

**STUDY ON THE EFFECT OF CONSTRAINED GROOVE
PRESSING ON THE MICROSTRUCTURE, MECHANICAL AND
FORMABILITY CHARACTERISTICS OF β -21S TITANIUM
ALLOY**

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by

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Submitted

*in fulfilment of the requirement of the Degree of Doctor of Philosophy
to the*



INDIAN INSTITUTE OF TECHNOLOGY, DELHI

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Dedicated to my

Beloved Sir

CERTIFICATE

This is to certify that the thesis entitled “**Study on the Effect of Constrained Groove Pressing on the Microstructure, Mechanical and Formability Characteristics of β -21S Titanium Alloy**” being submitted by **Mr. Mahesh Katakam** to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy in Department of Materials Science and Engineering is a bonafide research work carried out by him under our supervision and guidance. To the best of our knowledge, the thesis has reached the requisite standard. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.



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ABSTRACT

Titanium and its alloys have garnered significant attention in various industries due to their exceptional properties, including high strength-to-weight ratio, corrosion resistance, and biocompatibility. As the demand for lightweight and durable materials continue to rise across diverse applications such as aerospace, automotive, biomedical, and sporting goods, titanium alloys have emerged as a preferred choice. Among the titanium alloys, Ti-6Al-4V, also known as Grade 5 titanium, is one of the most widely used titanium alloys due to its exceptional combination of properties, making it vital in various industries. However, the metastable β titanium alloys have gained significance due to their attractive properties like high biocompatibility, high fatigue, corrosion resistance, and young's modulus close to that of the human bones. Though β titanium alloys exhibit numerous advantages, certain limitations such as coarse β grains, limited formability, relatively higher density and susceptibility to phase instability, particularly at elevated temperatures or under load, limit its consideration among the titanium alloy classes. Despite this, ongoing research and advancements in alloy design, processing methodologies, including those involving severe plastic deformation (SPD) process, and understanding of phase stability aim to mitigate these challenges and thereby, expand the potential applications of metastable β titanium alloys in various industries.

Among the metastable β titanium alloys, β -21S Ti-alloy exhibit a unique balance of strength, toughness, and weldability, particularly suited for aerospace structures, marine components, and medical implants. β -21S Ti-alloy is used for manufacturing the tail plug for the B-777 engine. Most of the research on β -21S Ti-alloy has been carried out extensively on microstructural characterization and mechanical properties of various solution treatment and aging processes to improve the strength, but the ductility has significantly reduced. However, studies involving processing techniques such as SPD process to modify β -21S Ti-alloy microstructure and eventually effect on its mechanical properties and formability characteristics have not been attempted. Among the SPD processes, constrained groove pressing (CGP) is considered as the most suitable process for deforming materials in the sheet form. Hence, the broad aim of the current study is to achieve grain refinement using CGP process for an optimum combination of strength and formability in the β -21S Ti-alloy.

The β -21S Ti-alloy demonstrates good ductility with moderate strength in the solution treated (ST) condition. So, severe plastic deformation processes like constrained groove pressing (CGP) and

constrained groove pressing – cross route (CGP-CR) techniques are used to achieve grain refinement in the β -21S Ti-alloy. The average grain size, tensile and anisotropy properties in the ST, CGP and CGP-CR conditions are determined. Aging of the CGP processed samples are carried out to alter the mechanical properties to achieve an optimum combination of strength and formability. The formability characteristics in terms of stretchability and drawability are characterized in ST, CGP and CGP-CR conditions. In addition, the tensile properties, anisotropy and formability in terms of stretchability, drawability and stretch flangeability of solution treated β -21S Ti-alloy has been compared with most widely used Ti-6Al-4V alloy to establish the specific advantages and limitations of β -21S Ti-alloy over Ti-6Al-4V alloy.

β -21S Ti-alloy sheets of 2 mm thick were used for the present study. Chemical composition analysis of the as-received material was conducted using X-ray fluorescence (XRF) and electron probe micro-analyzer (EPMA). Both methods predicted accurate quantification of elemental composition across multiple regions. Initially, the CGP and CGP-CR simulations were carried out using QForm software, considering sheet dimensions of 64 mm x 64 mm x 2 mm to estimate the effective plastic strain distribution and load required for CGP and CGP-CR processes. Grooved dies, flat dies, and constraint blocks were designed using SolidWorks software and manufactured using D2 steel via CNC machining. The Modified Hensel Spittel model proved to be the most suitable flow model for simulating the behavior of β -21S Ti-alloy sheets during CGP and CGP-CR processes. It was observed that strain inhomogeneity was more pronounced in the transverse direction (perpendicular to grooves) compared to the longitudinal direction (parallel to grooves) due to variations in shear and shear+bending regions. Experimentally, the β -21S Ti-alloy sheets were solutionized at 900°C for 30 min in uncoated and delta-glaze coated conditions. The uncoated sample exhibit a thick oxide layer while a glossy surface has formed on the delta-glaze coated sample. Oxygen diffusion during solution treatment is a significant concern for titanium alloys. Therefore, amount of oxygen diffused in the sample was evaluated through elemental mapping using electron probe micro-analyzer (EPMA). The investigations showed that the oxygen had diffused into the matrix of the uncoated sample while the delta-glaze coating acted as a barrier for the diffusion of oxygen atoms at higher temperatures. CGP experiments were conducted on a 300-ton hydraulic press for samples subjected to solution treatment using delta-glaze coating. Successful deformation was achieved in CGP up to a maximum strain of 3.48 (CGP-P3), while CGP-CR reached 4.64 (CGP-CR2). Simulation results has closely matched with the experimental values on

the estimated force. The hardness inhomogeneity observed in experiments corresponded to the strain inhomogeneity predicted by simulations, as both values decreased with increasing strain. Intermediate annealing after CGP-P2 was attempted but it did not improve in reaching higher CGP passes, indicating the limitations of the CGP process compared to CGP-CR. Consequently, CGP-CR emerged as the superior process for achieving higher strains with lower inhomogeneity.

Microstructural analysis was performed using optical microscopy, X-ray diffraction (XRD), and field emission scanning electron microscopy (FE-SEM). Furthermore, electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) were utilized to analyze microstructural features and twin-like structures. The optical microstructure of samples in ST, CGP and CGP-CR conditions reveal the presence of twin-like structures alongside grain refinement, with higher magnification showing different morphologies and the coexistence of slip bands. With increase in the CGP passes, grain refinement of $\sim 48\%$ (CGP up to 3 passes) and $\sim 62\%$ (CGP-CR up to 2 passes) was achieved. In addition, the fraction of twin-like structures increased from 7% to 22%, suggesting that accumulated strains lead to stress concentration and nucleation of twins. XRD analysis confirmed the presence of a single β phase and suppression of stress-induced martensitic transformation (SIMT) during deformation. The peak shifts and broadening in XRD patterns indicated the strain-induced lattice distortion and grain refinement, with higher broadening observed in CGP-CR, signifying the potential for higher grain refinement. EBSD analysis further revealed the twin-like structures to be either $\{332\}\langle 113 \rangle$ twins or kink bands and further grain boundary misorientation analysis suggests a transition from low angle grain boundaries to high angle grain boundaries with increasing strain. It was observed that during CGP-P1, the strain accumulated was primarily contributed to the higher grain refinement of approximately 39% along with the initiation of twin-like structures within the grains. However, at higher strains ($\epsilon > 2.32$), microstructure evolution showed that primary twins had evolved from the kink bands, while the secondary twins have formed within the primary twins. Additionally, the peak intensity ratio of $I(002)/I(112)$ increased with increasing strain accumulation, resulting in localized crystal rotation. The combined effect of the formation of kink bands and localized crystal rotation are expected to have played a vital role in activating the planes favorable for the deformation resulting in higher strain accumulation ($\epsilon=4.64$) by CGP-CR process at room temperature. TEM and selected area electron diffracton (SAED) images confirm the presence of twins and kink bands, with increasing strain leading to the evolution of primary and secondary twins from kink bands. A hypothesis is proposed

outlining the stage-wise evolution of complex microstructures during deformation, highlighting the role of dislocation density, strain accumulation, and crystal orientation changes in twin formation and grain refinement during severe plastic deformation processes like CGP and CGP-CR processes.

