

Finite Element Analysis of Aluminum-Vanadium Alloyed Titanium Billets Forged under Warm Forming Conditions Using DEFORM-3D

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ABSTRACT

Titanium alloys, particularly Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo, are extensively used in aerospace, automotive and biomedical applications because of their high specific strength, corrosion resistance and thermal stability. This study presents a comparative finite element analysis of the warm-forming behavior of these alloys using DEFORM-3D V6.1. Three-dimensional simulations of open-die forging were performed at billet temperatures of 200, 400, and 600 °C under press loads of 700, 1000 and 2500 tons. The thermo-mechanical responses were evaluated through damage, effective stress, effective strain, total displacement, ultimate temperature, material velocity and Z-load. The results show that Ti-6Al-6V-2Sn exhibited superior forgeability, achieving the lowest damage (0.106), minimum effective stress (331 MPa) and minimum Z-load (141 tons), indicating stable deformation and reduced forming resistance. In contrast, Ti-6Al-2Sn-4Zr-2Mo demonstrated higher flow strength, with minimum damage (0.295), effective strain (2.23 mm/mm) and effective stress (736 MPa) at 600 °C under a 1000-ton load, while requiring substantially higher forming loads because of its enhanced structural strength. Increasing billet temperature significantly reduced forming stress and Z-load for both alloys, confirming the beneficial effect of thermal softening during warm forging. The comparative process-property relationships established in this study provide practical guidelines for selecting suitable warm-forming conditions and demonstrate the capability of finite element simulation as a reliable tool for optimizing titanium alloy forging processes for advanced engineering applications.

Keywords: Finite Element Analysis, Deform-3D, Titanium alloy, Warm Forming, Optimization

1. INTRODUCTION

Titanium alloys have become critical engineering materials in industries such as aerospace, automotive, biomedical, marine, nuclear and chemical processing owing to their exceptional mechanical properties, corrosion resistance and biocompatibility, which enable the development of lightweight, high-strength components capable of withstanding extreme service conditions [1,2]. Among them, Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo alloys stand out because of their unique combination of strength, toughness, ductility and thermal stability, which makes them suitable for a wide range of high-performance applications where reliability and precision are paramount [3]. The manufacturing of titanium alloys, however, remains challenging due to their high strength at elevated temperatures and limited room-temperature formability, which necessitates the use of advanced forming techniques to improve manufacturability while retaining their desirable mechanical characteristics [4]. Warm forming, conducted above room temperature but below the recrystallization range, has emerged as an

effective alternative to conventional cold and hot forming because it reduces forming loads, improves ductility and enhances dimensional accuracy while limiting excessive grain growth. These advantages are particularly beneficial for aluminum-vanadium alloyed titanium alloys, where refined α - β microstructures contribute to improved fatigue resistance and mechanical performance [5]. By lowering material flow stress, warm forming enhances malleability without compromising structural integrity, enabling the production of high-quality titanium components with superior surface finish. However, optimization of forming temperature, strain rate and die geometry for such alloys remains insufficiently explored for industrial-scale applications [6]. To address these complexities, researchers have turned to computational modeling and advanced simulation tools. Finite Element Analysis (FEA) has revolutionized the design and optimization of metal forming processes by providing detailed insights into material deformation behavior, thermal effects and stress distribution during forming operations [7]. Among various FEA-based platforms, Deform-3D is widely

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recognized for its ability to simulate complex metal forming processes, including forging, extrusion and rolling, with high predictive accuracy [8].

