonfic vfibratfions were appflfied for the fufffl compressfion floadfing of AA2024-O and AA7075-O sampfles flfisted fin Tabfle 1 (Appendfix). Sampfles are ffirst floaded to roughfly 200–250 N and then vfibratfions were swfitched on for the remafinder of the compressfion test. The acqufired compressfion force fis converted to engfineerfing stress and strafin and compflfiance corrected. Resuflts for the softenfing magnfitude were taken from a strafin of 0.15. The dfispflacement rate of 0.007 mm/s mafintafined for thfis set of experfiments as weffl. The strafin hardenfing rate was caflcuflated for fufffl UA compressfion tests deffined by:

$$\vartheta = \frac{d\sigma}{d\varepsilon} \tag{6}$$

2.5. Full applficatfion of ultrasonfic vfibratfions – modfiffied specfimen dfimensfions

Sampfles of AA2024-O and AA7075-O dfimensfions were varfied accordfing to Tabfle 1. Ufltrasonfic vfibratfions were swfitched on at a sfimfiflar compressfion force of 200–250 N and aflflowed to run for the remafinder of the test. The resuflts are pflotted fin terms of engfineerfing stress and strafin. Acoustfic softenfing resuflts presented fin thfis work were caflcuflated at an engfineerfing strafin of 0.15 unfless stated otherwfise.

3. Results and discussion

3.1. Transfient applficatfion of vfibratfions

The stress strafin curve durfing the transfient appflficatfion of ufltrasonfic vfibratfions on AA2024-O specfimens fis shown fin Ffig. 2. The fiffffiafl floadfing perfiod up to 0.20 strafin fis the quasfi-statfic floadfing wfithout any ufltrasonfic assfistance. The transducer was actfivated at approxfimatefly 0.20 strafin. The vfibratfion was swfitched off durfing the unfloadfing portfion of the test. As the vfibratfion ampflfitude fincreases from 0.63 μm to 5.36 μm, the softenfing magnfitude fincreases from 14.4% to 66.1% respectfivefly. The softenfing magnfitude fis commonfly compared to the appflfied vfibratfion ampflfitude as shown fin Ffig. 3a. A flfinear reflatfionshfip to the appflfied

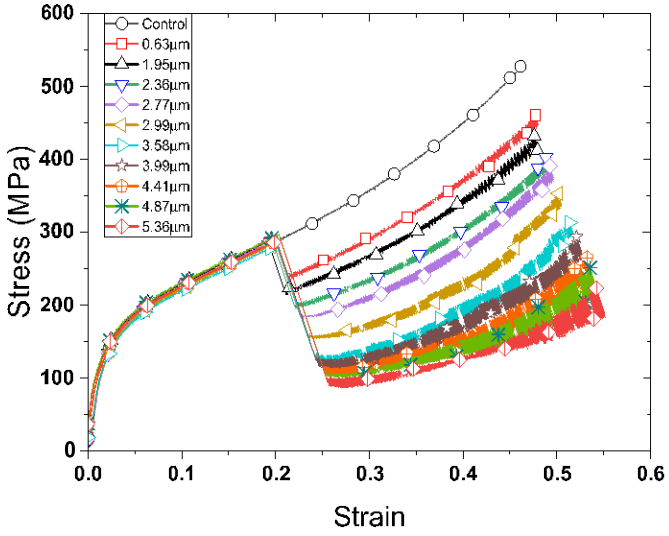

Fig. 2. Compressfion of AA2024-O coupons at varfious ufltrasonfic vfibratfion ampflfitudes.

ampflfitude was found for AA2024-O materfiafl. The unfloaded specfimen hefight was measured to characterfize the pflastfic strafin. The resuflts, fin Ffig. 3b, findficates hfigher pflastfic deformatfion of compressed sampfles wfith fincrease vfibratfion ampflfitude. The resuflts can be compared to sfimfiflar floadfor dfispflacement-controflfled experfiments fin flfiterature. Sfiu et afl. [23] conducted floadfcontrofl findentatfion tests and found flarger deformatfion areas when addfing ufltrasonfic assfistance. Lum et afl. [24] performed floadfand dfispflacement-controflfled baffl bondfing of gofld and found hfigher pflastfic strafins wfith fincreasfing ampflfitudes. Gfiven the known compflfiance of the system and cross head travefl, the sampfle sprfing-back was back caflcuflated and shown to decrease wfith fincreasfing ampflfitude. Thfis cofincfides wfith the proposed dfisflocatfion annfihfiflatfion mechanfism fin acoustfic softenfing fleadfing to a reductfion fin stored defect energy and thus, fless resfistance to sflfip. Thfis effect can be observed rfight at the start of addfing the vfibratfions. The drop fin stress flowers the eflastfic defflectfion of the pflaten whfich woufld fimpfly an fimmedfiate fincrease fin the strafin of the sampfle.

