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Experimental study and numerical simulation of $\alpha$ lamellar globularization for TC21 titanium alloy during multidirectional forging

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Abstract

Evolution of microstructure and the globularization mechanism of $\alpha$ lamellar for TC21 titanium alloy during multi-directional forging (MDF) were analyzed with the help of OM, SEM, EDS and TEM techniques, FE simulation was also used to observe the above process. The main conclusions are as follows: With the increase of temperature, forging cycle and single pass strain, the fraction of globularization of $\alpha$ lamellar gradually improved. The volume fraction of globularization of $\alpha$ lamellar achieves a high value about 85%, the average grain size of TC21 titanium alloy can be refined to 2 $\mu$m through MDFed at 910 °C with strain of 0.69 in 3 cycles. Forging cycle is the most key factor to obtain the ideal microstructure. Increasing temperature and MDFed pass can not only promote the fraction of DRX (dynamic recrystallization), but also achieve uniformity of deformation. The error between simulation and experiment is below 14%. DRX is the major globularization mechanism of the $\alpha$ lamellar during MDF. In the early stage of MDF process, the globularization mechanism is boundary splitting accompanied by CDRX (continuous dynamic recrystallization) and DDRX (discontinuous dynamic recrystallization), which is formed by the $\beta$ phase into $\alpha$ lamella along the sub-grain boundaries. In the later stage of the process, the globularization mechanism is termination migration, which is caused by elements diffusion due to variant curvature of different position of $\alpha$ lamellar, while a slow process for globularization.

1. Introduction

Due to its high strength, toughness, damage tolerance, TC21 titanium alloy, as a two-phase titanium alloy (Ti-alloy), has been widely used in aircraft, aerospace, and energy related field [1–7]. To process the alloys, thermo-mechanical processing is an efficient process, but it needs to control its microstructure in such a way to possess good mechanical properties and improve service life, since the microstructure of Ti-alloys is very sensitive to hot working process and process parameter configuration [8–11]. A fine equiaxed microstructure of Ti-alloys will match the better comprehensive performance requirements of aircraft parts, such as high strength and excellent fatigue properties [12]. Severe plastic deformation (SPD) methods are proven to obtain effectively the fine grained microstructure, and thus improve the performance of the alloy [13]. Multidirectional forging (MDF), as a typical method of SPD, has attracted great interest of the researchers due to its advantages of simplicity, low cost, and preparing bulk ultrafine crystal materials [14–17].

MDF has been widely studied in the last decades as an efficient method for their grain refinement and strengthening. MIURA H et al [18] performed MDF with five passes on the AZ61 magnesium alloy. An average grain size of 0.8 $\mu$m and tensile strength of 440 MPa was obtained. Manjunath et al [19] used a MDF die with a plunger to forge as-cast 7050 aluminum alloy by 0, 1, and 2 passes. The grain size was refined from 60 to 10 $\mu$m. Moreover, the defects such as porosity developed during the casting process were eliminated. It’s obvious that methods and parameters of the processing are undoubtedly important to the dynamic globalization of the
A few attempts have been reported to expose the globalization behavior and globalization mechanism of α lamellar of Ti-alloy. In Zhang Z.X. et al [23–25] work, a homogeneous UFG structure with an average grain size of about 0.5 μm of TC4 alloy has been achieved by MDF, and they proposed that the grain refinement mechanism is associated with continuous dynamic recrystallization (CDRX) and discontinuous dynamic recrystallization (DDRX). Margonlin and Cohen [26] showed the boundary splitting mechanism of α lamellar globalization. The unstable interphase α/α boundaries occurs due to the strain-induced at first, then the β phase wedged into the unstable boundaries under the driving force of the interface energy, and finally, the equiaxed α grains are formed via the α plate broke-up. Additionally, another interpretation of α lamellar globalization by Weiss et al [27], Peters et al [28] and Seshacharyula et al [29] lied that the shear strain caused the shearing of lamellae to form a new shearing interface, and the shearing interface segmented the α lamellar to induce the globalization. The termination migration of the α lamellar globalization mechanism had also been proposed, which the globalization is related to the diffusion of solute atoms [30]. With the development of CAE (Computer Aided Engineering), the technology has been widely applied in industry as a tool to simulate various manufacturing processes. Hongchao et al [31] predicted that the dynamic recrystallization (DRX) behavior and microstructure evolution of 33Cr23Ni8Mn3N heat-resistant steel by isothermal hot compression experiment and FE (finite element) simulation. Hong et al [32] via compared the simulated results with that of the experiment, the accuracy of the developed DRX models for FGH96 superalloy is validated during isothermal compression. To date, although the globalization mechanisms mentioned above present satisfactory interpretation for α lamellar globalization of several Ti-alloy, limited studies have been performed on the α lamellar globalization behavior of TC21 titanium alloy during the MDF process. Thus, it is necessary to examine the influence of MDF parameters over α lamellar globalization combine with FE simulation, and expose the globalization mechanism of the alloy.