Deform-3D enables engineers to experiment with different process parameters in a virtual environment, thereby reducing dependence on costly trial-and-error experimentation, minimizing production waste and facilitating data-driven process optimization. For titanium alloys, such simulations are particularly valuable as they allow for the prediction of material flow, temperature gradients and residual stresses, which are critical for achieving high-quality components [9]. Rajesh et al. demonstrated the utility of Deform-3D by modeling the open-die forging of Ti-6Al-4V billets in the temperature range of 500–1000°C, observing that effective strain decreased from 6.84 mm/mm at 500°C to 3.39 mm/mm at 1000°C, while the maximum effective stress was recorded at 715 MPa at 500°C [5]. Similarly, Rajesh et al. also used computational modeling to optimize precision forging operations for steel alloys such as 42CrMo4 and 16CrMo4 [10], while Graf et al. investigated the dynamic interaction between oxidation, microstructural evolution and alloying in steels during elevated-temperature forming, highlighting the significance of understanding thermo-mechanical interactions [11]. Lee et al. proposed an innovative warm-forging method for aluminum alloys to improve automotive component manufacturing by reducing weight and increasing precision [12], whereas Tomejak et al. optimized rotational compression parameters to achieve superior dimensional control during forging [13]. For titanium alloys, Wang et al. found that the strength of solution-treated Ti-6Al-6V-2Sn decreased with increasing aging temperature, further emphasizing the need for precise control of thermal and mechanical variables during forming [14]. These studies collectively demonstrate the power of FEA and simulation tools like Deform-3D in process optimization; however, they also highlight a significant gap in the application of such methods specifically to the warm forming of titanium alloys containing aluminum and vanadium.

The existing literature, while rich in studies on hot forging, cold forming and general titanium processing, lacks a comprehensive exploration of the warm-forming regime, where the synergistic benefits of reduced forming forces, enhanced ductility and minimized grain coarsening can be fully realized. Furthermore, limited attention has been paid to integrating simulation results with experimental validation, an essential step for translating computational insights into industrially viable manufacturing strategies [15]. This gap is particularly critical given the growing

demand for titanium components in aerospace and medical applications, where even minor deviations in dimensional accuracy, residual stress, or microstructural uniformity can compromise component performance. Additionally, while research has investigated the behavior of other materials such as stainless steels (AISI 304, AISI 316), tool steels (AISI H21) and various aluminum alloys under different forming and heat-treatment conditions, studies that systematically examine how temperature, strain rate, and forming velocity interact during the warm forming of titanium billets alloyed with aluminum and vanadium are limited [16]. Furthermore, the lack of research on residual stress control, surface quality improvement and defect minimization within this specific context represents a critical barrier to industrial adoption. These shortcomings underscore the need for a targeted study that leverages the capabilities of FEA and Deform-3D to not only simulate but also optimize warm-forming operations for Ti-Al-V billets, thereby bridging the gap between computational modeling and practical manufacturing.

The present study addresses an important research gap by providing a comprehensive comparative finite element analysis of the warm-forming behavior of two aerospace-grade titanium alloys, Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo, using DEFORM-3D. Unlike previous studies that primarily focused on a single alloy or limited processing conditions, this work systematically evaluates the combined effects of forming temperature and press load on damage, effective strain, effective stress, displacement, velocity, ultimate temperature and Z-load. The comparative assessment establishes the process-property relationships governing alloy forgeability and identifies the most favorable processing conditions for each alloy, offering practical guidelines for improving warm-forging efficiency, reducing forming loads, and enhancing component quality in advanced engineering applications.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Materials Description

In this study, two advanced titanium alloys Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo were selected for finite element analysis of the warm forming process using Deform-3D. A billet of dimensions 60 mm × 60 mm × 120 mm with a 15 mm corner radius was modeled using SolidWorks and imported into Deform-3D. The primary material of focus, Ti-6Al-6V-2Sn, an aluminum–

vanadium alloyed titanium grade was chosen due to its exceptional mechanical properties, thermal stability and corrosion resistance under elevated temperature and high-stress conditions [17].

Table I: Elemental Composition Table for Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo Alloys.