Tensile tests were carried out on samples in ST, CGP and CGP-CR conditions. In the case of CGP processed samples, the tensile samples were considered in both the longitudinal and the transverse directions, and the strain-hardening behavior was analyzed. The Hill's plastic strain ratio method was adopted to determine R-values. Hardness measurements were performed using a macro-Vickers hardness tester, and stretchability was evaluated using Erichsen cup test. The engineering stress-strain curves indicated that the ultimate tensile strength (UTS) increased with the number of passes for both CGP and CGP-CR samples, while elongation decreased. The presence of twins and kink bands played a crucial role in achieving an 18% increase in strength, with a 25% reduction in ductility, contrasting with other titanium alloys which typically experience a 10% strength increase but undergo a more significant 45-60% reduction in ductility after CGP-P1. Strain inhomogeneity significantly impact both strength and flow behavior, especially when samples were tested in the transverse and the longitudinal directions to the grooving. CGP processed samples tested longitudinally show higher strength compared to transverse samples, with enhanced hardening behavior in the latter. In CGP-CR samples, strength surpassed transverse CGP samples but remained lower than longitudinal ones. Despite variations in strength, similar elongation behaviors were observed, suggesting minimal influence of groove impressions on elongation. Flow softening behavior was observed in all conditions, with varying degrees of hardening and softening behavior in uniform plastic region. CGP samples exhibit improved hardening in the transverse direction than in the longitudinal direction which is attributed to microstructural heterogeneity. Finally, the room temperature mechanical properties and formability of β -21S Ti-alloy in solution treated condition and Ti-6Al-4V alloy in as-received condition are evaluated and compared. The alloys are subjected to various deformation modes, such as biaxial stretching, stretch flanging and deep drawing. Formability was characterized in terms of forming limit curve (FLC), limiting dome height (LDH), hole expansion ratio (HER) and limiting draw ratio (LDR). β -21S Ti-alloy exhibit flow softening with similar strength, higher ductility and lower anisotropy than Ti-6Al-4V. Forming limit curves (FLCs) of both alloys were determined by performing tests in different strain paths using the simplified Hecker's method. The FLCs showed that limit strains of β -21S Ti-alloy are marginally higher than Ti-6Al-4V. In addition, the LDH, HER and LDR values of β -21S Ti-alloy are

found to be higher than that of Ti-6Al-4V. Thus, the findings indicate better overall formability of metastable β -21S Ti-alloy making it more suitable than Ti-6Al-4V for room temperature forming applications.

Keywords: β -21S Ti-alloy, Ti-6Al-4V, constrained groove pressing, constrained groove pressing – cross route, twins, kink bands, slip bands, grain refinement, forming limit curve, limiting dome height, limiting dome height and limiting draw ratio.

सारांश

टाइटेनियम और इसकी मिश्र धातुएँ अपनी उत्कृष्ट गुणों, जैसे उच्च शक्ति-से-वजन अनुपात, संक्षारण प्रतिरोध, और जैव संगतता के कारण विभिन्न उद्योगों में महत्वपूर्ण ध्यान आकर्षित कर रही हैं। जैसे-जैसे हल्के और टिकाऊ सामग्रियों की मांग एयरोस्पेस, ऑटोमोटिव, बायोमेडिकल और खेल के सामान जैसे विविध अनुप्रयोगों में बढ़ रही है, टाइटेनियम मिश्र धातुएँ एक पसंदीदा विकल्प के रूप में उभर रही हैं। टाइटेनियम मिश्र धातुओं में, Ti-6Al-4V, जिसे ग्रेड 5 टाइटेनियम के नाम से भी जाना जाता है, अपने असाधारण गुणों के संयोजन के कारण विभिन्न उद्योगों में व्यापक रूप से उपयोग की जाने वाली मिश्र धातु है। हालांकि, मेटास्टेबल β टाइटेनियम मिश्र धातुओं ने उच्च जैव संगतता, उच्च थकान प्रतिरोध, संक्षारण प्रतिरोध, और मानव हड्डियों के समान यंग्स मापांक जैसी आकर्षक गुणों के कारण महत्वपूर्ण स्थान प्राप्त किया है। यद्यपि β टाइटेनियम मिश्र धातुएँ कई लाभ प्रदर्शित करती हैं, लेकिन इसमें कुछ सीमाएँ भी हैं, जैसे मोटे β अनाज, सीमित रूपांतरता, तुलनात्मक रूप से उच्च घनत्व, और विशेष रूप से उच्च तापमान या भार के तहत चरण अस्थिरता के प्रति संवेदनशीलता। इसके बावजूद, मिश्र धातु डिजाइन, प्रसंस्करण पद्धतियों में प्रगति, जिसमें गंभीर प्लास्टिक विकृति (SPD) प्रक्रिया शामिल है, और चरण स्थिरता को समझने में चल रहे शोध इन चुनौतियों को कम करने का प्रयास करते हैं और विभिन्न उद्योगों में मेटास्टेबल β टाइटेनियम मिश्र धातुओं के संभावित अनुप्रयोगों का विस्तार करने का प्रयास करते हैं।

मेटास्टेबल β टाइटेनियम मिश्र धातुओं में, β -21S Ti-मिश्र धातु ताकत, कठोरता और वेल्डेबिलिटी का एक अद्वितीय संतुलन प्रदर्शित करता है, जो विशेष रूप से एयरोस्पेस संरचनाओं, समुद्री घटकों और चिकित्सा प्रत्यारोपणों के लिए उपयुक्त है। बी-777 इंजन के टेल प्लग के निर्माण में β -21S Ti-मिश्र धातु का उपयोग किया जाता है। β -21S Ti-मिश्र धातु पर अधिकांश शोध माइक्रोस्ट्रक्चरल लक्षणों और विभिन्न समाधान उपचार और एजिंग प्रक्रियाओं के यांत्रिक गुणों पर व्यापक रूप से किए गए हैं ताकि इसकी ताकत में सुधार हो सके, लेकिन नम्यता में महत्वपूर्ण रूप से कमी आई है। हालांकि, एसपीडी प्रक्रिया जैसी प्रसंस्करण तकनीकों का उपयोग कर β -21S Ti-मिश्र धातु की माइक्रोस्ट्रक्चर में संशोधन और इसके यांत्रिक गुणों और रूपांतरता विशेषताओं पर प्रभाव का अध्ययन नहीं किया गया है। एसपीडी प्रक्रियाओं में, सीमित ग्रूव प्रेसिंग (सीजीपी) को शीट के रूप में सामग्रियों को विकृत करने के लिए सबसे उपयुक्त प्रक्रिया माना जाता है। इस प्रकार, वर्तमान अध्ययन का व्यापक उद्देश्य β -21S Ti-मिश्र धातु में अनाज परिशोधन के लिए सीजीपी प्रक्रिया का उपयोग करना है ताकि ताकत और रूपांतरता का एक इष्टतम संयोजन प्राप्त हो सके।