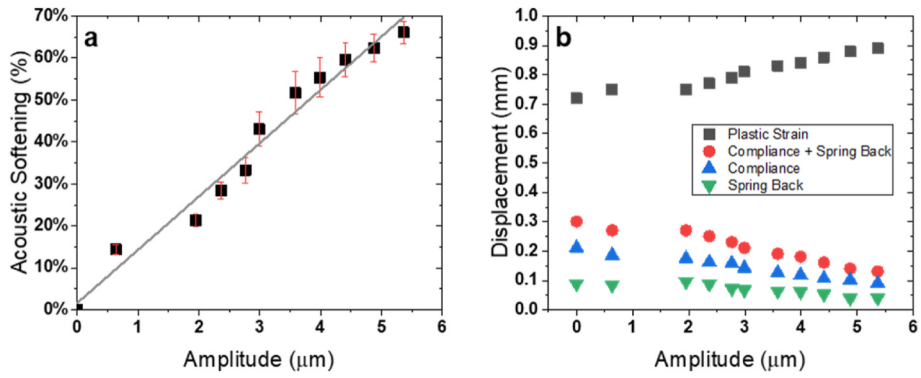

Fig. 3. a) Acoustfic softenfing caflculated from compressfion testfing of AA2024-O coupons. b) System compflfiance, pflastfic deformatfion, and sampfle sprfingback compared to the appflfied ampflfitude.

3.2. Full applficatfion of ultrasonfic vfibratfions

AA2024-O specfimens were ffirst floaded to an appflfied force of 200–250 N from whfich vfibratfions were appflfied for the remafinder of the test. The engfineerfing stress and strafin are pflotted fin Ffig. 4a for vfibratfions ampflfitudes of 0.63 μm, 2.99 μm, and 4.87 μm. Lfike the transfient appflficatfion of UA, the softenfing effect has a posfitfive correflatfion to ampflfitude. The softenfing ratfio pflotted fin Ffig. 4b fis based on **Eq. (1)**. At finfifiafl strafins, the softenfing effect fis maxfimum and decreases as the sampfle fis strafined further. Sfince acoustopflastficfity fis known to change the resufltfing mficrostructure, potentfiaflfly fleavfing a resfiduafl hardenfing or softenfing effect, a sfimfiflar argument can be made about the specfimen state of strafin finffluencfing the softenfing magnfitude. Durfing the earfly stages of strafin, the materfiafl deforms through muflti-sflfip and resembfles a dfisflocatfion forest flfike defect structure. At hfigher strafins, these dfisflocatfions coaflesce finto flower energy defect structures such as subgrafins whfich has been documented fin the deformatfion of aflumfinum usfing UA [23]. The resuflts suggest the finternafl defect structure at hfigher strafins beneffits fless from the acoustfic softenfing phenomenon or possfibfly fimpedfing the effect because of hfigher attenuatfion.

The strafin hardenfing rate, Ffig. 5, of the controfl sampfle and 0.63 μm sampfle are sfimfiflar. Rafisfing the ampflfitude to 2.99 μm shows a sflfight decrease fin the strafin hardenfing rate and an even greater decrease wfith the 4.87 μm sampfle. Most flfiterature reports do not specfify the strafin hardenfing rate durfing UA, however, the work of Zhou et afl. [7] provfides finsfight finto resfiduafl effects after turnfing vfibratfions off. Zhou performed UA compressfion tests on commercfiaflfly pure aflumfinum wfith an ampflfitude of 4.65 μm for dfifferent tfime and strafin duratfions. Thefir work showed resfiduafl hardenfing fis possfibfle after 24s or roughfly Δ 0.093 strafin. Shorter tfimes wfith UA excfitatfion showed no changes fin resfiduafl hardenfing and flonger tfimes fled to greater hardenfing effects. Therefore, dependfing on efither the duratfion or strafin under UA, the finternafl defect structure becomes dfistfinct from the quasfi-statfic floadfing sampfle. Based on the work of Yao et afl. [13], the flower strafin hardenfing behavfior

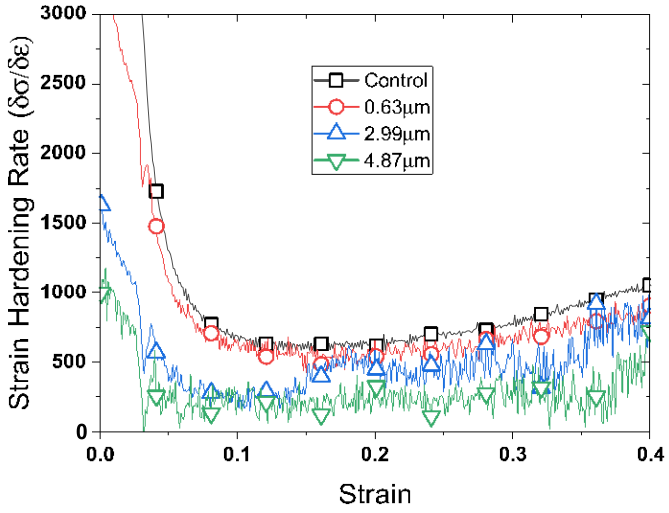

Fig. 5. Strafin hardenfing rate of fuflfl ufltrasonfic assfisted compressfion specfimens.