Elemental Composition (Wt. %)	Titanium alloy	
	Ti-6Al-6V-2Sn	Ti-6Al-2Sn-4Zr-2Mo
Titanium (Wt. %)	88.5 - 90.5	89.5 - 91.5
Aluminum (Wt. %)	5.5 - 6.5	5.5 - 6.5
Tin (Wt. %)	1.5 - 2.5	1.5 - 2.5
Vanadium (Wt. %)	5.5 - 6.5	-
Zirconium (Wt. %)	-	3.5 - 4.5
Molybdenum (Wt. %)	-	1.5 - 2.5

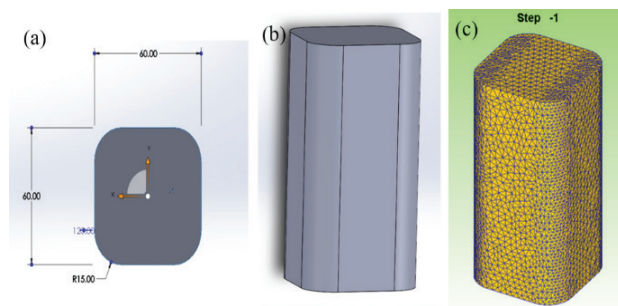


Fig. 1: (a) Dimensions of the billet material, (b) 3D model of the billet designed using SolidWorks, and (c) meshed geometry of the billet after the initial pre-processing step.

These attributes make it particularly well-suited for warm forming applications where dimensional stability, formability and high-temperature strength are critical. The alloy's microstructure, comprising a balanced mixture of α and β phases, provides enhanced toughness, creep resistance and fatigue life, all of which are essential for components subjected to cyclic mechanical and thermal loading. Additionally, the formation of a stable oxide layer at high temperatures offers significant protection against oxidation, further improving its durability in aggressive environments. Table I summarizes the elemental composition of the titanium alloys Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo. Fig. 1 illustrates the key stages of model preparation, including (a) the dimensions of the billet material, (b) the 3D model developed using SolidWorks and (c) the meshed geometry generated after the initial preprocessing step. For comparative analysis,

Ti-6Al-2Sn-4Zr-2Mo was also considered, as it exhibits excellent performance in extreme aerospace and power generation environments, particularly due to its elevated temperature capability (up to 1000°C), enhanced fracture toughness and superior creep strength. The inclusion of zirconium and molybdenum further improves its resistance to dynamic loading and corrosive media. Both materials offer compelling advantages for high-performance engineering applications. Their selection in this simulation study enables a comprehensive evaluation of material behavior under warm forming conditions, providing critical insights into deformation characteristics, process optimization and final component quality.

2.2 Methodology

Finite element simulations of the warm-forming process were performed using DEFORM-3D V6.1 to investigate the open-die forging behavior of Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo titanium alloys. The material behavior was described using the temperature- and strain-rate-dependent constitutive material model available in the DEFORM material database, where flow stress is expressed as a function of plastic strain, strain rate and temperature. The thermo-physical and mechanical properties were adopted from the validated DEFORM database and corresponding published literature for both alloys. A three-dimensional billet model was developed in SolidWorks and imported into DEFORM-3D for analysis under forming temperatures of 200, 400 and 600 °C. The simulations were conducted at an ambient temperature of 30 °C with a convection coefficient of 0.02 N/s/mm/°C. A refined finite-element mesh consisting of 9,184 nodes and 41,459 tetrahedral elements was employed to ensure numerical stability and prediction accuracy.

The open-die forging model consisted of two rigid dies (100 mm × 100 mm × 40 mm) with a corner radius of 15 mm. The upper die was constrained to move along the Z-axis, while the lower die remained fixed, reproducing the kinematic conditions of an industrial mechanical press. The simulation parameters and boundary conditions listed in Table II were consistently applied to all cases, while Fig. 2 presents the complete DEFORM-3D warm-forming simulation workflow. Simulations were performed under press loads of 700, 1000, and 2500 tons at billet temperatures of 200, 400 and 600 °C. The thermo-mechanical behavior of the titanium billets was modeled using the temperature- and strain-rate-dependent constitutive material model available in the DEFORM-3D material database, where flow stress is expressed as a function of plastic strain, strain rate, and temperature.