β -21S Ti-मिश्र धातु समाधान उपचारित (एसटी) स्थिति में मध्यम ताकत के साथ अच्छी नम्यता प्रदर्शित करता है। इसलिए, सीमित ग्रूव प्रेसिंग (सीजीपी) और सीमित ग्रूव प्रेसिंग – क्रॉस रूट (सीजीपी-सीआर) जैसी गंभीर प्लास्टिक विकृति प्रक्रियाओं का उपयोग β -21S Ti-मिश्र धातु में अनाज परिशोधन प्राप्त करने के लिए किया गया है। एसटी, सीजीपी, और सीजीपी-सीआर स्थितियों में औसत अनाज आकार, तन्यता, और अनियंत्रणीयता गुण निर्धारित किए गए। सीजीपी प्रसंस्कृत नमूनों की आयु निर्धारित कर उनके यांत्रिक गुणों को बदलने के लिए उनके गुणों में सुधार की संभावना का मूल्यांकन किया गया। स्ट्रेचेबिलिटी और ड्रॉएबिलिटी के संदर्भ में रूपांतरता गुणों को एसटी, सीजीपी और सीजीपी-सीआर स्थितियों में वर्णित किया गया। इसके अतिरिक्त, समाधान उपचारित β -21S Ti-मिश्र धातु की तन्यता, अनियंत्रणीयता, और स्ट्रेचेबिलिटी, ड्रॉएबिलिटी और स्ट्रेच फ्लैंगेबिलिटी के संदर्भ में रूपांतरता की तुलना व्यापक रूप से उपयोग की जाने वाली Ti-6Al-4V मिश्र धातु के साथ की गई ताकि β -21S Ti-मिश्र धातु के विशेष लाभ और सीमाओं को Ti-6Al-4V पर स्थापित किया जा सके।

वर्तमान अध्ययन के लिए 2 मिमी मोटाई की β -21S Ti-मिश्र धातु शीट्स का उपयोग किया गया। प्राप्त सामग्री का रासायनिक संरचना विश्लेषण X-रे फ्लोरोसेंस (XRF) और इलेक्ट्रॉन प्रोब माइक्रो-विश्लेषक (EPMA) का उपयोग करके किया गया। दोनों विधियों ने विभिन्न क्षेत्रों में तत्वों की सटीक मात्रा की भविष्यवाणी की। प्रारंभ में, सीजीपी और सीजीपी-सीआर सिमुलेशन QForm सॉफ्टवेयर का उपयोग करके किए गए थे, जिसमें शीट के आयामों के रूप में 64 मिमी x 64 मिमी x 2 मिमी को ध्यान में रखते हुए, सीजीपी और सीजीपी-सीआर प्रक्रियाओं के लिए आवश्यक प्रभावी प्लास्टिक तनाव वितरण और भार का अनुमान लगाया गया। ग्रूव डाइज़, फ्लैट डाइज़ और संयम ब्लॉक को SolidWorks सॉफ्टवेयर का उपयोग करके डिज़ाइन किया गया और D2 स्टील का उपयोग करके CNC मशीनिंग के माध्यम से निर्मित किया गया। सीजीपी और सीजीपी-सीआर प्रक्रियाओं के दौरान β -21S Ti-मिश्र धातु शीट्स के व्यवहार को सिमुलेट करने के लिए मॉडिफाइड हेंसल स्पिटेल मॉडल सबसे उपयुक्त प्रवाह मॉडल साबित हुआ। यह देखा गया कि तनाव की असंगति ट्रांसवर्स दिशा (ग्रूव्स के लंबवत) में अधिक थी, जबकि लॉन्गिट्यूडिनल दिशा (ग्रूव्स के समानांतर) में कम थी, जो शियर और शियर+बेंडिंग क्षेत्रों में भिन्नताओं के कारण थी। प्रयोगात्मक रूप से, β -21S Ti-मिश्र धातु शीट्स को बिना कोटिंग और डेल्टा-ग्लेज़ कोटेड स्थितियों में 900°C पर 30 मिनट के लिए समाधानित किया गया। बिना कोटिंग के नमूने पर एक मोटी ऑक्साइड परत देखी गई, जबकि डेल्टा-ग्लेज़ कोटेड नमूने पर एक चमकदार सतह बनी। समाधान उपचार के दौरान ऑक्सीजन का प्रसार टाइटेनियम मिश्र धातुओं के लिए एक महत्वपूर्ण चिंता है। इसलिए, नमूने में प्रसारित ऑक्सीजन की मात्रा का मूल्यांकन इलेक्ट्रॉन प्रोब माइक्रो-विश्लेषक (EPMA) का उपयोग करके तत्वीय मानचित्रण के माध्यम से किया

गया। अनुसंधान ने दिखाया कि बिना कोटिंग वाले नमूने में ऑक्सीजन ने मैट्रिक्स में प्रसारित किया था, जबकि डेल्टा-ग्लेज़ कोटिंग ने उच्च तापमान पर ऑक्सीजन परमाणुओं के प्रसार के लिए एक अवरोध के रूप में कार्य किया। डेल्टा-ग्लेज़ कोटिंग का उपयोग करके समाधान उपचारित नमूनों पर 300-टन हाइड्रोलिक प्रेस पर सीजीपी प्रयोग किए गए। सीजीपी में अधिकतम 3.48 (सीजीपी-पी3) तक तनाव पर सफल विकृति प्राप्त की गई, जबकि सीजीपी-सीआर ने 4.64 (सीजीपी-सीआर2) तक पहुंच बनाई। सिमुलेशन के परिणामों ने अनुमानित बल पर प्रयोगात्मक मानों के साथ निकटता से मेल खाया। प्रयोगों में देखी गई कठोरता असंगति सिमुलेशन द्वारा भविष्यवाणी की गई तनाव असंगति के अनुरूप थी, क्योंकि दोनों मान तनाव बढ़ने के साथ कम हुए। सीजीपी-पी2 के बाद मध्यवर्ती एनीलिंग का प्रयास किया गया, लेकिन यह उच्च सीजीपी पास तक पहुँचने में सुधार नहीं कर पाया, जो सीजीपी प्रक्रिया की सीमाओं को दर्शाता है। परिणामस्वरूप, सीजीपी-सीआर कम असंगति के साथ उच्च तनाव प्राप्त करने के लिए श्रेष्ठ प्रक्रिया के रूप में उभरा।