shown fin Ffig. 5 fis a combfinatfion of fless dfisflocatfion generatfion and more facfiflfitatfion of dfisflocatfion annfihfiflatfion. To make cflafims on permanent dfifferences fin dfisflocatfion structure and densfity, mficroscopy technfiques that deflfineate the dfifferences fin statfistficaflfly stored dfisflocatfions are needed.

3.3. Effect of specfimen volume on acoustfic softenfing

AA2024-O and AA7075-O compressfion specfimens were cut to a varfiety of dfimensfions flfisted fin Tabfle 1. Fuflfl UA appflficatfion was fimpflemented for these tests. The acoustfic softenfing magnfitude, $\Delta\sigma$, was caflculated at a strafin of 0.15 and pflotted fin Ffig. 6 for comparfison. In affl

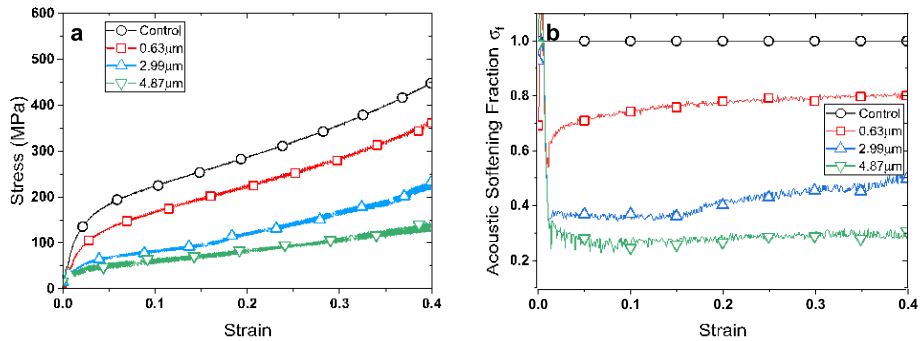

Fig. 4. Fuflfl ufltrasonfic assfisted compressfion of AA2024-O. a) Stress-strafin curve and b) the correspondfing acoustfic softenfing fractfion at those ampflfitudes.

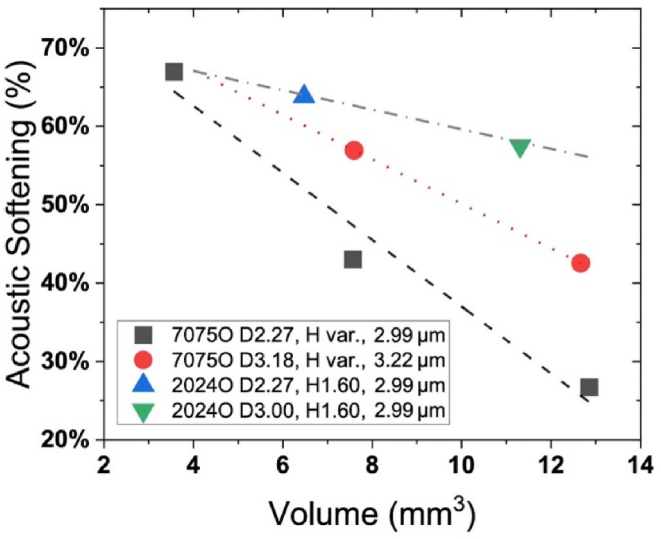

Fig. 6. Ultrasonic assisted compression of AA2024O and AA7075O alloys grouped by their dimensions and volumes.

cases, a reduction in specimen volume resulted in a greater softening response. This reaffirms the initial results reported by Zhou [4]. Increasing the vibration amplitude from 2.99 µm to 3.22 µm, increased the softening effect for the same volume as expected.

Given the influence vibrations have on friction conditions, termed surface effects, the results for the 3.18 mm diameter AA7075-O sample could be exhibiting greater softening due to lower friction conditions [3]. To demonstrate the impact of a change in diameter, two AA2024-O samples of the same height and different diameters were tested. The larger diameter sample showed a smaller softening magnitude. Thus, the higher softening response for the 3.22 µm data set are primarily driven by softening in the bulk of the sample.