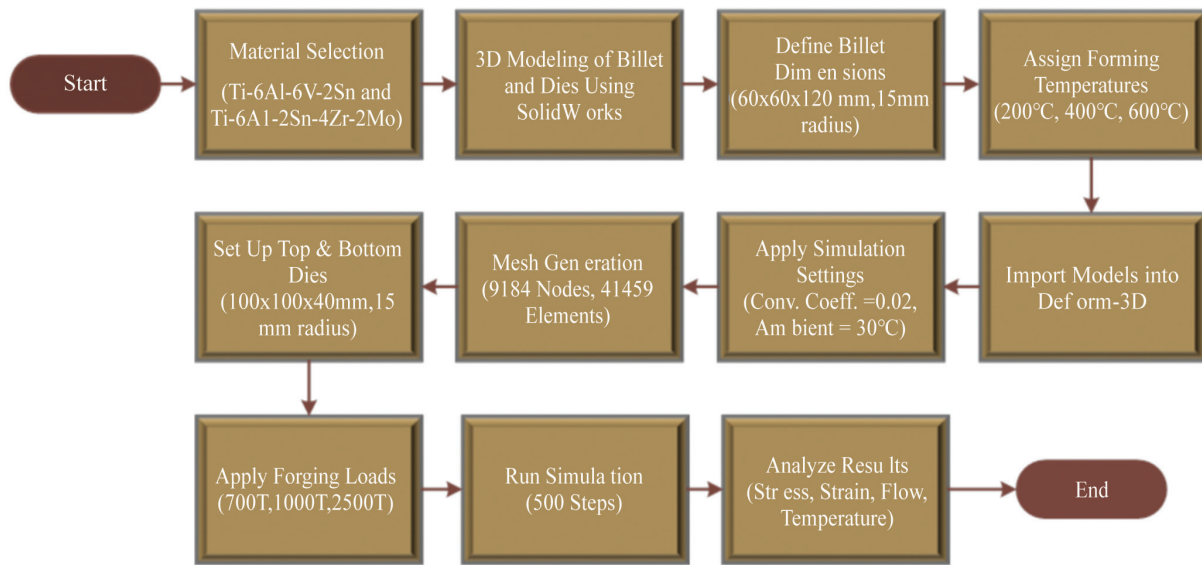


Fig. 2: Workflow of the Finite Element Simulation Process for Warm Forging of Titanium Alloys Using Deform-3D.

The governing finite element formulation employed a Lagrangian incremental approach to solve the coupled thermo-mechanical deformation problem. An ambient temperature of 30 °C and a convection coefficient of 0.02 N/s/mm/°C were applied as thermal boundary conditions. A limited mesh sensitivity analysis confirmed that further mesh refinement produced negligible changes in effective stress and forming load, ensuring satisfactory numerical accuracy. Each simulation was executed for 500 incremental steps, during which damage, effective stress, effective strain, displacement, temperature, velocity, and Z-load were continuously monitored. The numerical predictions were further verified through comparison with published warm-forging studies on titanium alloys, demonstrating good agreement with established thermo-mechanical deformation trends.

Table II: Simulation control parameters used for warm forging analysis in Deform-3D

Simulation Control	Value
Friction coefficient	0.25
Coefficient of convection	0.02 (N/sec/mm/°C)
Heat transfer coefficient	5
Total primary die travel	50 (mm)
Number of steps	500
Step increment	2

3. RESULTS AND DISCUSSION

This study employed Deform-3D V6.1 to conduct a detailed finite-element investigation of the warm-forming behavior of aerospace-grade titanium alloys Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo under varying thermo-mechanical conditions. The analysis focused on evaluating the influence of forging force and billet pre-heating temperature on damage evolution, material flow, stress distribution and forming load. Simulations were performed at three press loads (700, 1000, and 2500 tons) and three billet temperatures (200, 400, and 600 °C), summarized in Tables III and IV. For each alloy and process condition, key responses including damage, total displacement, effective strain, effective stress, ultimate temperature, material velocity and Z-load were monitored over 500 simulation steps, enabling a comprehensive comparison of the deformation behavior and forgeability of both titanium alloys. The first stage of the study evaluated billet deformation under a 700-ton press at forming temperatures of 200, 400 and 600 °C. Ti-6Al-6V-2Sn exhibited excellent deformation stability, with damage increasing only slightly from 0.106 to 0.116 as temperature increased, while effective strain remained within 1.36-1.49 mm/mm and displacement stayed nearly constant at 50.6–50.7 mm. A pronounced thermal softening effect was observed, as effective stress decreased from 568 MPa at 200 °C to 347 MPa at 600 °C, accompanied by a reduction in Z-load from 290 to 144 tons. In contrast, Ti-6Al-2Sn-4Zr-2Mo demonstrated substantially higher thermo-mechanical responses, with damage values between 0.298 and 0.351, effective strain

