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Development of a Continuous Rolling Process for Titanium Wires

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Manufacturing grade-2 titanium rods and wires imposes significant challenges on a continuous, high-speed rolling process due to its narrow operating temperature window. Certain manufacturers therefore adopted reversing rolling processes to obtain better control of both temperature and quality. This study utilizes numerical simulations to develop the optimal working condition, which facilitated a steel wire production line to successfully roll ø18mm and ø9mm titanium wire rods. The product dimensions satisfied JIS product specifications with the required surface and microstructure qualities. The results demonstrated that numerical simulation was an excellent complimentary tool in providing guidelines on challenging rolling procedures. The success of the production not only lowered product costs but also promoted a more efficient manufacturing process.

Keywords: Rolling simulation, Numerical analysis, Titanium wire production

1. INTRODUCTION

Titanium is a very versatile material utilized in a huge range of applications. The titanium industry responded to a substantial global demand growth from aircraft makers and industrial plant manufactures by increasing titanium sponge production from 74kt in 2003 to 176kt in 2008 (1). Demand is forecast to grow by 6% per year until 2015 resulting from the market for mill products of 140kt, requiring up to 200kt of titanium sponge. Grade-2 (Gr-2) titanium is probably the most widely used form of commercial pure titanium due to its low specific gravity, high specific strength, excellent corrosion resistance, weldability, formability, and biocompatibility. Gr-2 titanium has proven its usefulness in many applications including chemical processes, marine, aerospace, and power plant in which rod, bar, and sheet are the prime choice.

Commercial unalloyed and alloyed titanium are available as more than 30 different types of which Gr-2 and Gr-5 (Ti-6Al-4V) are currently chiefly used domestically with demand up to 4kt. Titanium is a dimorphic allotrope whose hexagonal close packed (HCP) α form changes into a body-centered cubic (BCC) β form at 882°C (2,3,4). Titanium is the ninth-most abundant element (0.63% by mass) in the Earth's crust (2,3), and the seventh-most abundant metal.

Table 1 lists Gr-2 titanium chemical compositions as specified by ASTM and in two commercial products. The mechanical properties of titanium are listed in Table 2.

Table 1 Chemical compositions of Gr-2 titanium

Composition (Wt%)		C (max)	N (max)	O (max)	H (max)	Fe (max)	Ti (min)
Handbook	ASTM Gr-2	0.10	0.03	0.25	0.015	0.30	98.885
ASTM B348	Gr-2	0.08	0.03	0.25	0.015	0.30	
Taiwan GMT	Gr-2	0.08	0.03	0.25	0.015	0.30	
	In prod.	0.02	0.0234	0.12	0.004	0.06	99.773
Japan Aichi Steel	Gr-2	0.08	0.03	0.20	0.015	0.25	
	In prod.	0.02	0.0038	0.11	0.003	0.02	99.843

Table 2 Mechanical properties of titanium

Yield Strength	Tensile Strength	Poisson Ratio	Elongation
275-410 MPa	344 MPa	0.37	20%
Modulus of Elasticity	Compressive Modulus	Shear Modulus	Reduction of Area
105 GPa	110 GPa	45 GPa	35%

Table 3 Unit area pressure for hot rolling process

Titanium Alloys	Unit Area Pressure, MPa	
	900˚C Rolling	600˚C Rolling
TA2	51.0	230.5
TC1	60.8	416.8
TC3	127.3	730.6
TA7	213.8	759.1

Producing Gr-2 titanium wire rod poses many challenges for the operational conditions of the furnace and rolling line. Gr-2 titanium is chemically very active with a high affinity for oxygen, nitrogen, and hydrogen. The proactive atmosphere utilized in the furnace or the electro slag to reheat or remelt titanium should ideally be free from hydrogen, nitrogen, and oxygen to prevent the formation of a hydride, nitride, and/or compound dioxide(5). A hydride layer can later lead to hydrogen-induced cracking while a nitride layer and thin titanium dioxide are very hard and inert.