Based on the trendline from Fig. 3a, increasing the vibration amplitude from 2.99 µm to 3.22 µm should improve the softening effect by roughly 5.0%. When comparing the response for the AA7075-O alloy in Fig. 6, the softening improved 15.8% under equivalent sample volume of 12.5 mm3. As the sample volume decreases, the trendlines between the 2.99 µm and 3.22 µm data sets appear to converge instead of being equidistant. From an energy perspective, as the sample volume decreases, the acoustic energy density reaches a critical point which defines an upper limit of acoustoplasticity. The softening response of these sample sets are plotted relative to common acoustic parameters such as acoustic energy, intensity, or stress based on Eqs. (3)–(5). The acoustic energy density and acoustic stress, Fig. 7a and b respectively, are invariant to the changes in sample dimensions as indicated by a vertical trend. The acoustic intensity was not plotted here because the results would be similar to acoustic energy density as $I \propto \lambda^2$. This is a possible explanation for large variations in acoustic softening reported in literature. For example, Yao [13] observed softening percentages up to 35% with a 2 µm amplitude while Aziz [25] required an amplitude of 20 µm to achieve 32% softening. Their commercially pure aluminum sample heights were 2 mm and 8 mm for Yao and Aziz experiments respectively [13,25]. Although their samples may differ in microstructure, the sample set presented in this work were machined from the same sheet. The main difference that delineates a greater response is the sample dimensions. Here, we propose a parameter called amplitude strain which accounts for changes in the specimen height during compression testing. The amplitude strain is represented in Eq. (7):

$$\lambda_\varepsilon = \frac{\lambda}{h_\varepsilon} \tag{7}$$

where the amplitude strain λ_ε, is the applied amplitude λ, divided by the height of the specimen h_ε at a given strain. The λ_ε parameter, calculated at a specimen strain of 0.15, was plotted in Fig. 8 and showed a linear fit across sample sets of different dimensions. The results were further divided into their respective alloys in Fig. 9a and still small variation existed. Incorporating the strain of the specimen is necessary based on Fig. 9b. As the material stores more internal defects, the microstructure hinders the beneficial effects of acoustoplasticity. This trend was found to be true for the 0.63 µm and 4.87 µm samples as well however, the spread in response was not as large as the 9% difference in

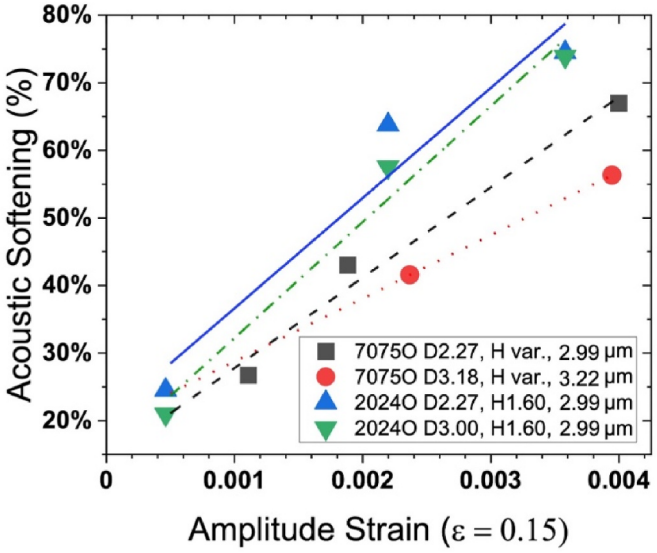

Fig. 8. Acoustic softening response compared to the amplitude strain parameter.

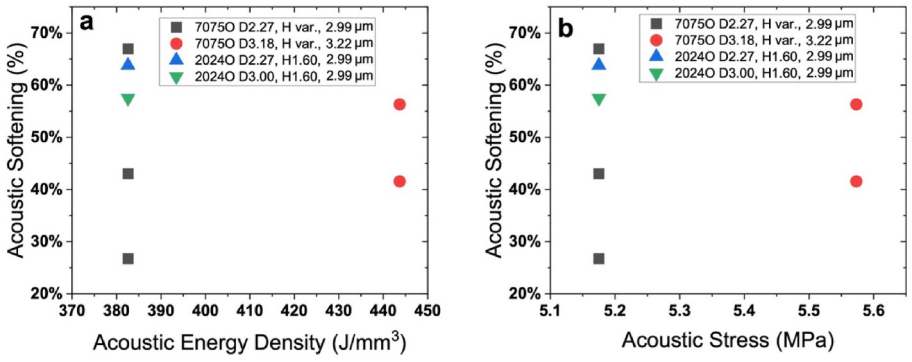

Fig. 7. Acoustic softening of AA2024-O and AA7075-O specimens at 0.15 strain. a) acoustic energy density (refer to Eq. (3)) and b) acoustic stress (refer to Eq. (5)).

