# Processed Text

aerospace article advanced material technology compressor blade small turbofan engine dmytropavlenko1 yaroslavdvirnyk1 2 andradoslawprzysowa3 1 mechanicalengineeringdepartment nationaluniversity zaporizhzhiapolytechnic 64zhukovskogost 69063zaporizhzhia ukraine dvirnyk gmail com 2 motorsichjsc 15motorostroiteleyave 69068zaporizhzhia ukraine 3 instytuttechnicznywojsklotniczych ul ksie ciaboles■awa6 01 494warsaw poland radoslaw przysowa itwl pl correspondence dvp1977dvp gmail com thispaperisanextendedversionofourpaperpublishedin10theasninternationalconferenceon innovationinaviation spacetothesatisfactionoftheeuropeancitizens abstract manufacturingcosts alongwithoperationalperformance areamongthemajorfactors determiningtheselectionofthepropulsionsystemforunmannedaerialvehicles uavs especially foraerialtargetsandcruisemissiles inthispaper thedesignrequirementsandoperatingparameters ofsmallturbofanenginesforsingle useandreusableuavsareanalysedtointroducealternative materialsandtechnologiesformanufacturingtheircompressorblades suchassinteredtitanium anewgenerationofaluminiumalloysand titaniumaluminides toassesstheinfluenceofsevere plasticdeformation spd onthehardeningefficiencyoftheproposedmaterials thealloyswith thecoarse grainedandsubmicrocrystallinestructurewerestudied changesinthephysicaland mechanicalpropertiesofmaterialsweretakenintoaccount thethermodynamicanalysisofthe compressorwasperformedinafiniteelementanalysissystem ansys todeterminetheimpact ofgaspressureandtemperatureontheaerodynamicsurfacesofcompressorbladesofallstages basedonthermalandstructuralanalysis thestressandtemperaturemapsoncompressorblades cid 1 cid 2 cid 3 cid 1 cid 4 cid 5 cid 6 cid 7 cid 8 cid 1 andvaneswereobtained takingintoaccountthephysicalandmechanicalpropertiesofadvanced cid 1 cid 2 cid 3 cid 4 cid 5 cid 6 cid 7 materialsandtechnologiesoftheirprocessing thesafetyfactorsofthecomponentswereestablished citation pavlenko dvirnyk basedontheassessmentoftheirstress strengthcharacteristics thankstonomograms thepossibility przysowa r advancedmaterialsand using new material five compressor stage confirmed view permissible technologiesforcompressorblades operatingtemperatureandsafetyfactor theproposedalternativematerialsforcompressorblades ofsmallturbofanengines aerospace andvanesmeetthedesignrequirementsoftheturbofanatlowermanufacturingcosts 2021 8 1 http dx doi org 10 3390 aerospace8010001 keywords turbofan unmannedaerialvehicles cruisemissile aerialtarget axialcompressor blade titaniumalloy aluminiumalloy titaniumaluminide safetyfactor received 5november2020 accepted 16december2020 published 22december2020 1 introduction publisher snote mdpistaysneu tralwithregardtojurisdictionalclaims currently one promising area aerospace defence industry inpublishedmapsandinstitutional development unmanned aerial system various purpose based affiliation onunmannedaerialvehicles uavs ofbothreusableandsingleuse ukrainian 1 global manufacturer offer gas turbine engine uavs various type 2 3 full scaleturbopropsandturbofans asarule arebasedonenginesdesignedformanned aircraft 4 smallturbofansarecustom made 5 6 theytypicallyhaveacompactand copyright 2020bytheauthors li simplifiedsingle shaftstructure determinedbythetacticalandtechnicalcharacteristicsof censeemdpi basel switzerland theplatform 7 articleisanopenaccessarticledistributed smallturbofanengines table1 aredesignedfortargetdrones streaker lakshya underthetermsandconditionsofthe cruisemissilessuchasr 360neptune kite kh 55 tomahawkandharpoon theirmain creativecommonsattribution ccby license http creativecommons org performancecharacteristicsincludeashortlifecycle ifusedasweapons smallsizeand license 4 0 weight result high thrust weight ratio also