There are three principle challenges to be met in the continuous rolling of titanium wire rod. Firstly, the hot material contacting the rollers with their low specific heat leads to a rapid fall in surface temperature. Secondly, continuous high-speed rolling can increase the internal temperatures of the work stock beyond the β transfuse temperature. Lastly, a poor heat transfer efficiency of the material can contribute to a steep temperature gradient between the internal and surface sections. Maintaining the temperature uniformity of the work stock is necessary to prevent introducing cracks, twisting, or breakage. A temperature gradient of 50~100˚C during rolling has been recommended to achieve good product quality. Additionally, the spread of the titanium is close to 40% more of that of the stainless steel so the roller profiles along with the gap setups require calibrating accurately to avoid the occurrence of overflow. It is a common practice to use a series of rolling stands in tandem to manufacture long products when a higher production rate being sought. The production line of the rolling stations, usually from 20 to 30 stands, is grouped into roughing, intermediate, prefinishing, and finishing stages. The work stock moves at increasing speed at each station to compensate for the progressive reduction of the cross-sectional areas. A billet, for instance, starting at 160mm^2 and rolling down to a finished rod of 5mm in diameter can have finishing speed as high as 120m/s. The rolling load of the stand depends heavily on the contact areas, rolling temperature, and the roughness of the contact surface. Everything being equal, increasing the work stock temperature to reduce the deformation resistance is beneficial to reducing the load to a more manageable level. Table 3 compares the rolling pressures exerted on a roller when rolling various types of titanium at two different temperatures.

Most of the mechanical energy is dissipated into heat during plastic deformation. The fraction of the rate of plastic work dissipated as heat for most metals is often assumed to be a constant parameter of 0.9(6). Due to the large quantity of energy dissipation under plastic work, Gr-2 titanium does not lend itself well to a continuous high-speed rolling process. Although continuous rolling at temperatures as low as 600°C are achievable, it is not uncommon that the process adopts manual operation with reversing mills that operate at 1.0~1.3 m/s rolling speed (7). Nippon Steel, however, successfully applied continuous rolling to produce 200kg ø8.5mm titanium alloy rod (8), and other wire rod products (9). Qin et al. further utilized alloy steel tandem mill to produce 1100kg ø10mm titanium heavy coils and indicated that the rolling speed affected the work stock temperature significantly (10).

This study made use of Finite Element Analysis (FEA) to analyze complex rolling conditions in order to address the continuous high-speed rolling challenges presented by Gr-2 titanium. The FEA analysis was carried out by the numerical software DEFORM to simulate the rolling process from rolling a bloom down to a billet and then into wire rods. Work stock temperature, rolling speed, frictional effects, and reduction ratio among other considerations were chosen to be the set of simulation variables so that their relative influences on rolling could be examined in detail. The results obtained from the FEA simulation were first validated by the trial products and then the process iterated to establish an optimal operating condition.

2.EXPERIMENTAL METHODS

The numerical simulation software DEFORM utilized in analyzing the rolling conditions consists of a pre-processor, a simulation engine, and a post-processor as three distinct functionalities. A representative digital model of the rolling process as depicted in Fig.1 was sketched in SolidWorks and then imported into the DEFORM pre-processor. The roller profiles shown in Fig.2 were adopted from actual rolling steel products and used to reduce the simulated variable size. The distances between the stations were from 800mm to 34,100mm, and the roller radii were between 360mm to 620mm. Each roller, assumed to be rigid, was meshed with 50,000 tetrahedron elements to accurately digitalize small corners. The rollers were constrained by the position boundary conditions, and the constant angular velocities were specified to simulate rolling. An initial element size of 5~10mm was used for the work stock but the size was later progressively reduced through the Automatic Mesh Generation (AMG) capability during simulation. AMG was applied only locally to elements with a degraded aspect ratio and the new mesh was generated through an averaging scheme.

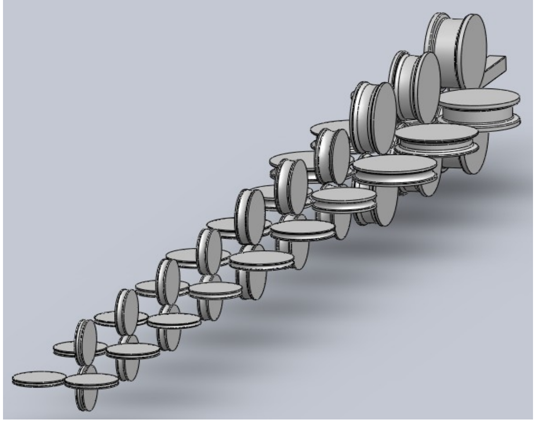


Fig.1. A representative rolling line.