सूक्ष्मसंरचनात्मक विश्लेषण ऑप्टिकल माइक्रोस्कोपी, एक्स-रे विवर्तन (XRD), और फील्ड एमिशन स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (FE-SEM) का उपयोग करके किया गया। इसके अतिरिक्त, इलेक्ट्रॉन बैकस्कैटर विवर्तन (EBSD) और ट्रांसमिशन इलेक्ट्रॉन माइक्रोस्कोपी (TEM) का उपयोग सूक्ष्मसंरचनात्मक विशेषताओं और द्विन-जैसी संरचनाओं का विश्लेषण करने के लिए किया गया। एसटी, सीजीपी और सीजीपी-सीआर स्थितियों में नमूनों के ऑप्टिकल माइक्रोस्ट्रक्चर ने अनाज परिशोधन के साथ-साथ द्विन-जैसी संरचनाओं की उपस्थिति का खुलासा किया, जिसमें उच्च आवर्धन ने विभिन्न रूपों और स्लिप बैंड्स के सह-अस्तित्व को दिखाया। सीजीपी पासों की वृद्धि के साथ, लगभग 48% (सीजीपी में 3 पास तक) और ~62% (सीजीपी-सीआर में 2 पास तक) का अनाज परिशोधन प्राप्त किया गया। इसके अतिरिक्त, द्विन-जैसी संरचनाओं का अंश 7% से 22% तक बढ़ गया, जिससे संकेत मिलता है कि संचित तनाव के कारण तनाव का संकेन्द्रण और ट्विन्स का नाभिक बनता है। XRD विश्लेषण ने एकल β चरण की उपस्थिति और विकृति के दौरान तनाव-प्रेरित मार्टेंसाइटिक परिवर्तन (SIMT) के दमन की पुष्टि की। XRD पैटर्न में पीक शिफ्ट और चौड़ाई ने तनाव-प्रेरित लैटिस विकृति और अनाज परिशोधन का संकेत दिया, जिसमें सीजीपी-सीआर में उच्च चौड़ाई देखी गई, जो उच्च अनाज परिशोधन की संभावनाओं को इंगित करती है। EBSD विश्लेषण ने द्विन-जैसी संरचनाओं को $\{332\}$ $\{113\}$ ट्विन्स या किंक बैंड्स के रूप में प्रकट किया और अनाज सीमा में अव्यवस्था विश्लेषण ने बढ़ते तनाव के साथ निम्न कोण अनाज सीमाओं से उच्च कोण अनाज सीमाओं की ओर संक्रमण का सुझाव दिया। यह देखा गया कि CGP-P1 के दौरान संचित तनाव का मुख्य योगदान लगभग 39% के उच्च अनाज परिशोधन के साथ-साथ अनाजों के भीतर द्विन-जैसी संरचनाओं के आरंभ में था। हालांकि, उच्च तनाव

($\epsilon > 2.32$) पर, सूक्ष्मसंरचना विकास ने दिखाया कि प्राथमिक ट्विन्स किंक बैंड्स से विकसित हुए, जबकि द्वितीयक ट्विन्स प्राथमिक ट्विन्स के भीतर बने। इसके अतिरिक्त, पीक तीव्रता अनुपात $I(002)/I(112)$ में बढ़ते तनाव संचय के साथ वृद्धि हुई, जिसके परिणामस्वरूप स्थानीय क्रिस्टल रोटेशन हुआ। किंक बैंड्स और स्थानीय क्रिस्टल रोटेशन के गठन का संयुक्त प्रभाव विकृति के लिए अनुकूल समतलों को सक्रिय करने में महत्वपूर्ण भूमिका निभाने की संभावना है, जिससे CGP-CR प्रक्रिया द्वारा कमरे के तापमान पर उच्च तनाव संचय ($\epsilon=4.64$) प्राप्त हुआ। TEM और चयनित क्षेत्र इलेक्ट्रॉन विवर्तन (SAED) छवियों ने ट्विन्स और किंक बैंड्स की उपस्थिति की पुष्टि की, जिसमें बढ़ते तनाव के साथ किंक बैंड्स से प्राथमिक और द्वितीयक ट्विन्स का विकास हुआ। एक परिकल्पना प्रस्तावित की गई है जो विकृति के दौरान जटिल सूक्ष्मसंरचनाओं के चरण-वार विकास को रेखांकित करती है, जिसमें ट्विन निर्माण और अनाज परिशोधन में अव्यवस्था घनत्व, तनाव संचय और क्रिस्टल अभिविन्यास परिवर्तनों की भूमिका को उजागर किया गया है, जैसे सीजीपी और सीजीपी-सीआर जैसी गंभीर प्लास्टिक विकृति प्रक्रियाओं में। ST, CGP और CGP-CR स्थितियों में नमूनों पर तन्यता परीक्षण किए गए। CGP प्रसंस्कृत नमूनों के मामले में, तन्यता नमूनों को अनुदैर्घ्य और अनुप्रस्थ दोनों दिशाओं में लिया गया और तनाव-कठोरता व्यवहार का विश्लेषण किया गया। R-मूल्यों को निर्धारित करने के लिए हिल की प्लास्टिक तनाव अनुपात विधि अपनाई गई। कठोरता माप के लिए मैक्रो-विकर्स कठोरता परीक्षक का उपयोग किया गया, और स्ट्रेचेबिलिटी का मूल्यांकन एरिक्सन कप परीक्षण का उपयोग करके किया गया। इंजीनियरिंग तनाव-तनाव वक्रों ने संकेत दिया कि दोनों CGP और CGP-CR नमूनों के लिए पासों की संख्या के साथ अंतिम तन्यता शक्ति (UTS) में वृद्धि हुई, जबकि लंबाई बढ़ने में कमी आई। ट्विन्स और किंक बैंड्स की उपस्थिति ने शक्ति में 18% वृद्धि करने में महत्वपूर्ण भूमिका निभाई, जबकि नम्यता में 25% की कमी आई, जो अन्य टाइटेनियम मिश्र धातुओं के विपरीत है, जिनमें आमतौर पर 10% शक्ति वृद्धि होती है, लेकिन CGP-P1 के बाद नम्यता में 45-60% की कमी होती है। तनाव असंगति ने शक्ति और प्रवाह व्यवहार दोनों पर महत्वपूर्ण प्रभाव डाला, विशेष रूप से जब नमूनों का परीक्षण ग्रूविंग की दिशा में अनुदैर्घ्य और अनुप्रस्थ दोनों में किया गया। अनुदैर्घ्य रूप से परीक्षण किए गए CGP प्रसंस्कृत नमूनों ने अनुप्रस्थ नमूनों की तुलना में अधिक शक्ति प्रदर्शित की, जिसमें बाद वाले में बढ़ी हुई कठोरता व्यवहार था। CGP-CR नमूनों में, शक्ति अनुप्रस्थ CGP नमूनों से अधिक थी, लेकिन अनुदैर्घ्य नमूनों से कम रही। शक्ति में बदलाव के बावजूद, समान लंबाई बढ़ने के व्यवहार देखे गए, जो लंबाई बढ़ने पर ग्रूव प्रभावों का न्यूनतम प्रभाव दर्शाता है। सभी स्थितियों में फ्लो सॉफ्टनिंग व्यवहार देखा गया, जिसमें समान प्लास्टिक क्षेत्र में कठोरता और सॉफ्टनिंग व्यवहार में विभिन्न स्तर थे। CGP नमूने अनुदैर्घ्य दिशा की तुलना में अनुप्रस्थ दिशा में बेहतर कठोरता प्रदर्शित करते हैं, जो सूक्ष्म संरचनात्मक असंगति को दर्शाता है। अंततः, समाधान उपचारित स्थिति में β -21S Ti-मिश्र धातु और प्राप्त स्थिति