operation unmanned aerospace2021 8 1 http dx doi org 10 3390 aerospace8010001 http www mdpi com journal aerospaceaerospace2021 8 1 2of16 platformcontributestothefactthattheyarenotsubjecttotheaviationsafetyregulations engine produced jsc motor sich 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1262 305 bgm 109tomahawk motorsich m 400 3 92 85 4 70 850 320 r 360neptunemissile ivchenkoprogress ai 305 3 04 61 5 08 650 232 ultralightaircraft soyuz r95 300 3 55 100 3 62 850 315 kh 55missile saturn 36mt 4 54 100 4 63 850 330 kh 59missile priceinduction dgen380 2 55 85 3 06 1126 469 personallightjet small turbofan engine radial axial compressor used currently variioustypesoftitaniumalloysaresuccessfullyusedformanufacturingthebladesand vane axial compressor 9 10 common vt6 ti 6al 4v vt3 1 ti 6 7al 2 5mo l 8cr 0 5fe 0 25si andvt8 ti 6 8al 3 5mo 0 32si forcompressorstages withincreasedairtemperaturealongthegaspath heat resistanttitaniumalloysofthe vt25 ti 6 8al 2 0mo 2 0zr 2 0sn l 0w 0 3si type used 11 12 last stage ofthecompressor takingintoaccountthetemperaturelevel heat resistantnickel based alloy inconel 718 ep718 id similar used common drawback material along high cost energy cost production poor machinability havingacombinationofthepropertiesnecessaryforthecompressorblades ofamannedaircraft sengine theyareredundantwhenusedonuavs thisleadstothe increasedcostofenginesanduavsingeneral tomeettherequirementsforuavpower plant necessary introduce new material technology reduce manufacturingcost several modern technology used manufacturing gas turbinesforuavs 13 withregardtocompressorblades anumberofcandidatematerials isconsidered forexample sinteredpowderalloys rareearthaluminiumalloys alloy basedontitaniumaluminidesandothers 14 15 atpresent onlysurfacesofcompressorbladesarehardened 16 primarilybylaser shockpeening 17 however surfacehardeningdoesnotmodifytheinnerstructureof thealloy therefore tosignificantlyincreasethestrengthandductilityofaircraftmaterials severeplasticdeformation spd technologiesareused 18 19 butthesizeofproduced ingotsisstilllimited whatismore foreachcompressorstage therearelimitationsboth operating temperature mechanical property met introducedmaterials inthiswork toreducethemanufacturingcostofaselectedsmallturbofanengine alternativematerialsandtechnologiesforproducingcompressoraerofoilsareintroduced evaluated ensure structural integrity static safety factor assessed bladesandvanesofindividualstages takingintoaccounttheiroperatingtemperature keyobjectivesofthisworkincludematerialselection strengthtesting airflowsimulation ofthecompressortoobtainpressurefieldsonaerofoilsurfacesofallstagesaswellasgasaerospace2021 8 1 3of16 temperatureandfinallythestructuralanalysisofcomponentswhichevaluatestheirstress andstaticsafetyfactor 2 materialsandmethods 2 1 twistextrusion variousspdmethods 20 21 areintroducedtoimprovemechanical physical functional property metal alloy forming submicrocrystalline struc ture 22 23 twistextrusion te isavariantofthesimpleshear deformationprocessthat wasintroducedbybeygelzimer 24 underteprocessing aprismaticbilletisextruded throughatwistdie inthiswork anumberofstandardandpowdermetalalloys table2 sourcedfrom variouscontractorswereprocessedwithte thetitaniumbilletsweremadefromannealed vt8rodsofincreasedquality 32mmindiameter gost26492 85 producedbyvsmpo avismacorporation sinteredtitaniumwassynthesisedinlaboratorybypressingand subsequent vacuum sintering powder mixture based pt5 titanium powder tu u14 10 026 98 producedbythezaporizhzhiatitanium magnesiumplant thegrainsize was160 500µm 25 table2 analysedalloys theircompositionandrelatedpublications vt8 ti 6 8al 3 5mo 0 32si ost190013 81 gost26492 85 25 31 composition mass impurity max ti al