The present work aims to investigate the α lamellar globalization behavior of titanium alloy TC21 during MDF processing through experimental study and numerical simulation. The influence of MDF parameters, such as temperature, strain and cycle, over the α lamellar globalization was examined. The globalization mechanism of the alloy during MDF process has been proposed. The work is helpful for in-depth understanding of α lamellar globalization behavior of the alloy during MDF processing. It also provides a referential significance for prediction of α lamellar globalization in MDF processing.

2. Material and the experiment procedure

The as-received Ti-alloy is the ingot forged below β-transus temperature, then heat treated at 860 °C for 30 min, followed by air cooling [33]. Its chemical composition (wt%) is 6Al, 2Zr, 2Sn, 3Mo, 1Cr, 2 Nb, 0.1Si, and the balance Ti. The initial microstructure consists of Widmanstatten structure with α cluster, as shown in figure 1. The β-transus temperature of the Ti-alloy tested using a metallographic technique is about 955 °C.

The alloy samples were machined into cylindrical specimens with a size of the diameter of 20 mm and the height of 40 mm by a wire cutting machine. MDF tests were conducted at the temperature range of 850 °C–940 °C, the single pass strain range of 0.36 ~ 1.2, and the cycle of 1 ~ 3. The specimens are forged sequentially in the x, y and z directions (as so called ‘MDF cycle’), as shown in figure 2. In addition, an orthogonal test scheme of multi-direction forging was designed to obtain the feasible deformation conditions, as shown in table 1. The samples were cooled in water immediately after each MDF cycle to retain the deformation microstructure.

After MDF, the samples for metallographic examination were taken from the cross-sections parallel to the last forging direction (LFD). The metallographic samples were grinded with emery papers and polished with 0.05 μm Al2O3, followed by etching in a solution of 8% HF, 9% HNO3 and 83% H2O. Microstructure observation of the MDFed samples were characterized by XIP-6A metallographic microscope (OM), Nova Nano SEM450 field emission scanning electron microscope (SEM and EDS), JEM-200CX transmission electron microscopy microscope (TEM) and electron back-scattering diffraction (EBSD). And quantitatively microstructural characterization was analyzed via IPP 6.0 (Image Pro Plus 6.0) software. According to the literature, the structure with equiaxed ratio ≤ 2.5 is defined as globalized microstructure [34].

3. Results and discussion

3.1. Microstructure evolution

Optical microstructures associated with globalization of the alloy after 1 MDF cycle at the temperature of 940 °C with various single pass strain are shown in figure 3. Observation reveals the occurrence of the α lamellar globalization of the alloy during MDF processing. The initial microstructure of the alloy displays...
Figure 1. Ingot (a) and initial microstructure (b) and (c) of TC21 titanium alloy.

Figure 2. Schematic diagram of MDF in 1 Cycle.
Widmanstätten structure with several \( \alpha \) clusters. After the MDF to 1 cycle with the single pass strain of 0.51, a few small globularized grains was observed, while the non-globularized \( \alpha \) plate at initial grains boundaries can be seen, as shown in figure 3(a). It suggests that the globularized grain occurs initially in the initial grains interior during the MDF processing. The original \( \beta \) grain boundary is observed clearly. Furthermore, the globularized fraction of about 20\% is very small and thus no significant grain refinement happened at the deformation condition. When the single pass strain is increased to 0.69, more globularized grains occurred, resulting in the globularized fraction of about 60\%, as shown in figure 3(b). With the single pass strain of 1.2 (shown in figure 3(c)), the globularized grains became more evident, resulting in an almost complete globularized microstructure with the globularized fraction of about 80\%. It is obvious that the remarkable grain refinement by globularization was obtained. When the cumulative strain reaches the critical value, the low angle grain boundary will migrate. With the growth of sub-grain, the misorientation of subgrain increases, and the low angle grain boundary begins to transform into high angle grain boundary, which is also the sign of the beginning of dynamic recrystallization.