में Ti-6Al-4V मिश्र धातु की कमरे के तापमान पर यांत्रिक गुण और रूपांतरता का मूल्यांकन और तुलना की गई। मिश्र धातुओं को द्वि-अक्षीय स्ट्रेचिंग, स्ट्रेच फ्लैगिंग और डीप ड्रॉइंग जैसी विभिन्न विकृति विधाओं के अधीन किया गया। रूपांतरता का निर्धारण फॉर्मिंग लिमिट कर्व (FLC), लिमिटिंग डोम हाइट (LDH), होल एक्सपेंशन रेशियो (HER) और लिमिटिंग ड्रॉ रेशियो (LDR) के संदर्भ में किया गया। β -21S Ti-मिश्र धातु Ti-6Al-4V की तुलना में समान शक्ति, उच्च नम्यता और कम अनियंत्रणीयता के साथ फ्लो सॉफ्टनिंग प्रदर्शित करता है। दोनों मिश्र धातुओं के फॉर्मिंग लिमिट कर्व (FLCs) को विभिन्न तनाव पथों में परीक्षण करके सरल हेकर की विधि का उपयोग करके निर्धारित किया गया। FLCs ने दिखाया कि β -21S Ti-मिश्र धातु की सीमा तनाव Ti-6Al-4V से थोड़ा अधिक है। इसके अतिरिक्त, β -21S Ti-मिश्र धातु के LDH, HER और LDR मान Ti-6Al-4V की तुलना में अधिक पाए गए। इस प्रकार, निष्कर्षों से संकेत मिलता है कि मेटास्टेबल β -21S Ti-मिश्र धातु की समग्र रूपांतरता बेहतर है, जो इसे कमरे के तापमान पर फॉर्मिंग अनुप्रयोगों के लिए Ti-6Al-4V की तुलना में अधिक उपयुक्त बनाती है।

कीवर्ड्स: β -21S Ti-मिश्र धातु, Ti-6Al-4V, सीमित ग्रूव प्रेसिंग, सीमित ग्रूव प्रेसिंग – क्रॉस रूट, ट्विन्स, किंक बैंड्स, स्लिप बैंड्स, अनाज परिशोधन, फॉर्मिंग लिमिट कर्व, लिमिटिंग डोम हाइट, और लिमिटिंग ड्रॉ रेशियो।

Table of Contents

Acknowledgements	ii
Abstract	v
सारांश	x
Table of Contents	xv
List of Figures	xix
List of Tables	xxviii
List of Abbreviations	xxx
Nomenclature	xxxii
Chapter 1 – Introduction	
1.1. Titanium and its Alloys	1
1.2. Severe Plastic Deformation (SPD)	6
1.2.1. Constrained Groove Pressing (CGP)	7
1.2.2. Constrained Groove Pressing – Cross Route (CGP-CR)	8
1.3. Formability	9
Chapter 2 – Literature Review	
2.1. Introduction	12
2.2. Metastable β -Ti alloys	12
2.2.1. Background of β -21S Ti-Alloy	13
2.3. Effect of Severe Plastic Deformation (SPD) on Grain Refinement	14
2.3.1. Constrained Groove Pressing (CGP)	14
2.3.2. Constrained Groove Pressing – Cross Route (CGP-CR)	17
2.3.3. Other Severe Plastic Deformation Processes	19
2.4. Microstructure Evolution During Plastic Deformation	20
2.5. Solution Treatment and Aging Behavior of Metastable β -Ti Alloys	23
2.6. Mechanical Properties	27
2.6.1. Constrained Groove Pressing (CGP)	27
2.6.2. Constrained Groove Pressing – Cross Route (CGP-CR)	30
2.6.3. Solution Treatment and Aging	31
2.7. Formability	35
2.8. Anisotropy	37
2.9. Summary and Research Gaps	38
Chapter 3 – Motivation and Objectives	
3.1. Motivation	39
3.2. Objectives	40

Chapter 4 – Materials and Methodology	
4.1. Materials and its Chemical Composition	41
4.1.1. X-Ray Fluorescence (XRF)	41
4.1.2. Electron Probe Micro-analyzer (EPMA)	41
4.2. Methodologies	42
4.2.1. Simulation of CGP and CGP-CR Processes	42
4.2.2. CGP Experiments	45
4.3. Heat Treatment, Surface Grinding and Aging	47
4.4. Material Characterization Techniques	47
4.4.1. Sample Preparation	47
4.4.2. Optical Microscopy	48
4.4.3. X-Ray Diffraction (XRD)	48
4.4.4. Scanning Electron Microscopy (SEM)	49
4.4.4.1. Field Emission Scanning Electron Microscopy (FE-SEM)	49
4.4.4.2. Tabletop Scanning Electron Microscopy (Tabletop SEM)	49
4.4.5. Electron Backscatter Diffraction (EBSD)	49
4.4.6. Transmission Electron Microscopy (TEM)	50
4.5. Mechanical Properties	50
4.5.1. Tensile Testing	50
4.5.2. Anisotropy	51
4.5.3. Hardness	52
4.6. Formability Tests	53
4.6.1. Stretchability	53
4.6.1.1. Erichsen Cup Test	53
4.6.1.2. Limiting Dome Height (LDH) Test	54
4.6.2. Drawability (Deep Drawing)	55
4.6.3. Hole Expansion Test (HET)	55
4.6.4. Forming Limit Diagram (FLD) Test	56
Chapter 5 – Simulation of Constrained Groove Pressing of β -21S Titanium Alloy with Experimental Validation	
5.1. Introduction	58
5.2. Prediction of Force and Strain Inhomogeneity in CGP by Simulation	59
5.2.1. Flow Curve of β -21S Ti-Alloy in Solution Treated Condition	59
5.2.2. Selection of Flow Stress Model	59
5.2.3. Simulation Results of CGP Process	61
5.2.4. Effective Plastic Strain Distribution	66

5.2.5. Force Prediction	70
5.3. Experimental Results of CGP and CGP-CR Processes	72
5.3.1. Effect of Delta-Glaze Coating on Surface Characteristics of β -21S Ti-Alloy Samples	72
5.3.2. Effect of Delta-Glaze Coating on CGP Process	77
5.3.3. Comparison of Microstructural Features	78
5.3.4. Effect of Delta-Glaze Coating on Mechanical Properties Before and After CGP	79
5.3.5. Comparison of CGP and CGP-CR Processes Using Delta-Glaze Coating	83
5.3.6. Effect of Intermediate Annealing in CGP Process	86
5.4. Summary	88
Chapter 6 – Effect of Processing Route on Microstructure Evolution and Grain Refinement of β -21S Ti-Alloy	
6.1 Introduction	89
6.2 Microstructure Characterization of Solution Treated and CGP Processed Samples	90
6.2.1 Optical Microstructure	90
6.2.2 X-Ray Diffraction Analysis	92
6.2.3 Electron Back Scattered Diffraction Analysis	94
6.2.4 Heterogeneity in Microstructure	100
6.3 Effect of Grain Rotation During CGP Process	101
6.4 Hypothesis of Microstructural Evolution	102
6.5 Comparison of CGP and CGP-CR Processes with ECAP and HPT	106
6.6 Summary	107
Chapter 7 – Influence of Microstructure Evolution on the Mechanical Properties and Formability of β -21S Ti-Alloy	
7.1. Introduction	108
7.2. Tensile Properties and Anisotropy in Solution Treated Condition	109
7.2.1. Tensile Properties	109
7.2.2. Anisotropic Parameters	111
7.3. Tensile Properties of CGP and CGP-CR Samples	112
7.4. Plastic Flow Behavior (Strengthening Mechanism)	114
7.5. Significance of Loading Direction in CGP Samples	123
7.6. Effect of Recrystallization on Flow Behavior	127
7.7. Effect of Aging on Flow Behavior	128
7.8. Formability	131