mo sn si c fe zr n h base 5 8 7 0 2 8 3 8 0 4 0 2 0 4 0 1 0 3 0 5 0 15 0 05 0 015 γ tial ti 46al 5nb 2w 32 34 ti al nb w base 44 47 4 2 5 5 1 5 2 5 7055 sc al zn mg cu sc ost190013 81 35 40 ai zn mg cu zr sc fe mn si ti cr ni base 6 8 8 4 1 5 2 5 1 6 2 9 0 1 0 5 0 1 0 25 0 13 0 01 0 03 0 01 0 01 0 01 thebillet figure1 was70mmlongwiththecross sectionof18 28mm itwas placedinamatrixwithahelicalchannelofrectangularcrosssectionwithanangleofthe helix inclination te axis extrusion pressure fp 1600 mpa studiedalloys toincreasetheirplasticity backpressurebp 200mpawasappliedtothe frontendofthebillet totransmitbackpressure adeformablemediumwasused waseitheramixturebasedonthelow meltingglassoracopperbillet 41 therearedifferentapproachestomodellingandoptimisingtheteprocess 42 43 usuallybasedonfemethods calculationsandexperimentsareaimedtoobtainhighplas ticstrainanduniformultrafinegrains 21 inthisworkthebeygelzimer sapproach 41 44 isfollowed thetotalrelativesheardeformationλperpasswascalculatedasfollows 41 2 λ tanγ 1 max 3 whereγ isthemaximuminclinationanglebetweenthetwistlineandtheextrusionaxis max asthedeflectionangleofthehelicalchannelwas45 forallinvestigatedmaterials totalsheardeformationperpasswasapproximately1 15 fivetepasseswerecarriedout sothetotalrelativesheardeformationofthebilletwas5 77 aerospace2021 8 1 4of16 figure1 deformationofaporousbilletbytwistextrusion 1 beforete 2 deformationzone 3 afterte fp forwardpressure bp backpressure theporosityofthespecimenswasmeasuredbythehydrostaticweighingmethod gost18847 84 andbyanalysingthemicrographsofmetallographicspecimens gost 9391 80 45 inthefirstcase thespecimensweresubmergedintodistilledwater whose temperaturewasmeasuredbyamercurythermometer therewasnoporosityinspecimens madeofvt8titaniumalloy afterte aslight withinafewpercent increaseinporositywas observed whichcouldbeassociatedwithanincreaseinthenumberofcrystallatticedefects fortheinvestigationofstructureandthefractographicanalysisoffracturesurfaces aneophotlightmicroscopeandajeolscanningelectronmicroscopewasused 46 theaveragegrainsizeinthesamplesafterfivetepasseswasintherangeof200 500nm fortitaniumalloys 45 thegrainsizeintheoriginalmaterialwas150 300μm 2 2 sinteredtitanium one well known method reducing manufacturing cost axial compressorisusingsinteredtitaniumalloys 47 48 buttheirresidualporosityandlow ductility reason used aircraft engine narrow circle lightly loaded non critical component therefore powder material needconsolidationandgrainrefinement whichcanbeeffectivelyachievedbythespd processofhigh pressuretorsion hpt 49 50 however hptcanproduceonlyverysmall sampleswhichcannotbeusedformanufacturingcompressorblades therefore ourrecent paper 51 usesthephysicalsimilarityoftheprocessesoccurringinathinlayerofmaterial duringhptandtetosimulatetwistextrusionwiththeavailablehptdata inthiswork amongothers alloyssynthesisedfromamixtureofselectedpowder component 25 52 wereevaluated dopedelements pureal moandsimetals mixed matrix titanium powder mixer drum 60 80 rpm ensure requiredchemicalcompositionofthetestalloyaftersintering thepowdersweresubjected tosingle actioncompactioninrigiddiesatroomtemperature thecompactionforcewas 730 760mpa thecompactsweresinteredinvacuumintherangeof1250 1270 cwithan isothermalholdingtimeof2 5 3handcooleddowninthefurnaceinvacuum ourpreviouspaper 46 showedthatthecharacteristicsofsinteredtitaniumalloys subjectedtospdinsomeindicatorsexceedsimilarvaluesforregularalloysincastand deformedstates thepreliminarystructuralanalysisofbladesmadeofsinteredtitanium withsubsequentspdconfirmedthattheirsafetymarginmeetstheoperatingconditions 53 aerospace2021 8 1 5of16 however animportantfactorthatlimitstheuseofalloysinthecompressordesignisthe elevated temperature caused