of 2.26-2.31 mm/mm and stress decreasing from 1410 MPa to 756 MPa with increasing temperature. Its Z-load also declined from 577 to 296 tons, although it remained significantly higher than that of Ti-6Al-6V-2Sn. The second stage employed a 1000-ton press under identical thermal conditions. Ti-6Al-6V-2Sn maintained low damage (0.108-0.114) and moderate strain, while effective stress decreased from 581 MPa to 331 MPa as temperature increased from 200 °C to 600 °C. Correspondingly, Z-load dropped from 300 to 148 tons, confirming enhanced plastic flow at elevated temperature. Ti-6Al-2Sn-4Zr-2Mo again showed higher damage (0.295-0.348), strain (2.23-2.27 mm/mm) and stress (1410-736 MPa), demonstrating its greater resistance to deformation and higher forming load requirements. Although effective stress decreased considerably with increasing temperature, the Ti-6Al-2Sn-4Zr-2Mo alloy consistently exhibited stress levels nearly twice those of Ti-6Al-6V-2Sn, confirming the

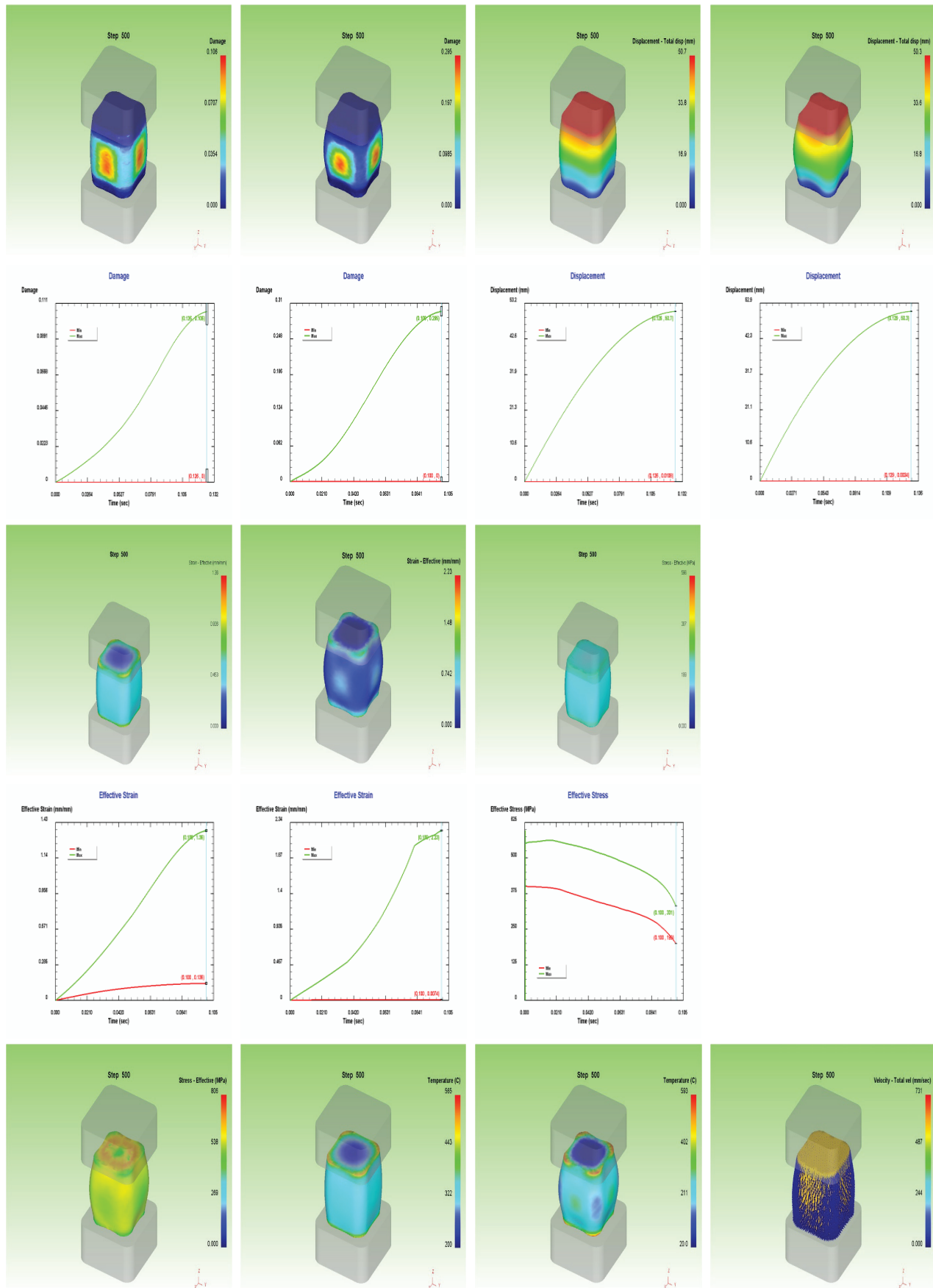
superior strength of the Sn-Zr-Mo system. Its forging load decreased from 579 tons at 200 °C to 299 tons at 600 °C, yet remained substantially higher than that of the Al-V-Sn alloy under identical conditions. Material velocity increased with press load and temperature for both alloys, reaching approximately 46 mm/s for Ti-6Al-6V-2Sn and 47 mm/s for Ti-6Al-2Sn-4Zr-2Mo, indicating improved material flow during warm deformation. Under heavy-duty industrial conditions using a 2500-ton press, Ti-6Al-6V-2Sn maintained low damage (0.109-0.116) and stable strain (1.41-1.49 mm/mm), while its effective stress and Z-load decreased from 561 MPa and 286 tons to 346 MPa and 141 tons respectively. Conversely, Ti-6Al-2Sn-4Zr-2Mo showed higher damage (0.336-0.374) and a maximum Z-load of 701 tons at 600 °C due to strain hardening associated with large strain accumulation (~2.30 mm/mm).