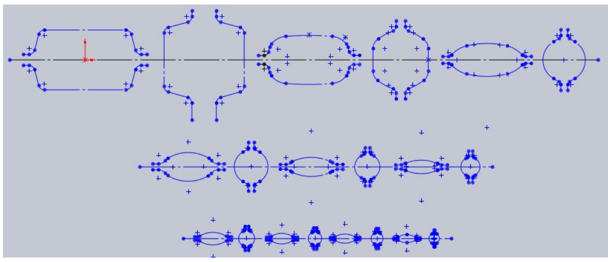


Fig.2. Roller profiles with gap setups.

The initial rolling temperature was set to 820~880°C with uniform temperature distribution. The material model was the built-in titanium Type 2 material database. Since residual stress and springback were of no primary interest in the simulation, a plastic material modeling was chosen. The specified flow stress, therefore, was a function of temperature, effective plastic strain, and effective strain rate. A tabular data format was incorporated with value interpolation performed for the required values in-between the given data points. The mechanical work to heat conversion coefficient was determined to be in the range of 0.6~0.9 to accommodate the varied deformation strain rates. Thermal expansion, fracture criteria, and emissivity were not considered in the simulation.

As indicated by Wang et al.(11), the temperature increase was proportional to the rolling speed when the speed was below 12m/s. Therefore, 50~70% of the designated top speed of the production mill was selected to accommodate this effect. Heat dissipation of the work stock was modeled by only conduction and convection. A heat transfer coefficient of 5~11 N/sec/mm/°C was specified for the conduction and a forced air convection coefficient of 10~200 W/m^{2}K was used.

The rolling friction of plastic processing is a complex phenomenon and differs in many aspects from general mechanical friction. The frictional forces are considerably greater than those of mechanical friction causing the underside of the new material to be exposed resulting in the so-called localized bonding(7). The material flow at the contact interface that is restrained by the roller profiles can exhibit partial bonding, sliding, and sticking situations. To more accurately describe these frictions, a shear friction model was considered in this study. The friction is determined by the material yield shear stress multiplied by a constant factor of 0.3~0.7. A relative contact tolerance of 0.002 was used in contact tracking and detection so that the friction model could take effect properly. The tip of the work stock was not initially shaped such that the roller gap, contact pressure, and the roughness of the interface became dominant factors for the angle of bite. The average reduction ratio of the process was 19.6% with minimal and maximal values of 14.8% and 28.3%, respectively.

Rolling a work stock can be performed in two ways: (a) pushing rollers to the specific positions while keeping the work stock stationary and then starting rolling; or (b) pushing the work stock with a rigid object and rolling simultaneously. The second approach was used in this study to more accurately simulate the angle of bite and the frictional effect. The billet rolling consisted of 3~5 reversing passes, one 45° rotating motion, and 4 vertical-horizontal finishing passes. A box profile was used in the reversing passes while the finishing passes used square and diamond profiles. Maximal rolling speed reached 5.5m/s and the final finishing speed was approximately 1.5m/s. The wire rod rolling involved more than 20 stands, and a portion of their rolling schedule along with the elongation rate is listed in Table 4.

Simulations were performed based on the roughing, intermediating, and finishing rolling stages in which each stage required to solve a set of coupled temperature-displacement equation with more than 300,000 degrees of freedoms. Equations were solved by the conjugated gradient method with direct iteration. Given the largest temporal integration step of 0.01, each stage of the simulation for one design variable study required 24~36 hours of run time on a parallel workstation using quad processors.