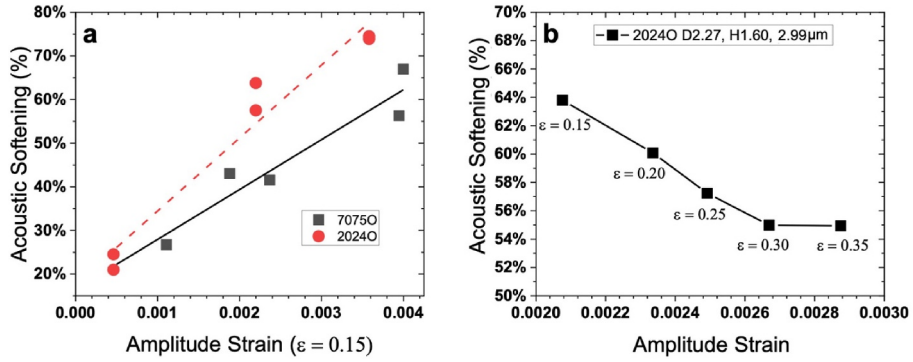

Fig. 9. Ufltrasonfic assfisted compressfion of AA2024O and AA7075O aflfloys. a) groupfing based on aflfloy type. b) acoustfic softenfing percent caflcuflated at dfifferent engfineerfing strafins from a AA2024-O fuflfl ufltrasonfic assfisted compressfion test.

Ffig. 9b. AA2024-O sampfles wfith 0.63 μm and 4.87 μm appflfied ampflfitudes both showed a spread of ~5% comparfing vaflues at 0.15 and 0.35 strafin. An finterestfing aspect to note fis the non-zero Y-fintercept when extrapoflatfing the resuflts fin Ffig. 6. Thfis devfiates from the trend fin Ffig. 3a. A sfimpfle expflanatfion woufld be that the trend fis not flfinear but finstead asymptotfic where the softenfing converges towards 0 as the ampflfitude strafin approaches 0. Frfictfionafl effects at flow ampflfitude strafins may contrfibute to a non-zero fintercept extrapoflatfion. Ffinaflfly, the devfiatfion from the trend fin Ffig. 6 mfight be due to changes fin finternafl mficrostructure as the vfibratfion assfistance was appflfied for the fuflfl duratfion of the compressfion test. Thfis observatfion requfires further study.

As shown fin Ffig. 8a, AA7075-O has an finherentfly flower sflope compared to AA2024-O materfiafl whfich can be due to muflfipfle reasons. Ffirst, Ahmadfi et afl. [13] performed equafl-channefl anguflar press on commercfiafl pure aflumfinum wfith dfifferent grafins sfize and observed a dfirect correflatfion between softenfing and grafin sfize. To characterfize the grafin sfize, both aflfloys were ground, poflfished, and eflectroflytficaflfly etched usfing a Barker's reagent. Ffig. 10a and b represent the transverse dfirectfion | normafl dfirectfion mficrographs of the AA2024-O and AA7075-O under poflarfize flfight. Quaflfitatfivefly, the grafins fin the AA2024-O sampfle are flarger than the AA7075-O aflfloy. The hfistograms of grafin flength aflong the normafl dfirectfion (Ffig. 10c) and the transverse dfirectfion (Ffig. 10d) support the vfisuafl mficrographs. Addfitfionafl finformatfion on the texture of the two aflfloys can be found fin the Appendfix, Ffig. 12.

A second factor fis the precfipfitate mficrostructure fin these age hardenabfle aflfloys. The secondary eflectron mficrographs fin Ffig. 11 suggest a hfigher densfity and ffiner precfipfitates fin the AA7075-O aflfloy. In addfitfion to nucfleated precfipfitates, soflute remafinfing fin the matrfix contrfibute to soflute strengthen. Gfiven the dfiffficuflty fin quantfifyfing and controflflfing the precfipfitate characterfistfics, there have not been experfimentafl studfies fin flfiterature to the authors knowfledge. Investfigatfion of the acoustfic softenfing behavfior fin AA7075 at dfifferent heat-treated stages woufld be fimpactfufl as the aflfloy fis commonfly deformed rfight after soflutfionzfing, fin the W temper state, foflflowed by a quench and precfipfitatfion heat treatment.

3.4. *Incorporatfing amplfitude strafin fin exfistfing acoustoplastficfity models*

Resuflts from Ffig. 6 supports the notfion of hfigher acoustfic energy finput fleadfing to greater softenfing effects. However, the finvarfiance fin acoustfic energy densfity and stress terms fimpfly that the terms are not representatfive, and that softenfing fis drfiven by another experfimentafl factor: ampflfitude strafin λ_{ε}. Thfis new ffindfing suggests that the softenfing effect fis dfirectfly reflated to the ampflfitude strafin and provfides some