air compression gas path also given high rotational speed engine close 40 50 thousand revolution per minute stress analysisresultsdependheavilyonthecalculatedpressurefield astheinformationonthe operatingtemperatureandpressureinthecompressorstagesofsmallturbofanenginesis verylimited 54 55 airflowandthermalanalysisisperformedinthiswork 2 3 aluminium basedalloys aluminiumalloyswithlithiumandscandiumarewellsuitedtobeusedinturbofan engine giventheirhighspecificstrengthwhichexceedsthoseoftitaniumalloys 35 37 spd effectively hardens cast structure aluminium could used instead homogenization annealing 40 56 however necessary take account operating temperature component since heat resistance aluminium alloy significantlylowerthanthatoftitaniumandnickelones intermetallicfe al basedalloyscouldpotentiallysubstitutemoreexpensivesuper 3 alloysandcreep resistantsteels theyarecharacterizedbyacombinationofinteresting functionalcharacteristicssuchasexcellentresistancetooxidation sulfidationandcarburiz ing goodresistancetoseawatercorrosion wear erosion orcavitation andhighstrength toweightratio 57 58 inthiswork avariantofthestandardaerospacealuminiumalloy7055 scwasused al zn mg cu sc itwasobtainedinlaboratorybymeltingwiththeadditiveofscandium itsinitialporositywas3 4

anditreducedtolessthan1 5 afterte lightweight heat
resistantandweldablealloysbasedontitaniumaluminides 34
makeitpossibletodesignmoreefficientcompressors thesematerialsofferanumberof uniqueproperties
lowdensity relativelyhighmeltingpoint highmodulusofelasticity resistancetooxidationandfire
highspecificheatresistance andsoforth theyarewell suited last stage compressor blade effectiveness
controversial ononehand duetothecombinationofspecificstrengthandheatresistance theycan replace
traditional nickel based alloy 33 59 hand technology manufacturing processing quite energy intensive
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satisfactoryforaircraftcomponents inparticularforaero engine inthiscase apromising cost
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inparticularcompressorblades wasself propagating high
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anditdecreasedto4 5 afterte takingintoaccountthatthistechnologynotonlyreducesthecostofmanufacturing
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effectivelyreducesthelevelofdynamicloadsandvibration 62
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theobtainedpressureandtemperaturefieldswereapplieddirectlytoaerofoilsurfacesto
determinethestressesandstrainsincomponents 63 65 theanalysiswasperformedfor a6
stageaxialcompressor figure2 thefanisnotconsideredinthispaperasitsblades
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bothstaticandfatiguestrengthareevaluatedfornewcomponents 69 70
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thevonmisesstressinthecompressorblades 3 resultsanddiscussion
figure6showsthecalculatedpressurefieldsonbladesurfaces andtheflowtempera ture
theflowtemperaturewasusedastheinitialdataforthermalanalysisastheboundary
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9of16 obtainedoperatingtemperatureofthecompressorbladesmakesitpossibletoevaluatethe
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figure6 pressureandtemperaturefieldonbladesurfaces figure7
temperaturefieldforbladesandvanesofstage6 thecalculatedstressdistributionintheaerofoils figure8