3.RESULTS AND DISCUSSIONS

3.1 Billet Rolling

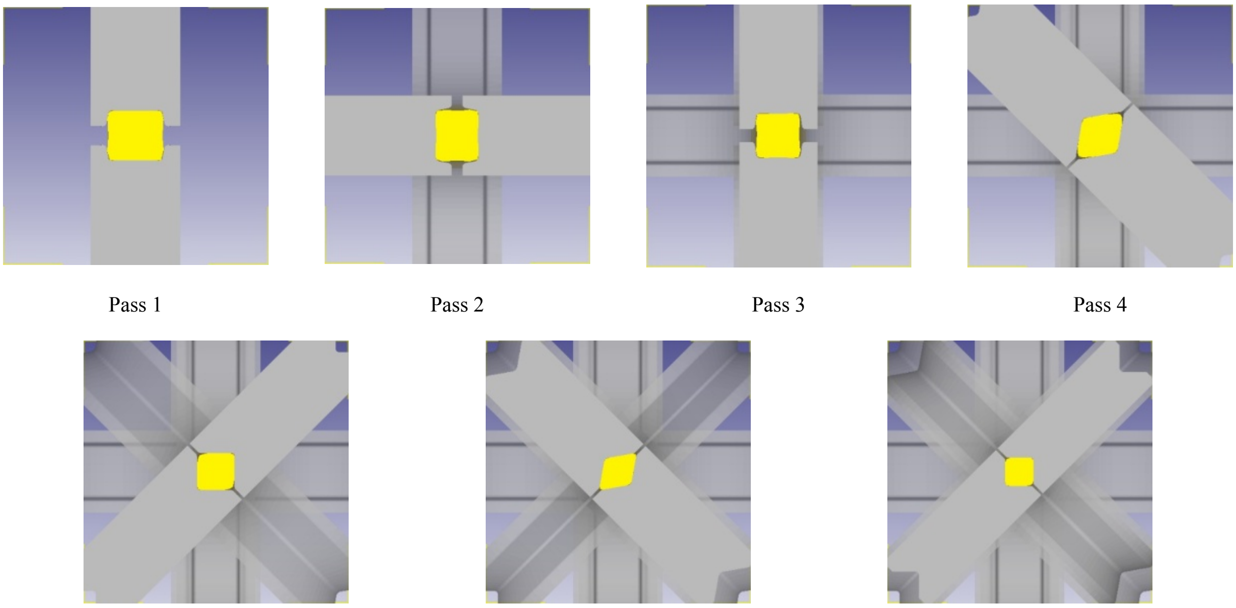
The simulation of a 5-pass reversing schedule was first conducted and the results showed that curving was likely to be amplified because of the low temperature around skid marks. Such a temperature gradient resulted in strain differences that were compounded with a flipping motion and led to two-way curving at the head section. Further analyses indicated that reducing the number of passes to 3 and minimizing the temperature difference to 10~50˚C yielded satisfactory results in resolving these issues. Severe upward curving after the second pass observed during trial production was also successfully eliminated with the same temperature adjustment. Adding cooling water is not recommended at this stage since the rapid heat dissipation causes a surface temperature drop of 50~150˚C. Accommodating this temperature drop required re-calibrating the sensitivity of the Head-Mounted Displays (HMD) to 700~800˚C in order to properly detect the location of the work stock.

The second continuous rolling stage progressively reduced the cross section dimension down to 118mm^2. A continuous, higher speed deformation process led to a larger deformation strain, greater strain rate, and higher work stock temperature. A moderate cooling and adequate support of the work stock was provided to prevent bending under low material strength. Support rolls were used full time and the pull back roll was fixed and extended to provide maximal support. The fly cutter had been turned off to prevent any bending moment being exerted on the work stock. By utilizing the simulation results to fine-tune the manufacturing process, four 20m long titanium billets weighted approximately 5000kg were successfully produced with qualifying dimensions. The dimensions were used to validate the simulation results, which were observed to be within 2% of those of the practical products. The progressive change on the stock profile is depicted in Fig.3. Figure 4 captures the moment that the bloom entered the second stage rolling process.

Undesirable surface defects such as helical marks, overlapping, and twisting are often caused by faulty roller gap setups resulting from inaccurate spread calculations. Additional simulations were therefore conducted to clarify the titanium spread tendency during rolling. Table 5 tabulates the spread calculation for three temperatures simulated using the 3-pass schedule. The results showed that the spread deviated slightly from that of the reference steel but was within an acceptable range. Simulation did not reveal any overflow or underflow situations as observed also in production. The final products, therefore, were free from any surface defects.

Table 4 Rolling sequence and profile reduction ratio

Mill Line	Stand No.	Cross-Sectional Area	Elongation Ratio	Mill Line	Stand No.	Cross-Sectional Area	Elongation Ratio
Stage A	H1	13729.0		Stage A	H11	1305.3	1.22
	V2				V12	1046.3	1.25
	H3	10711.0	1.28		H13	891.7	1.17
	V4	8011.8	1.34		V14	730.6	1.22
	H5	5747.8	1.39		H15	610.4	1.20
	V6	4300.8	1.34		V16	510.7	1.20
	H7	3399.6	1.27		H17	432.5	1.18
	V8	2734.0	1.24		V18	363.1	1.19
	H9	2060.8	1.33	Stage B	H19	312.1	1.16
	V10	1590.4	1.30		V20	261.1	1.20


Pass 1 Pass 2 Pass 3 Pass 4

Pass 5 Pass 6 Pass 7

Fig.3. Progressive profile changes of the bloom rolling.