7.8.1. Stretchability	131
7.8.1.1. Erichsen Cup Test	132
7.8.2. Formability Comparison of β -21S and Ti-6Al-4V Alloys	133
7.8.2.1. Forming Limit Diagram (FLD)	134
7.8.2.2. Limiting Dome Height (LDH) Test	136
7.8.2.3. Stretch Flangeability	138
7.8.2.4. Drawability	139
7.9. Summary	141
Chapter 8 – Conclusions and Future Work	
8.1. Conclusions	143
8.2. Future Scope	144
References	145
Annexure - 1	161

List of Figures

Figure No.	Title	Page No.
1.1	Pseudo-binary titanium isomorphous phase diagram.	2
1.2	MoEq values of β -Ti alloys.	4
1.3	Fabrication of B-777 engine tail plug using β -21S Ti-alloy	5
1.4	Sequence of steps in one pass of CGP process.	8
1.5	Sequence of steps in one pass of CGP-CR process.	9
2.1	TEM micrographs of CGP processed aluminium samples after (a) one pressing, (b) two pressings, and (c) 16 pressings.	15
2.2	TEM images of CGP processed CP-Ti (shear bands shown by arrows): (a) 3 passes at room temperature and (b) 4 passes at 300 °C.	16
2.3	Microstructures of Ti-6Al-4V: (a) as-received, (b) CGP-P1, and (c) CGP-P2 processed at 550°C.	17
2.4	Variation of inhomogeneity factor with number of passes in CGP-CR along rolling direction and transverse direction.	18
2.5	Variation of grain size of the Cu-38Zn alloy as a function of the accumulated strain. Single-O and Cross-O stand for single-orientation and cross-route pressing, respectively.	18
2.6	Inverse pole figure (IPF) map of Ti-15Mo sample after (a) 2 passes and (b) 4 passes of ECAP.	19
2.7	EBSD images of Ti-3873 after 20% of tensile strain: (a) Band contrast, (b) Inverse pole figure map, and (c) Misorientation along the AB arrow shown in (b).	21
2.8	EBSD maps of Ti-4733 after (a) solution treatment at 1000 °C for 30 min and (b) 70% cold-rolled and annealed at 840 °C for 5 min.	22
2.9	Microstructure of β -21S Ti-alloy in different conditions: (a) ST+A1, (b) ST+A2, and (c) ST+DA.	24

2.10	Thermomechanical processing routes for different metastable β alloys. T1 and T2 refer to recrystallized and recovered temperatures, respectively, v1 and v2 indicate high and low heating rate, respectively, ST is solution treatment, WQ is water quenching, CD is cold rolling, RH is rate of heating, and A is aging.	25
2.11	BSE images showing the microstructures β -21S Ti-alloy in different heat treated conditions: (a, b) fine α precipitates; (c, d) coarse α precipitates.	26
2.12	(a) Hardness variation across the sample and (b) Stress-strain curves of CP-Ti. CGP1 and CGP2 indicate the sample after 4 passes and 8 passes, respectively.	27
2.13	Stress-strain curves of Ti6Al4V in as-received (AR) and CGP processed (at 550°C) condition.	28
2.14	Variation in tensile properties of aluminium with accumulated strain in CGP.	29
2.15	Variation of tensile properties of aluminium with number of CGP passes.	30
2.16	Variation of tensile properties of Cu-Zn alloy with number of CGP passes.	30
2.17	Variation of mechanical properties of low carbon steel samples along RD with number of CGP-CR passes.	31
2.18	(a) Tensile stress-strain curves in various heat treatment conditions, and (b) Yield strength in various heat treatment conditions at different working temperatures.	32
2.19	(a) Engineering stress-strain curves of β -21S Ti-alloy in different heat treatment conditions in plastic region, and (b) effect of heat treatment on UTS and tensile elongation.	34
2.20	Strength vs elongation (%) for different metastable β alloys in different conditions.	34
2.21	FLD of Ti-6Al-4V at 400 °C	36
2.22	Deep drawn cups of CP-Ti at various forming temperatures	37
4.1	Dimensions of CGP dies (a) CGP top and bottom grooving dies, (b) enlarged view of the grooved section with dimensions (as encircled in (a)), and (c) constraining block.	43
4.2	CGP blank meshed with triangular elements.	44

4.3	Constrained groove pressing tool setup: (a) grooved dies, and (b) flat dies.	45
4.4	The fabricated CGP dies: (a) grooved dies and (b) flat dies along with constraining block.	46
4.5	Experimental setup with CGP die assembly on the hydraulic press.	46
4.6	(a) CGP sample before and after cold rolling up to 5% thickness reduction, (b) sub-size tensile sample dimensions as per ASTM E8M standard, (c) tensile test specimen taken from CGP processed sample in transverse direction.	51
4.7	Tensile test specimen orientations with respect to the rolling direction (RD).	52
4.8	Erichsen cup test.	54
4.9	(a) Hemispherical bottom punch used in LDH test, (b) Flat bottom punch used in deep drawing test and (c) Conical punch used in HET.	55
4.10	Schematic representation of (a) limiting dome height test, (b) cylindrical cup deep drawing test setup, and (c) hole expansion test.	56
4.11	(a) Grid marked sample, (b) fibre laser marking machine, (c) grid pattern analyzer and (d) software interface to measure major and minor strains.	57
5.1	Stress-strain curves of β -21S Ti-alloy in solution treated condition.	59
5.2	Experimental flow curve of β -21S Ti-alloy in solution treated condition and the flow curve predicted by modified Hensel Spittle model.	61
5.3	Stage wise effective plastic strain distribution during sequential pressing of grooving and flattening in CGP process.	62
5.4	Stage wise effective plastic strain distribution during sequential pressing of grooving and flattening in CGP-CR process.	63
5.5	Sample rotation by 180° about the normal axis (a) after stage 2 – flattening and (b) before stage 3 – grooving. The perpendicular rolling direction of the sheet remains perpendicular to the die grooves for stage 3 of CGP process.	64
5.6	Sample rotation by 90° about the normal axis (a) after stage 4 – flattening and (b) before stage 5 – grooving. The perpendicular rolling direction of the sample becomes parallel to the die grooves from stage 5 of CGP-CR process.	65

5.7	Stage wise effective plastic strain distribution about the normal direction of the sample in two passes of CGP process.	65
5.8	Stage wise effective plastic strain distribution about the normal direction of the sample in one pass of CGP-CR process.	66
5.9	Effective plastic strain variation of CGP-P1 and CGP-P2 samples in the transverse direction and the longitudinal direction to the die grooves.	67
5.10	Strain inhomogeneity factor of CGP-P1, CGP-P2 and CGP-CR samples in the transverse and the longitudinal directions.	67
5.11	Schematic illustration of shear and shear+bending regions during CGP.	68
5.12	Gradient in strain accumulation at shear and shear+bending regions in CGP.	68
5.13	Effective plastic strain distribution in (a) CGP-P2 (8 th stage), and (b) CGP-CR1 (8 th stage); Variation of effective plastic strain along (c) transverse direction and (d) longitudinal direction to die groove after flattening in 6 th and 8 th stages.	69
5.14	Force-displacement curves obtained from simulation of CGP and CGP-CR processes.	71
5.15	Solution treated sample in (a) uncoated condition (oxide layer), and (b) delta-glaze coated condition (glossy surface).	73
5.16	β -21S Ti-alloy sample surface variations in solution treated condition (a, c) without protective coating, (b, d) with protective coating. (a, b) SEM images and (c, d) elemental mapping of oxygen indicated in red colour.	74
5.17	XRD plots of solution treated samples in (a) uncoated and (b) delta-glaze coated conditions, at different depths from surface.	76
5.18	CGP-P2 sample of β -21S Ti-alloy in (a) uncoated and (b) delta-glaze coated conditions.	77
5.19	Optical microstructures of uncoated and delta-glaze coated β -21S Ti-alloy samples in (a, b) solution treated (ST), and (c, d) CGP-P1 conditions.	78
5.20	Engineering stress – engineering strain curves of uncoated and delta-glaze coated β -21S Ti-alloy samples in solution treated and CGP-P1 conditions.	80