madeitpossibletoevalu atecandidatematerialsandprocessingtechnologiesinviewoftheirstructuralintegrity valuesofmaximumequivalentstressandstaticsafetyfactorofbladesandvanesmade fromadvancedmaterialsandtechnologiesaregivenintables5and6 materialswithsafety factorlessthanthethresholdof1 1cannotbeusedintheparticularstage 72 thisvalue wasselectedbythemanufactureronthebasisofindustrialexperienceandreliabilitydata undercertainconditions suchalowsfthresholdisacceptableinaircraftcomponents especiallyforunmannedandsingle useplatforms analysingtheobtaineddata wecanconcludethatthecandidatematerialsandpro cessingtechnologiescanbeusedformanufacturingcompressorcomponents considering thatmaterialselectionbythetemperatureandstrengthcriteriaiscomplicatedduetothe varietyoflimitingfactors nomogramsweredevelopedforthispurpose figures9and10 itcanbenotedthatvt8alloyislimitedtorotorstages1 2intermsofitsstrengthreliability theuseofspdmethodsexpandsthescopeofitsapplicationuptothe7thstage however intermsofthetemperaturelimit vt8usageislimitedtobladesofthefirstfivestages aerospace2021 8 1 10of16 figure8 vonmissesstressinbladesandvanesmadefromvt8_spk_spdinengineemergencymode table5 equivalentstressandstaticsafetyfactorofbladesmadefromcandidatematerials rotorstage r1 r2 r3 r4 r5 r6 σmax sf σmax sf σmax sf σmax sf σmax sf σmax sf alloy process mpa mpa mpa mpa mpa mpa vt8 480 2 1 77 481 1 1 77 805 8 1 05 893 3 0 95 717 6 1 19 864 5 0 98 vt8_spd 481 9 2 39 451 6 2 25 802 4 1 43 859 4 1 34 718 4 1 60 889 4 1 29 vt8_spk 477 2 0 94 517 3 0 87 801 2 0 56 938 6 0 48 719 9 0 63 882 2 0 51 vt8_spk_spd 481 7 1 99 474 2 2 02 804 3 1 91 886 0 1 08 717 4 1 33 872 2 1 10 γtial 483 6 1 34 473 6 1 37 803 1 0 81 892 3 0 73 717 2 0 91 873 5 0 74 γtial_spd 483 6 1 82 462 9 1 90 801 3 1 10 877 3 1 00 717 5 1 23 885 5 0 99 7055 sc 460 0 0 13 451 1 0 13 789 8 0 08 877 0 0 07 717 0 0 08 922 4 0 07 7055 sc_spd 460 0 0 39 450 9 0 40 789 0 0 23 868 7 0 21 717 3 0 25 928 3 0 19 table6 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theformationofasubmicrocrystallinestructureintheentirecross sectionandthehomog enizationofalloyingelements contributestoasignificantincreaseinstrengthand asa consequence theexpansionoftheirapplicationtoallstages atthesametime theoperatingtemperatureofthesubmicrocrystallinealloyislower thanonewiththestandardstructurewhichdoesnotallowfortheirusein6thstageblades figure9 consideringthatthecompressorvanesexperiencealoadonlyfromtheflow fieldofapplicationofthevt8alloyislimitedonlybyitsoperatingtemperature regardless ofthetechnologyofproductionandprocessing despitethegreatstrength thesintered titaniumprocessedwithte incomparisonwiththeregularsinteredalloy hastheoperating temperaturelowerby40 c whichmaylimititsuse takingintoaccountthelowercostof obtainingsinteredtitaniumalloys theiruseisthemostrationalinthebladesofthefirst fivestages aerospace2021 8 1 11of16 700 600 500 400 300 200 100 0 1 2 3 4 5 6 compressor stage co erutarepmet stator rotor vt8 vt8_spd vt8_spk vt8_spk_spd tial tial_spd 7055 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alloysbasedontitaniumaluminidesarethemostheatresistantoftheconsidered one whichpredeterminestheiruseformanufacturingbladesofthelastcompressorstages fromthepointofviewofthepermissibleoperatingtemperature thisalloycanbeapplied tobladesofallstagesregardlessoftheirstructuralstate table3 atthesametime thepointofviewofstrengthreliabilityforblades theiruseisalloweduptostage2without additionalstrainhardeningandupto3rdstagewithteprocessing table5 stator stage safety factor vane made titanium aluminides higherthanthethreshold table6 thus thisalloycanbeusedformanufacturingvanes ofstages5and6 forwhich duetotemperaturelimitations lightertitaniumalloysmay notbeapplicable nevertheless thereplacementofmoreheat resistantinconel718alloys withtitaniumaluminideswouldreducetheweightofgasturbineengines itshouldbenotedthattheconsideredtemperaturelimitationsofsubmicrocrystalline alloysareassociatedwiththeonsetofrecrystallizationprocesses consideringthatthis processestakearelativelylongtime 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