Table III: Comprehensive results for Ti-6Al-6V-2Sn under varying force and temperature conditions.

Force (Ton)	Temperature (°C)	Damage	Total Displacement (mm)	Effective Strain (mm/mm)	Effective Stress (MPa)	Ultimate Temperature (°C)	Total Velocity (mm/sec)	Z Load (Tons)
700	200	0.106	50.7	1.36	568	517	38.1	290
	400	0.109	50.7	1.41	445	618	38	217
	600	0.116	50.6	1.49	347	729	37.8	144
1000	200	0.108	50.7	1.36	581	554	46.5	300
	400	0.11	50.7	1.4	445	636	46.4	224
	600	0.114	50.6	1.47	331	744	46.2	148
2500	200	0.109	50.7	1.41	561	551	36.5	286
	400	0.109	50.6	1.41	443	615	36.4	213
	600	0.116	50.6	1.49	346	726	36.3	141

Table IV: Comprehensive results for Ti-6Al-2Sn-4Zr-2Mo under varying force and temperature conditions.

Force (Ton)	Temperature (°C)	Damage	Total Displacement (mm)	Effective Strain (mm/mm)	Effective Stress (MPa)	Ultimate Temperature (°C)	Total Velocity (mm/sec)	Z Load (Tons)
700	200	0.351	50.3	2.26	1410	665	38.4	577
	400	0.331	50.4	2.31	1080	748	38.2	437
	600	0.298	50.4	2.27	756	830	37.9	296
1000	200	0.348	50.4	2.25	1410	676	46.9	579
	400	0.332	50.4	2.27	1070	760	46.9	400
	600	0.295	50.4	2.23	736	843	46.3	299
2500	200	0.353	50.3	2.29	1410	664	36.9	576
	400	0.336	50.3	2.25	1080	742	36.8	436
	600	0.374	50.3	2.3	1760	591	36.1	701