5.21	Hardness variation along the rolling direction of solution treated and CGP-P1 samples (transverse to grooving).	82
5.22	SEM fractographs of uncoated and delta-glaze coated β -21S Ti-alloy samples in (a, b) solution treated (ST) and (c, d) CGP-P1 conditions.	83
5.23	β -21S Ti-alloy samples subjected to CGP process up to 3 passes (CGP-P1, CGP-P2 and CGP-P3) and CGP-CR process up to 2 passes (CGP-CR1 and CGP-CR2).	84
5.24	Comparison of predicted force by FE simulation with experimental values in different conditions at the last stage of the respective pass.	85
5.25	Comparison of hardness inhomogeneity factor along the transverse and the longitudinal directions in different conditions.	86
5.26	Optical microstructures of CGP-P2 after intermediate partial annealing at (a) 820°C-5min, (b) 820°C-10min, (c) 820°C-15min, (d) 500°C-10min, (e) 500°C-30min, and (f) 580°C-30min.	87
6.1	Optical microstructures of CGP and CGP-CR samples at different passes showing grain refinement with the number of passes and formation of band-like structures along with slip bands during the deformation.	91
6.2	Optical microstructures at higher magnifications revealing the different morphologies of the twin-like structures in (a, b) CGP-P2, and (c) CGP-CR2.	91
6.3	XRD peaks of ST, CGP and CGP-CR samples after each pass.	93
6.4	TEM image of CGP-P2 revealing the dislocation free zones.	94
6.5	EBSD IPF maps in different conditions: (a) solution treated (ST), (b) CGP-P1, (c) CGP-P2, (d) CGP-P3, (e) CGP-CR1, and (f) CGP-CR2.	95
6.6	EBSD phase maps in different conditions: (a) ST, (b) CGP-P3, and (c) CGP-CR2. Red color indicates the titanium hexagonal crystal structure, and blue color indicates the titanium cubic crystal structure.	95
6.7	Grain boundary misorientation angle distribution of (a) ST, (b) CGP-P1, (c) CGP-P2, (d) CGP-P3, (e) CGP-CR1, and (f) CGP-CR2 samples.	96

6.8	Misorientation between matrix and the twin-like structure of CGP-P2 sample at A and B. The misorientation ($\sim 50^\circ$) at A indicates $\{332\}\langle 113 \rangle$ twins while at B, the misorientation ($\sim 10^\circ$) indicates the kink bands.	97
6.9	(a) TEM image of kink bands in the matrix with dislocations pile-up within the kink band, and (b) SAED pattern of kink band at SA in (a).	98
6.10	KAM maps of (a) ST, (b) CGP-P1, (c) CGP-CR2, (d) CGP-CR1 and (e) CGP-CR2 samples. Blue color indicates the low misorientation indicating the lower strain accumulation and red color indicates the higher misorientation indicating the higher strain accumulation.	99
6.11	(a) CGP-P2 sample polished till the black line indicated in the image, (b) Microstructure revealing the presence of high fraction of twin-like structures in shear region at location 1 which represents the inner surface after polishing, and (c) Microstructure revealing the presence of low fraction of twin-like structures in shear region at location 2 which represents the outer surface after polishing.	100
6.12	Variation of peak intensity ratio of $I(002)/I(112)$ in different passes of CGP and CGP-CR processes.	102
6.13	(a) EBSD IPF map of intersections of twin-like structures, and (b) EBSD kernel average misorientation map of (a). The linear profile misorientation (c) at A identified as kink bands and (d) at B indicating the evolution of twin within kink band.	104
6.14	Evolution of secondary twins within the primary twin of CGP-CR2 sample.	104
6.15	(a) TEM image revealing the evolution of twin from kink band, and (b) SAED pattern from selected area (SA) of (a) where T represents twin and M represents matrix, the distorted diffraction spots indicating the kink band.	105
6.16	Schematic illustration of grain refinement and microstructure evolution during CGP passes.	106
7.1	(a) Stress-strain curves in solution treated condition, and (b) Intense planar slip bands formed during tensile deformation.	109
7.2	True stress – true strain curves of solution treated samples in three different orientations to RD.	110

7.3	True longitudinal strain – true width strain plots used for determination of R^H -value of β -21S Ti-alloy.	111
7.4	Tensile samples of (a) CGP-P2 in the transverse direction, (b) CGP-P2 in the longitudinal direction and (c) CGP-CR1.	113
7.5	Engineering stress – strain curves of ST, CGP and CGP-CR samples after different passes. In the case of CGP, T indicates the transverse sample and L indicates the longitudinal sample.	113
7.6	Work hardening rate vs true plastic strain curves in different conditions: (a) ST, and (b) CGP-P1 in the transverse direction, (c) CGP-P1 in the longitudinal direction, (d) CGP-P2 in the transverse direction, (e) CGP-P2 in the longitudinal direction, (f) CGP-P3 in the longitudinal direction, (g) CGP-CR1 and (h) CGP-CR2.	117
7.7	Crussard-Jaoul plots (log work hardening rate vs log true plastic strain) in different conditions: (a) ST, (b) CGP-P1 in the transverse direction, (c) CGP-P1 in the longitudinal direction, (d) CGP-P2 in the transverse direction, (e) CGP-P2 in the longitudinal direction, (f) CGP-P3 in the longitudinal direction, (g) CGP-CR1 and (h) CGP-CR2 demonstrating the amount of hardening (left side of the dotted line) and softening behavior (right side of the dotted line) in plastic region.	119
7.8	Slip band interactions (red arrows) within the grain and the continuous slip lines (yellow arrows) across the grains in ST tensile sample.	121
7.9	Dislocation average free path of CGP and CGP-CR samples.	122
7.10	EBSD maps of CGP-P2 surface: (a) IPF map, and (b) KAM map.	124
7.11	SEM images in CGP-P2 condition near the fracture region of (a) sample tested in the transverse direction revealing the elongated grains, (b) sample tested in the longitudinal direction revealing the equiaxed grains.	125
7.12	Schematic illustration of dislocation generation and microstructural changes in tensile loading in the transverse direction: (a) CGP-P2 initial sample, (b) dislocation generation during deformation, and (c) high dislocation forest at the multiple band-like structures resulting in grain elongation.	126
7.13	Schematic illustration of dislocation generation and microstructure change for tensile loading in the longitudinal direction: (a) CGP-P2 initial sample, (b)	126