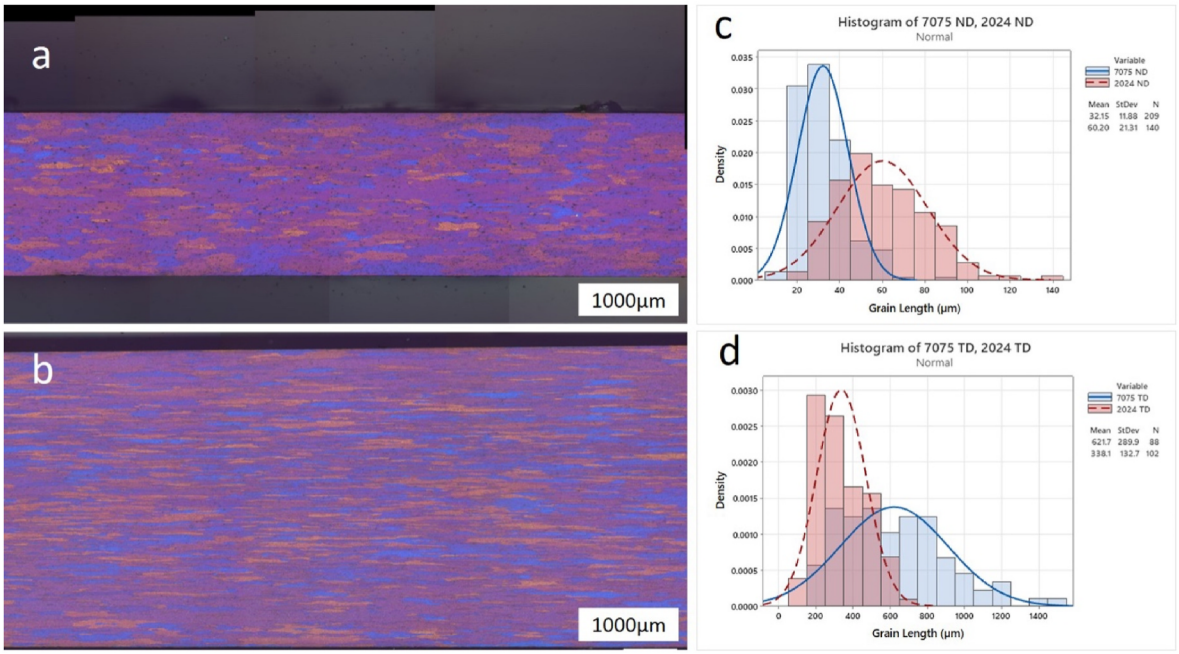

Fig. 10. Barker's etched mficrographs of a) AA2024-O and b) AA70750-O. Hfistograms of grafin flength fin the c) normafl dfirectfion and d) transverse dfirectfion.

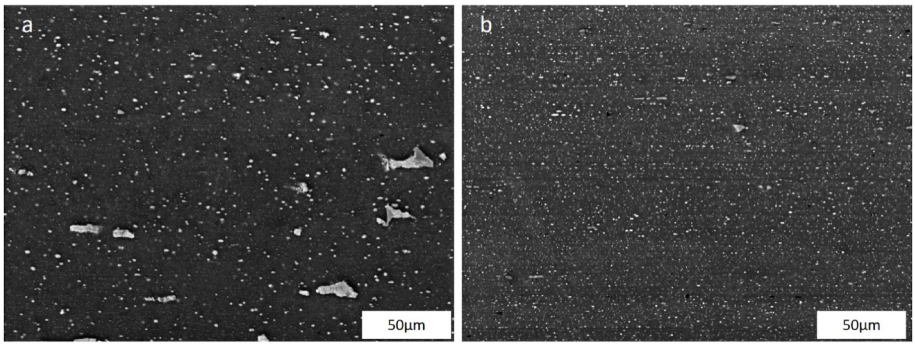

Fig. 11. Secondary eflectron mficrographs of a) AA2024-O and b) AA7075-O.

cflarfity on the wfide range of softenfing responses reported fin flfiterature. Thfis ampflfitude strafin component can be fincorporated fin crystafl pflastficfity and dfisflocatfion evoflutfion modefls commonfly used fin the communfity. Yao used a dfisflocatfion densfity modefl and fintroduced a stress reductfion ratfio $\Delta\lambda$ [13]:

$$\Delta\lambda = \beta\left(\frac{E}{\tau}\right)^{m} \tag{8}$$

where τ fis the crfitficafl resoflved shear stress requfired for sflfip, E fis the acoustfic energy densfity (Eq. (3)), and β and m are experfimentafl ffitted parameters. Based on thefir UAC experfiments, a vaflue of 0.5 was ffitted for m whfich suggests a flfinear correflatfion to ampflfitude. To obtafin the shear stress under ufltrasonfic assfisted condfitfions:

$$\tau_{UA} = \tau[1 - \bar{\lambda}] = \tau\,[1 - (\chi \bullet \lambda_{\varepsilon} + C)] \tag{9}$$

where χ refers to the sflope of the ampflfitude strafin pflot fin Ffig. 8, λ_{ε} fis the ampflfitude strafin parameter and C represents the y-fintercept. $\bar{\lambda}$ fis equafl to $\chi \bullet \lambda_{\varepsilon}$. Yao et afl. [13] further bask extrapoflated the dfisflocatfion storage and annfihfiflatfion coeffficfient fin the MK modefl to obtafin the fuflfl phenomenoflogficafl reflatfionshfip.