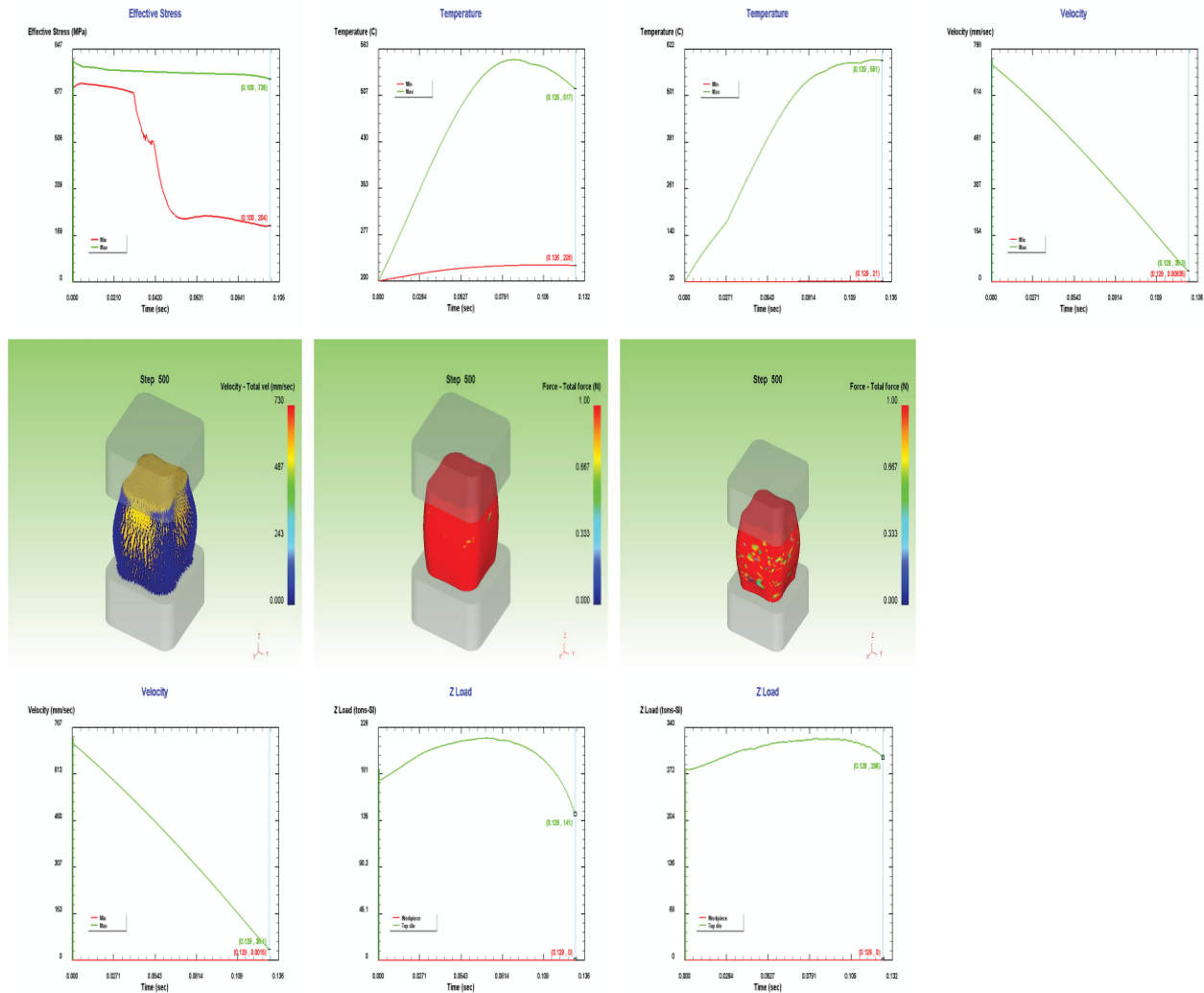


Fig. 3: Comparative thermo-mechanical distributions of Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo under optimized warm-forming conditions, showing minimum damage, total displacement, effective strain, effective stress, ultimate temperature, total velocity and Z-load at 500 simulation steps and corresponding simulation times. Subfigures (a–b) represent damage, (c–d) displacement, (e–f) effective strain, (g–h) effective stress, (i–j) ultimate temperature, (k–l) total velocity and (m–n) Z-load distributions for both titanium alloys under different forming temperatures and press loads.

Fig. 3 presents a comprehensive comparison of the thermo-mechanical responses of Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo under the investigated warm-forming conditions, highlighting the combined effects of billet temperature and alloy composition on deformation behavior. The numerical results demonstrate that increasing the billet temperature from 200 °C to 600 °C substantially reduces flow stress and forming load, with the Z-load decreasing by approximately 50% for Ti-6Al-6V-2Sn and 40-50% for Ti-6Al-2Sn-4Zr-2Mo. This trend is consistent with previously published experimental and finite-element investigations on titanium alloy warm forging, which reported progressive thermal softening,

reduced forging force and improved material flow with increasing deformation temperature. Similarly, Ti-6Al-6V-2Sn exhibited excellent forgeability, characterized by very low damage (<0.12), moderate effective strain (~ 1.4 mm/mm), low effective stress (331 MPa), and a minimum Z-load of 141 tons, indicating stable plastic deformation and a low likelihood of defect initiation. In contrast, Ti-6Al-2Sn-4Zr-2Mo displayed higher damage (0.295-0.374), larger effective strain (~ 2.3 mm/mm) and significantly higher effective stress (736 MPa), reflecting its greater resistance to plastic flow due to solid-solution and precipitation strengthening. Despite exhibiting similar total displacement (~ 50 mm), the Sn-Zr-Mo alloy