Table 5 Spread calculation for various rolling temperatures

	950℃		850℃		750℃		Designed	
	W	H	W	H	W	H	W	H
	220.0	260.0	220.0	260.0	220.0	260.0	220.0	260.0
Pass 1	229.787	212.163	231.946	211.186	230.636	211.523	230.0	212.0
Pass 2	177.434	223.686	177.073	220.502	177.002	224.094	177.0	223.0
Pass 3	183.915	184.282	183.15	184.364	186.804	185.023	183.7	185.0
Diff.	dW	dH	dW	dH	dW	dH	dW	dH
Pass 1	9.787	-47.837	11.946	-48.814	10.636	-48.477	10.0	-48.0
Pass 2	-52.353	11.523	-54.873	9.316	-53.634	12.571	-53.0	11.0
Pass 3	6.481	-39.404	6.077	-36.138	9.802	-39.071	6.7	-38.0
	Spread %							
Pass 1	-20.46%		-24.47%		-21.94%		-20.83%	
Pass 2	-22.01%		-16.98%		-23.44%		-20.75%	
Pass 3	-16.45%		-16.82%		-25.09%		-17.63%	

3.2 Wire Rod Rolling

Small radii titanium wire rod rolling was more challenging than the billet rolling because of its significantly higher processing speed, involving a greater numbers of passes, higher elevated temperatures, and much less material to work with. The foremost requirement in the wire rod simulation was to acquire the adaptation of roller speed. The rolling speed was deemed optimal when the material filled the roller profile properly with an adequate tension between the rollers. As predicted by the simulation for a representative 18 stands, the speed profile increased non-linearly to satisfy the accumulative reduction effect. Figure 5 compares the simulation results with production trial data. It clearly showed that both results were highly consistent and the deviations were from -0.49% to 7.21% with an average of 5.02%. The greater discrepancies at the intermediate and prefinishing stages were due to manual adjustments during production to the downstream roller gaps to address a slight underflow. Once the final rolling speed had been determined, a high quality work stock profile was achieved as depicted in Fig.6. Cooling during the process was performed for half of the rolling section in order to maintain the stock temperature at about 740~870˚C. Small coils of ø8mm titanium wire rods were produced at this stage.

Fig.4. Bloom entered second stage rolling station.

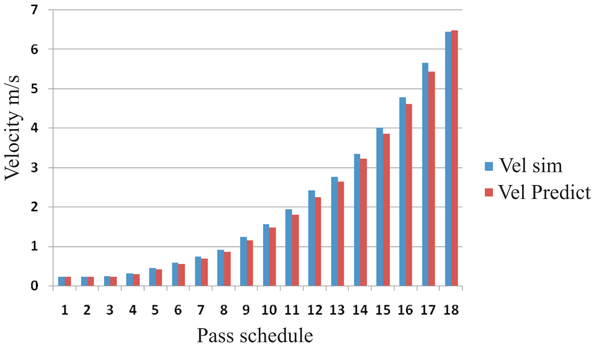


Fig.5. Comparison of simulated and predicted velocities.

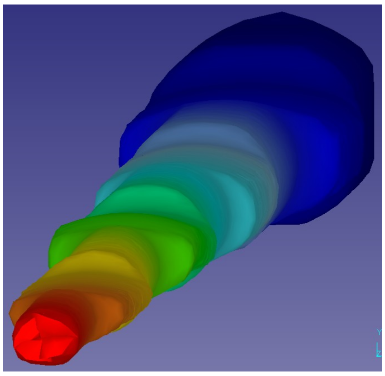


Fig.6. Work stock profile during rolling.