The influence of the MDF temperature and the MDF cycle at a single pass strain of 0.7 on the microstructure associated with globularization is illustrated in figure 4. It was observed that the volume fraction of the globularized grains increased with increasing the MDF temperature at the given MDF cycle and single pass strain. The kinked \( \alpha \) plate and a few small globularized grains can be observed at the MDF temperature of 850
No significant grain refinement of the alloy can be achieved for the reason of the small globularization fraction about 30% (shown in figure 4(a)). As the MDF temperature were increased to 880 °C and 910 °C, more globularized grains of the alloy were observed, and the size of globularized grains increased in comparison with that processed at 850 °C. When the MDF temperature is increased to 880 °C, more globularized grains occurred, resulting in the globularized fraction of about 50%, as shown in figure 4(b). When the MDF temperature is increased to 910 °C and 940 °C, the microstructure shows that the globularization fraction is about 85% and 90%, respectively (shown in figures 4(c), (d)). However, the remarkable grain refinement of the alloy MDFed at the temperature of 940 °C did not happen due to the fact of the globularized grains growth and far away compete with globularization. It suggests that it is difficult to obtain the complete globularization of the alloy, only when higher single pass strain and MDF cycle can be provided. By increasing the temperature of multi-directional forging, the atomic diffusion rate can be increased, which is conducive to the wedge of beta phase into alpha lamellar and promote globularization. However, if the strain is less, even if the forging temperature is increased to 940 °C, the globularization volume fraction of lamella is very limited (e.g. Figure 3(a)). Figures 4(c) (e) and (f) shows the influence of MDF cycle on globularization of the alloy at the temperature of 910 °C and the single pass strain of 0.69. It can be seen that with the increase of MDF cycle, the globularized fraction increase and the globularized grains size decrease. The microstructure of the alloy after 1 cycle presents the characteristic of incomplete globularization, which severe arch bending α plate and several equiaxed fine grains formed by globularization were distinctly observed. As MDF cycle is increased to 2 cycles, more globularized grains of the alloy with the dynamic globularized fraction of increase about 50% to 70% were very much evident (shown in figures 4(e) and (f)). By further MDFed to 3 cycles (as shown in figure 4(c), complete globularization and significant grain refinement of the alloy can be obtained, which the globularization grain size is about 2 μm. In

Figure 4. Optical microstructures of TC21 Ti-alloy under different MDF conditions at the single pass strain of 0.69: (a) 850 °C, 3cycle; (b) 880 °C, 3cycle; (c) 910 °C, 3cycle; (d) 940 °C, 3cycle; (e) 910 °C, 1cycle; (f) 910 °C, 2cycle.
fact, by increasing the forging cycle, the strain can also be accumulated. Furthermore, the risk of alloy damage and cracking due to too large single pass deformation can be avoided. Therefore, by controlling the appropriate forging cycle, the microstructure of the alloy can be globularized more evenly. Therefore, the reasonable selection of forging cycle is a very key factor to obtain the ideal globularized structure.

3.2. globularization mechanisms
3.2.1. Boundary splitting
As shown in figure 5, the TEM and SEM observations expose the process of segmentation of the α lamellar during the stage of MDF process. The three types of segmentation way can be observed via the TEM and SEM observations. Figure 5(a)–(c) display that the shearing surfaces (type A), the thermal grooves (type B) and sub-boundary (type C) located in the α lamellar. The occurrence of shearing surfaces can be ascribed to shear deformation, whereas the thermal groove is related to the diffusion of atoms. However, the sub-boundary is attributed to arrangement of dislocations. The occurrence of shearing surface, the thermal groove and sub-boundary can be largely attributed to boundary splitting mechanism. The appearance of boundary splitting is associated to the instability of the interface of α/α boundaries or α/β boundaries which are formed during MDF. For lamellar structures and micro-defects, can reduce the stability of the system, and result in the structure transformed into an equiaxed morphology with a low energy. Therefore, the atomic diffusion transfer from the defect positions to the surfaces to reduce the surface energy. Consequently, the driving force is associated to the reduction of interface energy. The formation of these defects can be largely attributed to shearing surfaces and substructure caused by thermo-mechanical processes. During MDF process, the α lamellar is completely destroyed under the severe deformation, as shown in figure 4(c).