showed more pronounced strain localization and required substantially higher forming loads. The simulations further revealed strong thermo-mechanical coupling, with ultimate billet temperatures increasing from 517-744 °C for Ti-6Al-6V-2Sn and 591-843 °C for Ti-6Al-2Sn-4Zr-2Mo because of adiabatic heating during deformation. Moreover, the effective stress curves exhibited a progressive decrease with simulation time, confirming thermal softening and dynamic recovery mechanisms reported in experimental warm-forging studies. Overall, the close agreement between the present numerical trends and published experimental observations supports the reliability of the DEFORM-3D simulations and demonstrates the superior warm-forging characteristics of Ti-6Al-6V-2Sn compared with Ti-6Al-2Sn-4Zr-2Mo.

4. CONCLUSIONS

This study presents a comprehensive comparative finite element investigation of the warm-forming behavior of two aerospace-grade titanium alloys, Ti-6Al-6V-2Sn and Ti-6Al-2Sn-4Zr-2Mo, using DEFORM-3D under different billet temperatures and press loads. Unlike previous studies that primarily focused on a single alloy or limited processing conditions, this work systematically established the relationships between thermo-mechanical parameters and key deformation characteristics, including damage, effective stress, strain, displacement, velocity, ultimate temperature and Z-load. The results demonstrated that Ti-6Al-6V-2Sn exhibited superior forgeability, achieving the lowest damage (0.106), minimum effective stress (331 MPa), and lowest Z-load (141 tons), indicating reduced forming resistance and improved process efficiency. In contrast, Ti-6Al-2Sn-4Zr-2Mo maintained higher strength but required greater forming loads because of its increased flow stress and strain localization. The comparative process-property analysis provides practical guidelines for selecting suitable warm-forming conditions, thereby improving energy efficiency, die life and component quality. These findings contribute valuable reference data for the numerical design and optimization of warm-forging operations for advanced titanium alloys. Future work will focus on experimental validation, constitutive model refinement, microstructural evolution and the integration of finite element simulation with advanced manufacturing technologies for high-performance titanium components.

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