A quantitative understanding of the temperature variation with respect to the changing rolling speed was of paramount importance to fine-tuning the process for heavy coil production. Only one pass was performed with the rolling speed increasing from 1.0m/s to 20.0m/s at incremental speedups of 1.0m/s. Three reference points - center, rolling side, and spread side were tracked to record the temperature variations. The simulation results shown in Fig.7 implied that the heat dissipation at the contact surface was significant at low speed but gradually became insignificant at high speed. The temperature uniformity of the work stock was achieved better at a higher rolling speed. The results also indicated that the rolling speeds of previous trials were slightly overshot since the central temperature was above the β transfuse temperature. Given these simulation results, the production line rolling speed was lowered an additional 8%.

Incorrect roll gap setups affect not only the roundness of the final product, but they could also yield ill effects on the rolling temperature. As demonstrated by Fig.8, narrowing a roll gap by 3mm corresponded to a 5˚C increase in the central temperature. The increase may not seem apparent but the compounding effects of the tandem rolling and the progressive increase of rolling speed could elevate the temperature significantly. The roll gap, therefore, was re-calibrated to open up 0.4mm to increasing parting from stand 16 onward. The adjustments enhanced both temperature control and product quality in the later production stage.

3.3 Final Production and Suggestions

The FEA results obtained were aggregated as the production guidelines to facilitate the manufacturing department in production preparation and addressing additional process concerns. Through collaboration between the technical and manufacturing departments, a heavy coil of ø18mm titanium rod weighing 680kg was first produced (see Fig.9) followed by a ø9mm 634kg titanium wire. Both products satisfied JIS product specifications and there were negligible surface defects.

Successful titanium wire production required overcoming certain manufacturing difficulties. Several considerations provided below were concluded from the FEA simulations to assist in the manufacturing process:

(a)Desired initial rolling temperature was around 800~850˚C with no temperature difference larger than 50˚C at any location, if there was any.

(b)Rolling speed could be set to above 5m/s and below 15m/s. Adequate cooling was a necessity at even higher rolling speeds.

(c)Although the spread was comparable to that of low carbon steel in wire rod rolling, accurate roll gaps