3.2.2. Dynamic recrystallization
As shown in figures 6 and 7, SEM and EBSD observations performed the globularization of the α lamellar samples after MDF. As shown in figure 7(a), the segments of a lamellar were mainly surrounded by high angle grain boundaries (HAGBs) (which were represented by the purple lines), which means that the occurrence of recrystallization inside the α lamellar. The rotation of low angle grain boundaries (LAGBs) (which were represented by the yellow lines) leads to their progressively increase in misorientation angle, and eventually result in globularization of α grains. Moreover, from figures 7 (a) and (b), it can be seen that sub-grains surrounded by LAGBs are formed in the globularized grains. With the increase of strain, the sub-grains gradually rotate, resulting in the increasing misorientation between sub-grains, making the LAGBs gradually change into HAGBs, to form new recrystallized grains. And as shown in figure 7(c), a high fraction of the HAGBs was obtained about 38.93%, suggested the occurrence of continuous dynamic recrystallization (CDRX), which was in accordance with the observations in figure 7(a). Meanwhile, it is clear from figure 6 the discontinuous dynamic recrystallization (DDRX) grains formulated along the boundaries. In addition, the nucleation site of DDRX is usually at the trigeminal grain boundary. And the average grain size (figure 7(d)) of the α grains was
1.95 μm. As shown in figure 7(b), represents the Schmid factor distribution map and chart. It can be seen that the Schmid factor varied from 0.04, represented as black, to 0.48, represented as white. Grains in figure 7(b) were mainly represented by gray and white, it suggests that the c-axis is parallel to the final pass forging axis, namely, grains have ‘soft’ orientation. Some α phases in this ‘soft’ orientation position are segmentation and globularization, while some α phase in ‘hard’ orientation position still retains the lamellar microstructure morphology. Figure 7(e) displays pole figure (PF) maps of α phase and β phase in TC21 Ti-alloy. After multidirectional deformation, the α phase shows a strong {0001}\//ND basal texture. It suggests that the c-axis is perpendicular to the ND. It is noteworthy that [0001] basal a-axis slip is the main pattern of plastic deformation. The pattern can be attributed to the movement of dislocation and lower value of CRSS (critical shear stress) on base. The PF maps reveal that a more random Burgers orientation relationship is obtained between some α phase and β phase. It can be inferred that bending or rotating of α phase result in the Burgers orientation relationship broken (figure 7(e)) [35]. Additionally, the recrystallization behavior of TC21 Ti-alloy during MDF process was displayed via EBSD analysis. The recrystallized volume fraction was about 66% (figures 7(f) and (g)) by means of forging under the above condition.

3.2.3. Termination migration
In order to further identify the globularization of the α lamellar during the MDF process, SEM and EDS was examined in figures 8 and 9. As shown in figure 8, clear differences in colors can be found surrounding α lamellars, which suggests most likely producing of diffusion process between α phase and β phase. EDS observations performed the occurrence of diffusion, as shown in figure 9. Different element content displays the distinction in the three positions. It is clear that from position 1 to 3, the content of α-stabilizer element ‘Al’ present a decreasing trend, whereas the content of β-stabilizer elements Mo and Cr gradually increase, while the content of the neutral elements Sn and Zr still maintain steady and no significant changes. In the case of these changes, there is diffusion zone between α phase and β phase. Termination migration is a vital mechanism to revealed microstructure globularization behavior, which is based on diffusion theory. The termination migration included the atoms transfer from the termination and defect positions to the flat surface of the α lamellar, and the driving force can be largely attributed to different curvature between them. Therefore, the degrees of globularization are different due to their different curvature. The positions with the larger curvature have higher potential energy, higher potential energy more easily drive the diffusion of solute atoms, the solute atoms diffuse from the terminations to the flat interfaces result in the globularization of α lamellar. The process of termination migration can be defined as static globularization. It suggested that terminal migration occurs not only during heat treatment process but also during the thermal deformation process.