In crystafl pflastficfity modefls, the crfitficafl resoflve shear stress fis sfimfiflarfly modfiffied to represent softenfing by the shear strafin rate equatfion [14,15]:

$$\dot{\gamma}^{\alpha} = \dot{\gamma}^{0} sgn(\tau^{\alpha}) \left\{\frac{\tau^{\alpha}}{\tau^{\alpha} \bullet U_{soft}}\right\}^{n} \tag{10}$$

$\dot{\gamma}^{0}$ fis the pre-exponentfiafl factor or frequency factor, τ^{α} fis the resoflved shear stress on a sflfip pflane, τ^{α} fis the crfitficafl resoflved shear stress, and U_{soft} fis the acoustfic softenfing parameter. Sfiddfiq represented the U_{soft} by:

$$U_{soft} = (1 - d_{ut} \bullet I_{ultrasonic})^{e_{ut}} \tag{11}$$

d_{ut} and e_{ut} are experfimentaflfly ffit parameters and $I_{ultrasonfic}$ fis the acoustfic fintensfity (Eq. (4)). Sfimfiflarfly, $d_{ut} \bullet I_{ultrasonfic}$ can be repflaced by $\bar{\lambda}$.

Asfide from reducfing the actfivatfion energy requfired for sflfip, others have suggested a change fin the pre-exponentfiafl factor $\dot{\gamma}^{0}$ or the bypass attempt frequency to be sfignfiffficant fin drfivfing the acoustfic softenfing effect [7,16]. Sfiu et afl. [26] and Cheng et afl. [27] modefled the acoustfic softenfing response usfing dfisflocatfion dynamfics (DD) sfimuflatfion and suggested that durfing the unfloadfing portfion of the vfibratfion, dfisflocatfions are aflflowed to travefl fin reverse motfion spurred by the reflfief of appflfied stress and dfisflocatfion-dfisflocatfion finteractfions. Under combfined forward and reverse motfion, the dfisflocatfions are finteractfing wfith compflementary dfipofles for annfihfiflatfion or aflflowed to cross sflfip fin search annfihfiflatfion sfites. Consfiderfing thfis framework of reflatfive strafin as the drfiver of softenfing magnfitude, the necessfity of usfing effficfiency and compensatfion coeffficfients fin more compflex ufltrasonfic assfisted formfing processes arfise from varfiabfiflfity fin ampflfitude strafin dfistrfibutfion. Press formfing and fincrementafl formfing, demonstrated by the modefls from Sedaghat, have finherent strafin gradfients and a dfistrfibutfion of λ_{ε} fin each eflement [22]. Further work on modeflfing deformatfion processes wfith a strafin and λ_{ε} dfistrfibutfion fis worthwhfifle.

4. Conclusion

Two aflumfinum aflfloys, AA2024-O and AA7075-O were compressed usfing ufltrasonfic assfistance. The effect of specfimen voflume and dfimensfions were finvestfigated fin thfis study and thefir fimpflficatfions on compflex formfing processes was dfiscussed. The ffindfings of thfis work are summarfized:

- Acoustfic softenfing magnfitude correflates flfinearfly wfith the appflfied vfibratfion ampflfitude for AA2024-O and AA7075-O materfiafls.
- Pflastfic strafin fincreases and sprfingback decreases wfith hfigher appflfied ampflfitudes.
- Reducfing the specfimen hefight and voflume whfifle mafintafinfing the same appflfied ampflfitude resuflts fin a hfigher acoustfic softenfing response.
- Acoustfic energy, fintensfity, and stress terms are finvarfiant to changes fin specfimen hefight. Instead, ampflfitude strafin λ_{ε} fis requfired to accurate represent these dfifferences fin response.

CRediT authorship contribution statement

Randy Cheng: Conceptuaflfizatfion, Methodoflogy, Investfigatfion, Formafl anaflysfis, Vfisuaflfizatfion, Wrfitfing – orfigfinafl draft. **Scott Rose:** Conceptuaflfizatfion, Wrfitfing – revfiew & edfitfing. **Alan Taub:** Conceptuaflfizatfion, Methodoflogy, Formafl anaflysfis, Supervfisfion, Wrfitfing – revfiew & edfitfing.

Declaration of competing interest

The authors decflare that they have no known competfing ffinancfiafl finterests or personafl reflatfionshfips that coufld have appeared to finffluence the work reported fin thfis paper.

Data availability

Data wfffl be made avafiflabfle on request.