	dislocation generation during deformation, and (c) dislocation annihilation in shear zone and dislocation accumulation at the band-like structures.	
7.14	EBSD IPF maps of CGP-CR pass-2 (a) before recrystallization and (b) after recrystallization at 850°C for 15 min.	127
7.15	(a, b) true stress-true strain plots and work hardening plots, and (c, d) C-J plots of CGP-CR2 samples. (a, c) before recrystallization and (b, d) after recrystallization.	128
7.16	Stress-strain curves of solution treated (ST) samples aged at different temperatures and time.	129
7.17	SEM images of ST samples aged at 480°C for (a) 8 h and (b) 16 h followed by air cooling, (c) high magnification image of (a), and (d) high magnification image of (b) revealing the fine α precipitates within the grains and along the grain boundaries.	129
7.18	Stress-strain curves of solution treated (ST) samples double aged at different conditions.	130
7.19	SEM images of ST samples aged at (a) 650°C for 8 h followed by 550°C for 8 h through air cooling, (b) 690°C for 8 h followed by 640°C for 8 h through furnace cooling, (c) high magnification image of (a) revealing the fine α precipitates within the grains and along the grain boundaries, and (d) high magnification image of (b) revealing the coarse α precipitates within the grains.	131
7.20	Erichsen cup samples tested in ST, CGP-P1, CGP-P2, CGP-P3 and CGP-CR1 conditions.	132
7.21	(a) True stress – true strain curves of Ti-6Al-4V in three different orientations to RD, (b) True longitudinal strain – true width strain plots used for determination of RH-value of Ti-6Al-4V.	134
7.22	Forming limit diagrams of (a) β -21S Ti-alloy (at necking) and (b) Ti-6Al-4V (maximum safe and failure).	135
7.23	Tested FLD samples of different widths of (a) β -21S Ti-alloy, (b) Ti-6Al-4V at failure, and (c) Ti-6Al-4V just before failure (maximum safe condition).	135
7.24	LDH test samples of (a) β -21S Ti-alloy and (b) Ti-6Al-4V alloy.	137

7.25	Load displacement curves of β -21S Ti-alloy and Ti-6Al-4V alloys in LDH tests.	138
7.26	Hole expansion test samples of β -21S Ti-alloy and Ti-6Al-4V alloys.	139
7.27	Deep drawn cups of (a) β -21S Ti-alloy and (b) Ti-6Al-4V with two initial blank diameters.	140
7.28	Variation of % thinning in deep drawn cups of β -21S Ti-alloy and Ti-6Al-4V alloys.	141

List of Tables

Table No.	Title	Page No.
1.1	Critical concentration (wt.%) of β stabilizing elements.	3
1.2	Prominent metastable β alloys and their applications.	4
2.1	Standard heat treatment cycles of β -21S Ti-alloy and the microstructures.	24
2.2	Two step aging of β -21S Ti-alloy in different heat treatment conditions.	25
2.3	Comparison of mechanical properties of GP and CGP of CP-Ti.	30
2.4	Mechanical properties of β -21S Ti-alloy after different heat treatment cycles.	32
2.5	Tensile properties of β -21S Ti-alloy in different aging conditions.	33
2.6	Tensile properties and anisotropic parameters of β -21S Ti-alloy.	38
4.1	Chemical composition of β -21S Ti-alloy (in wt.%).	42
4.2	Dimensions of the tools and the blank for CGP process.	44
4.3	Tools and blank parameters.	44
5.1	Coefficients in different flow stress models determined by regression analysis and the corresponding sum of squares error (SSE).	60
5.2	Strain inhomogeneity factor in CGP and CGP-CR processes after 6 th and 8 th stages of processing.	70
5.3	Peak force estimation in CGP-P1, CGP-P2 and CGP-CR by analytical method and from simulation of CGP process.	72
5.4	Quantitative metallography of uncoated and delta-glaze coated CGP-P1 samples.	79
5.5	Mechanical properties of uncoated and delta-glaze coated samples in different conditions.	80
6.1	Quantification of grain size, grain refinement and twin-like area fraction of ST, CGP and CGP-CR samples.	92

7.1	Tensile properties of solution treated β -21S Ti-alloy at different orientations.	110
7.2	Anisotropic parameters of solution treated β -21S Ti-alloy.	111
7.3	Comparison of increase in UTS and decrease in % elongation (failure strain) in different materials from their initial condition (solution treated or annealed) to post CGP-P1 condition.	114
7.4	Mechanical properties of ST, CGP and CGP-CR samples and the % hardening and % softening plastic regions (T - transverse and L - longitudinal).	120
7.5	Erichsen cup height values of ST, CGP and CGP-CR samples after different passes.	132
7.6	Comparison of experimental results of LDH test.	137
7.7	Comparison of hole expansion test (HET) results.	139
7.8	Comparison of deep drawing test results.	140

List of Abbreviations

HCP	- Hexagonal Close-Packed
BCC	- Body-Centered Cubic
CP-Ti	- Commercially Pure Titanium
Mo _{eq}	- Molybdenum Equivalence.
UFG	- Ultrafine-Grained
NG	- Nano-Grained
SPD	- Severe Plastic Deformation
ECAP	- Equal Channel Angular Pressing
ARB	- Accumulative Roll Bonding
FSP	- Friction Stir Processing
HPT	- High Pressure Torsion
RCS	- Repetitive Corrugation and Straightening
CGP	- Constrained Groove Pressing
CGR	- Constrained Groove Rolling
STS	- Severe Torsional Straining
FEA	- Finite Element Analysis
CGP-CR	- Constrained Groove Pressing – Cross Route
CGP-P1	– CGP Pass-1
CGP-P2	– CGP Pass-2
CGP-P3	– CGP Pass-3
CGP-CR1	– CGP-CR Pass-1
CGP-CR2	– CGP-CR Pass-2
GBS	- Grain Boundary Sliding
CDRX	- Continuous Dynamic Recrystallization
ST	– Solution Treatment
WQ	– Water Quenching
CD	– Cold Rolling,
RH	- Rate of Heating
PFZ	- Precipitate Free Zones

YS - Yield Strength
UTS - Ultimate Tensile Strength
GP - Groove Pressing
FLD - Forming Limit Diagram
LDH - Limiting Dome Height
HER - Hole Expansion Ratio
HET - Hole Expansion Test
EDM - Electro Discharge Machine
LDR - Limiting Draw Ratio
XRF - X-Ray Fluorescence
EPMA - Electron Probe Micro-Analyzer
XRD - X-Ray Diffraction
FE-SEM - Field Emission Scanning Electron Microscopy
EBSD - Electron Backscatter Diffraction
TEM - Transmission Electron Microscopy
IF - Inhomogeneity Factor
BHF - Blank Holder Force
LVDT - Linear Variable Displacement Transducers
SSE - Sum of Squares Error
Lagbs - Low-Angle Grain Boundaries
Hagbs - High-Angle Grain Boundaries
KAM - Kernel Average Misorientation
C-J - Crussard-Jaoul

Nomenclature

α – Alpha Phase

β - Beta Phase

ω - Omega Phase

ω_a - Athermal Omega

ω_{iso} - Isothermal Omega

θ - Groove Angle

ε_{eff} - Effective Plastic Strain

n - Strain Hardening Exponent

\bar{R} - Normal Anisotropy

ΔR - Planar Anisotropy

K - Strength Coefficient

R - Plastic Strain Ratio

R^H - Hill's Plastic Strain Ratio

σ_f - Flow Stress

ε – Strain

$\dot{\varepsilon}$ - Strain Rate

T – Temperature

m_1, m_2, \dots, m_9 - Material Constants

S_i - Strain at the i^{th} Point

S_{avg} - Average Equivalent Strain

F_{max} - Peak Force