Among the above three globularization mechanisms, dynamic recrystallization mechanism is the main globularizing mechanism in the multi-directional forging process of TC21 titanium alloy. For the boundary splitting mechanism, the shear band formed under the action of external force, shear band assists continuous...
Figure 7. EBSD results of microstructure of TC21 Ti-alloy MDFed at 910 °C for single pass strain of 0.69, and 3 cycles: (a) grain boundary distribution map; (b) Schmid factor distribution map and chart; (c) misorientation angle distribution chart of α phase; (d) grain size diameter distribution chart of α phase; (e) pole figure of α phase; (f) recrystallized image; (g) recrystallized fraction chart.
dynamic recrystallization, and the formation of grain boundary is related to the occurrence of continuous dynamic recrystallization in $\alpha$ lamellar. For termination migration mechanism, it has a certain effect on the spheroidization of the lamella at the end of multidirectional forging process, but the atomic diffusion needs higher temperature and sufficient holding time to significantly reduce the equiaxial ratio of the lamellar structure.

### 3.3. FE simulation and verification

#### 3.3.1. FE model

Hot deformation is a dynamic process of complex fields. The FEM is used to systematically verify the model established. The FEM can very strongly predict the microstructure and verify the model established of materials during thermal processing, and the FEM can also largely avoid the drawbacks of the traditional trial and error method. Based on a multi-field coupled finite element model for provides support for the study of TC21 titanium alloy in MDF. The DEFORM model of as-annealed cylinders are exhibited in figure 10. The FE model as summarized in table 1, the MDF process of cylindrical specimen was simulated using the DEFORM-3D software with the aim at compare with the MDF tests and and further analysed its microstructure evolution. The boundary conditions of the sample during simulation are as follows: mesh number, 20000; minimum boundary size, 0.678926 mm; ambient temperature, 20 °C; convection coefficient between the sample and air, 0.02 N/s/
mm/ °C; heat transfer coefficient between the sample and the dies (top die and bottom die), 11 N s⁻¹ mm⁻¹ the motion rates of the top die, 10 mm s⁻¹; and coefficient of friction between the sample and the dies was assumed as 0.3. The multidirectional forging (MDF) behavior and microstructure evolution of TC21 titanium alloy are investigated by FEM simulation (850 ∼ 970 °C, 1 ∼ 3 pass for single pass true strain of 0.69 with the obtained material models. The established DRX models are imported into Deform-3D, Seven sets of deformation conditions (T = 850 °C, 3pass; T = 880 °C, 3pass; T = 910 °C, 3pass; T = 940 °C, 3pass; T = 970 °C, 3pass; T = 940 °C, 2pass; and T = 940 °C, 1pass;) are selected to simulate the MDF experiment.

3.3.2. Strain distribution
Figure 12 shows the distributions of predicted strain for MDFed TC21 titanium alloy under the pass of 3 and at the temperature of 940 °C, respectively. When the workpiece is subjected to a MDF simulation experiment, the deformation is non-uniform. According to the published results, the deformation is mainly divided into three deformation regions according to the size of the deformation as shown in figure 11: the region marked as A is the large deformation zone of the core, and its deformation is large; the region marked as B is the small deformation zone, which is also the difficult deformation zone, and the small deformation zone was called as ‘dead zone’; and the region marked as C is the free deformation zone, the deformation is between the large deformation zone (marked A) and the small deformation zone (marked B). As shown in figure 12, along the directions of the last forging axis and radial line, the strain shows a symmetrical distribution. The maximum strain locates in the core, while the minimum value generate where the surface contact with the die in the first pass, the minimum generate in other positions after the first forging pass (figures 12(g), (f) and (d)). The effective strain of the surface contact.
Figure 12 Predicted distribution of effective strain for TC21 titanium alloy MDFed in 3 pass and (a) 850 °C, (b) 880 °C, (c) 910 °C, (d) 940 °C, (e) 970 °C, and at 940 °C and (f) 2 pass, (g) 1 pass.
with the die is obviously influenced by coefficient of friction between the sample and the dies. Accompanied by increasing temperature (figures 12(a)–(e)) and forging pass (figures 12(g), (f) and (d)), the strain distribution became more and more even. It is remarkable to note that the distribution of effective strain is influenced by the deformation conditions of MDFed pass, the value of effective strain increase from 0.584 to 1.64, accompanied by the MDFed pass from 1 to 3. However, the value of effective strain is about 1.64 at any temperature in the condition. It means higher MDFed pass can promote the effective strain. The standard deviations (see ‘S.D.’ in figure 12) at different deformation conditions show an uneven distribution of effective strain in MDFed specimens. Hence, it can be inferred that increasing temperature and MDFed pass will achieve uniformity of deformation.