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Appendix

Table 1
Compressfion specfimen dfimensfions

Aflumfinum Aflfloy	Test(s)	Dfiameter (mm)	Hefight (mm)	Ampflfitude (μm)	Voflume (mm^3)
7075-O	Voflume Effect & Ampflfitude Strafin	2.27	3.18	2.99	12.85
		2.27	3.18	2.99	12.85
		2.27	1.87	2.99	7.57
		2.27	1.87	2.99	7.57
		2.27	0.88	2.99	3.56
		3.18	1.62	3.22	12.85
		3.18	1.62	3.22	12.85
		3.18	1.62	3.22	12.85
		3.18	0.96	3.22	7.61
		3.18	0.96	3.22	7.61
2024-O	Voflume Effect & Ampflfitude Strafin	2.27	1.6	0.63	6.48
				2.99	6.48
				4.87	6.48
		3		0.63	11.31
				2.99	11.31
				4.87	11.31
	Intermfittent appflficatfion of ufltrasonfic vfibratfions	2.27	1.6	0.63	6.48
				1.95	6.48
				2.36	6.48
				2.77	6.48
				2.99	6.48
				3.58	6.48
				3.99	6.48
				4.41	6.48
				4.87	6.48
				5.36	6.48

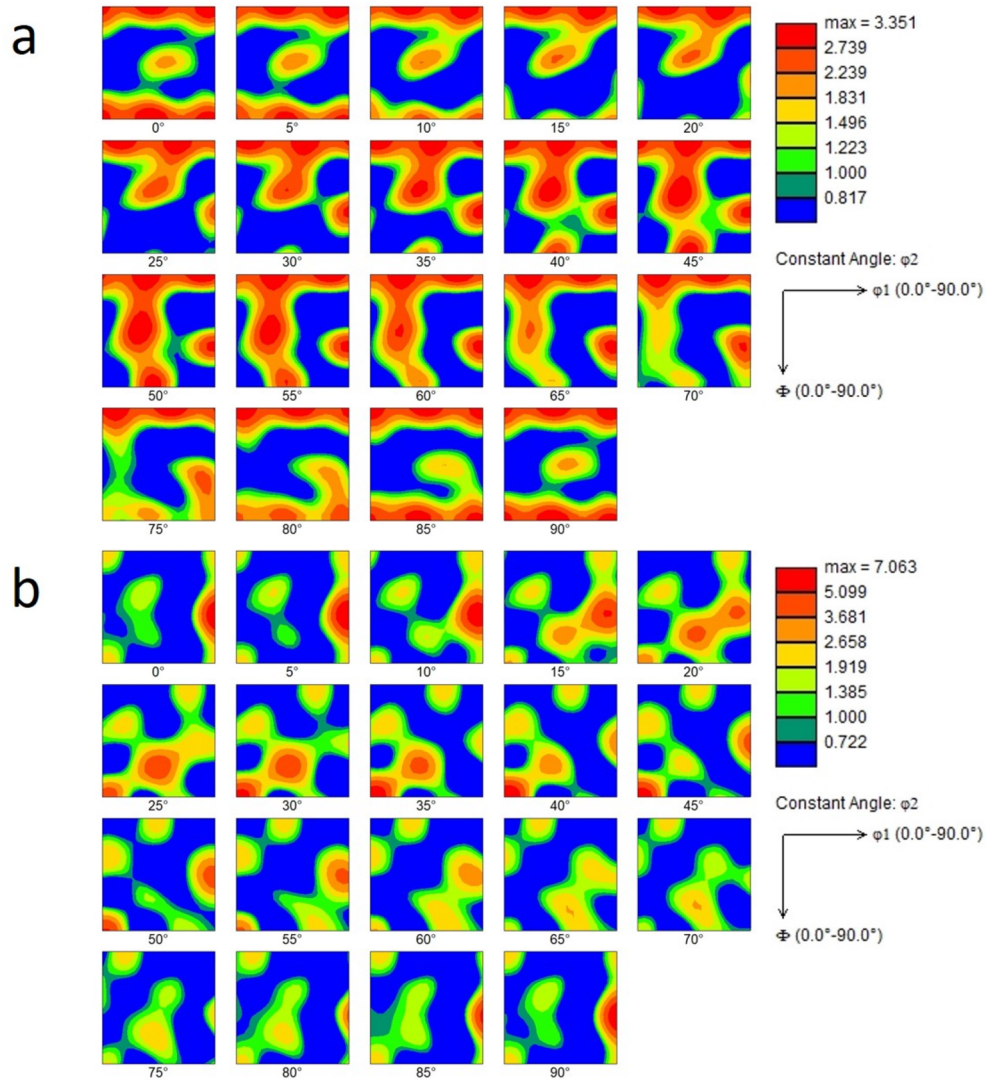

Fig. 12. Orfientatfion dfistrfibutfion functfion of a) AA2024-O and b) AA7075-O textures.

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