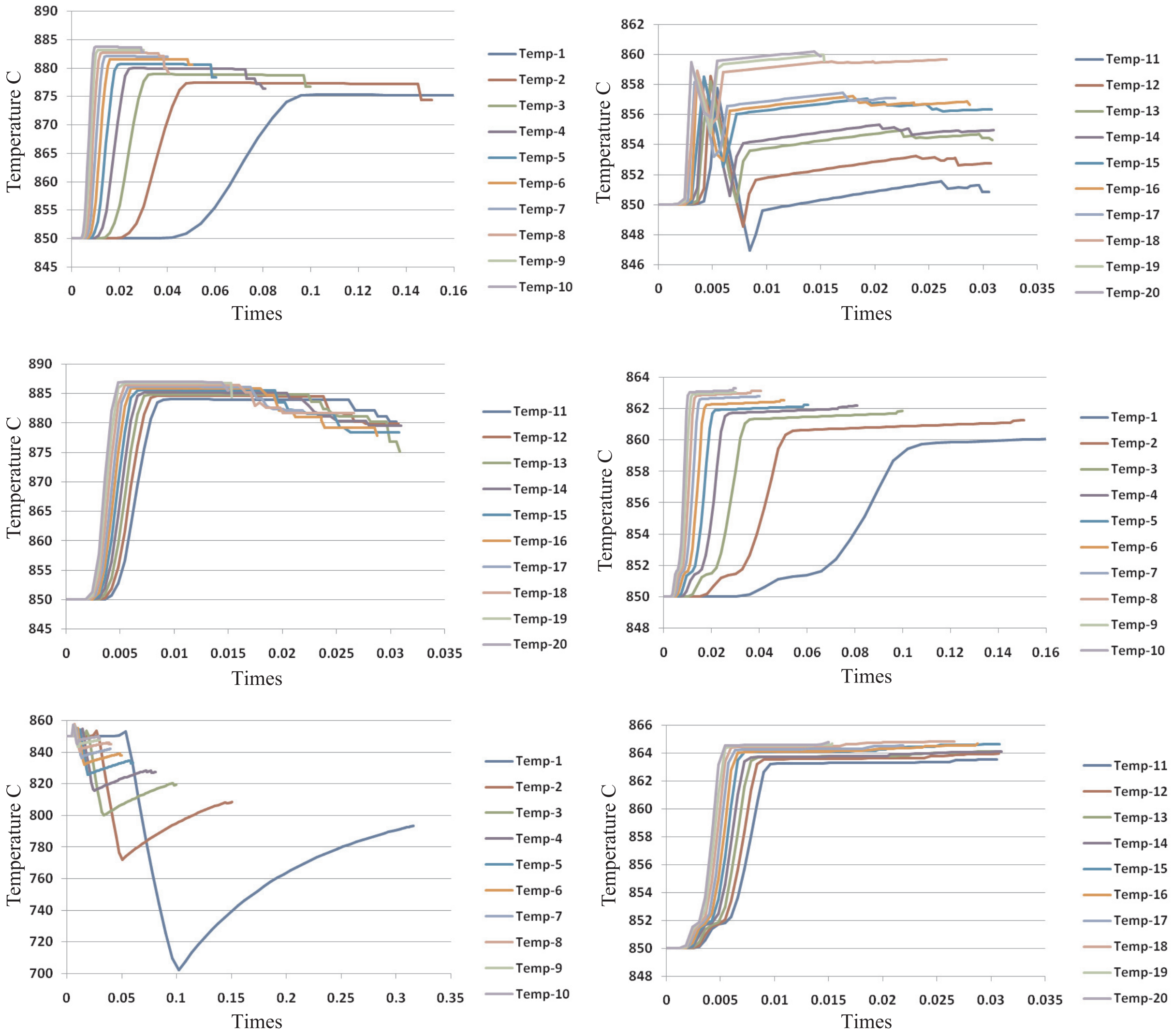


Fig.7. Velocity varied temperature distributions (Left: 1~10m/s; Right: 11~20m/s; Top to down: center, rolling surface, and spread surface).

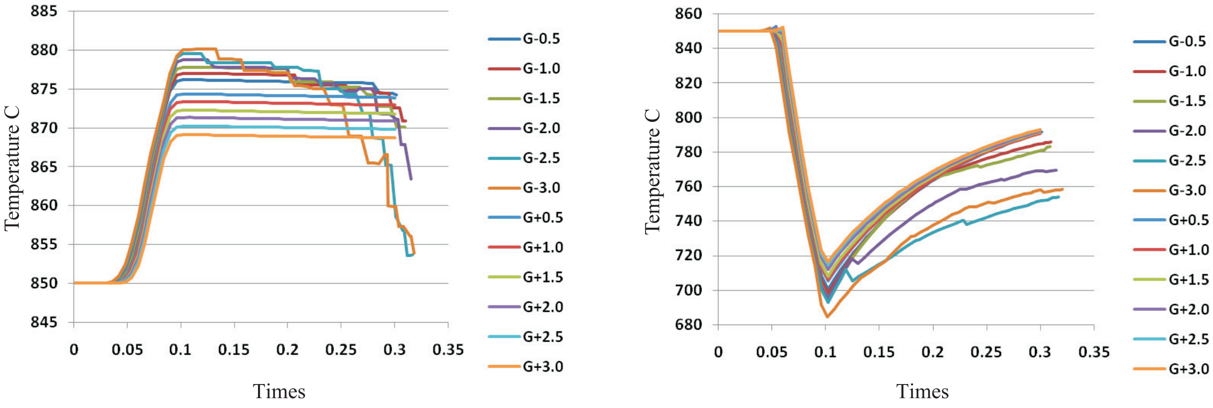


Fig.8. Gap varied temperature distributions (Left: center; Right: rolling surface).

were needed to avoid twisting and irregular temperature variations.

(d) The so-called crocodile mouth was more apparent and sometimes skewed, so properly trimming off the leading section was a good precaution to avoid biting errors.

(e) Temperature uniformity for billet rolling was important to prevent curving during a multi-pass rolling. Lowering the initial rolling temperature and reducing the cooling water usage could further improve the straightness of the product.

Fig.9. ø18mm titanium rod finished product.

4.CONCLUSIONS

FEA was successfully applied to the rolling process to meet the challenges of a continuous high-speed titanium wire rod production. It is evident that numerical simulation was extremely beneficial to analyze the complex working conditions. The simulation not only enhanced the quantitative and qualitative understanding of a highly dynamic rolling process, but it was also able to establish a feasible set of operating guidelines. With the capability to develop a continuous rolling process and to produce high quality titanium wire rods was a monumental accomplishment for the production department. A future scale of economy for titanium product manufacturing can therefore be realized through the leap of this technological advancement.

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