3.3.3. DRX simulation and verification
The simulated results of DRX fraction distributions of α lamellar for MDFed TC21 titanium alloy under the pass of 3 and at the temperature of 940 °C are presented in figure 13. In view of the above, DRX (dynamic recrystallization) is the main mechanism of α lamellar globalization. Therefore, it has certain reference significance for predict α lamellar globalization via simulate its DRX fraction distributions. The predicted average fraction of DRX for MDFed specimens increasing is along with increasing temperature or forging pass, which is in agreement with the regularity of the experimental one. It is clear from figures 13(g), (f) and (d), that the distribution of DRX fraction is influenced by the deformation conditions of MDFed pass, the value of DRX fraction increase from 20.1% to 62%, accompanied by the MDFed pass from 1 to 3. Furthermore, the distribution of DRX fraction is also affected by MDFed temperature. The value of DRX fraction increase from 41.8% to 62.3%, accompanied by the MDFed temperature from 850 °C to 970 °C(figures 13(a)–(e)). Within the section of the sample, the maximum DRX fraction generates in the core, while the minimum DRX fraction occurs to the small deformation zone. It was means that the variation of effective strain results in the inhomogeneous distribution of DRX fraction inside the sample predominantly. It also means the distributions of effective strain would directly affect the evolution of DRX. Incomplete DRX can be identified to occur in the center of all the specimens MDFed under 1 forging pass or at 850 °C (figure 13). It can be deduced that lower MDFed temperature and pass can hardly provide enough energy to achieve globalization of α lamellar. In case of many obvious features of material deformation is associated to inhomogeneous distribution of strain within the sample, and from a consideration of this while illustrating real MDF test. As discussed already, the predicted average fraction of DRX is 62% MDFed in 940 °C–0.69–3 pass shown in figure 13(d), while the experiment result of globalization fraction is 60% shown in figure 3(b). Furthermore, MDFed in 910 °C–0.69–3 pass, the result of the simulation and experiment is 57.7% and 50%, respectively (figures 4(e) and 13(c)). The error between simulation and experiment is less than 15%. It means the result of simulation is in agreement with the regularity of the experimental one, confirming that the established DRX models can better predict the microstructure evolution in MDF of TC21 titanium alloy.

4. Conclusions
During multidirectional forging (MDF) in the α + β phase region of TC21 titanium alloy with lamellar microstructure, the substructure evolution of α phase was analyzed via experimental study and numerical simulation to clarify the globularizing evolution of α lamellar. The main conclusions are as follows:

1. The volume fraction of globularization of α lamellar and the uniformity of microstructure improved with the increase of temperature, deformation, and cycle of MDF. The MDF cycle has the main effect on the lamellar globularizing fraction and microstructure uniformity of the alloy. The volume fraction of globularization of α lamellar achieves a high value about 85%, the average grain size of TC21 titanium alloy can be refined to 2 μm through MDFed at 910 °C with strain of 0.69 in 3 cycles.

2. The α lamellar globularization mechanism of TC21 during MDF mainly include boundary splitting, continuous dynamic recrystallization (CDRX), discontinuous dynamic recrystallization (DDRX), and termination migration. The major globularizing mechanism of TC21 titanium alloy during MDF is dynamic recrystallization (DRX). In the early stage of MDF, the DRX occurrence due to the movement of dislocations and the rotation of sub-grains or the migration of grain boundaries, it leads to the separation of grain boundaries in the end. And [0001] basal a-axis slip is the mainly pattern of plastic deformation. In the later stage, due to atomic diffusion, termination migration of α lamellar with low equiaxed ratio can be observed. However, the process of atomic diffusion is slow, and the effect of termination migration mechanism on the globularizing of lamellar is limited.
Figure 13. Predicted distribution of DRX fraction for TC21 titanium alloy MDFed in 3 pass and (a) 850 °C, (b) 880 °C, (c) 910 °C, (d) 940 °C, (e) 970 °C, and at 940 °C and (f) 2 pass, (g) 1 pass.
Increasing temperature and MDFed pass can not only promote the fraction of DRX, but also achieve uniformity of deformation for TC21 titanium alloy. The error between simulation and experiment is less than 14%, confirming that the established DRX models can better predict the microstructure evolution in MDF of TC21 titanium alloy.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declarations

Conflicts of interest

The authors declare that they have no conflict of interest.

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