Materials Research Proceedings 28 (2023) 629-637 https://doi.org/10.21741/9781644902479-68

Study of forming defects and failure occurrence in the radial-axial rolling of super duplex stainless steel rings

MURILLO-MARRODÁN Alberto[1,a *], GARCÍA GIL Eduardo[1,b], FERNANDEZ-GAMBOA Unai[1,c], CONDE Aintzane[1,d] and LOZARES Jokin[1,e]

[1] Department of Mechanics, Design and Industrial Management, University of Deusto, Avda Universidades 24, Bilbao 48007, Spain

[a]alberto.murillo@deusto.es, [b]e.garcia@deusto.es, [c]unai.gamboa@opendeusto.es, [d]aintzane.conde@deusto.es, [e]jokin.lozares@deusto.es

Keywords: Radial-Axial Ring Rolling, Super Duplex Stainless Steel, VDOE, Cracks, Fishtail

Abstract. Welding neck flanges are commonly manufactured by radial-axial ring rolling (RARR). The service conditions of these elements are very demanding (mechanical loads and corrosive environments). For this reason, materials such as super duplex stainless steel (SDSS) are used, which could present workability problems under certain process conditions. In this work, a study of forming defects and failure occurrence in the RARR of SDSS flanges has been proposed. Firstly, a finite element model of the industrial RARR process was developed and validated. Then, a multivariate factorial analysis based on a virtual design of experiments was performed to identify the determinant parameters of the process. The diameter of the mandrel was identified as the most determinant parameter. An increase in diameter reduces the probability of developing underfilling defects and the development of cracks in the flange neck. The mandrel radial speed has no significant effect on the cracking of underfill defects while reducing the rotational speed of the king-roll could improve the uniformity of the deformation distribution in the flange section.

Introduction

The oil and gas industry demands extreme operating conditions, often combining high pressures with highly corrosive environments. In pipelines, flanges of 25 %Cr super duplex stainless steels (SDSSs) are generally used, as they require high strength and corrosion resistance [1]. The UNS S32760, which is considered an SDSS, meets these requirements thanks to the mixture of both austenite and ferrite which leads to a material with excellent mechanical properties and corrosion resistance. In addition, it typically contains 25% Cr and 7% Ni-doped with a small amount of N, (0.3%) providing improved corrosion properties, and allowing its use in the marine environment [2]. However, cracks could be generated in welding neck flanges made of SDSS during hot forming and thus, its workability at high temperatures could be limited under certain conditions [3].

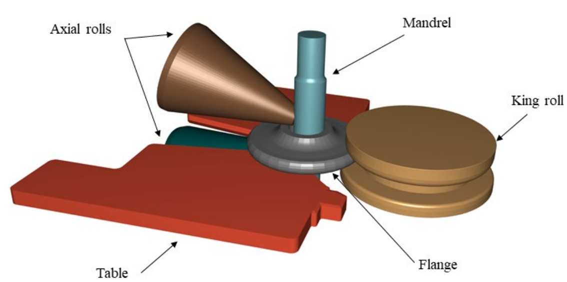
Weld-neck flange rings of high diameter are manufactured on ring rolling machines, by enlarging the diameter of ring blanks. In this hot forming process, first, the blanks are heated to the forging temperature. Then, the RARR machine reduces the wall thickness using the king-roll and mandrel. In addition, two axial rolls act simultaneously to decrease the height of the blanks [4]. In this hot forming process, one of the most problematic issues is controlling fishtail and underfilling defects [5]. The fishtail could be defined as an undesirable plastic deformation at the ring's upper surface, which leads to a geometrical defect as there is a lack of material in that region. Giorleo et al. [6] investigated the influence of the mandrel idle speed on the fishtail, keeping the king-roll rotation speed constant. Nevertheless, they concluded that the effect of mandrel idle speed on fishtail was not significant. Zhou et al. [7] identified that a higher king-roll rotational speed increases fishtail, given that deformation is concentrated in the surface area of the ring in the axial direction, as the diameter increase per revolution decreases. Allegri et al. [8] proposed a non-constant rotational speed of the main roller to keep the angular velocity of the ring constant. They conclude that maintaining a constant rotational speed in the ring could decrease fishtail dimension by 50%.

Regarding material damage and crack development, the ductility of SDSS decreases with lower temperature and higher strain rate, which facilitates the occurrence of plastic flow instabilities. The uneven uniformity of both strain and temperature in the ring section could lead to material failure [9]. Zhou et al. [10] highlighted the importance of uniform deformation and temperature distributions during RARR, given that they not only result in microstructure defects such as band structure and mixed crystals but also lead to internal cracks or even cause the interruption of the process. Meng et al. [11] analyzed the effect of geometries of king-roll and mandrel on material deformation uniformity. An increase in king-roll diameter was associated with better deformation uniformity, but caused workability problems due to the higher cooling rate, while mandrel geometry increase showed only positive effects on plastic deformation distribution.

In this work, a Virtual Design of Experiments (VDOE) has been proposed, using finite element method simulations of the RARR process to analyze the effect of selected process parameters on the development of cracks and forming defects on welding neck flanges made of S32760 SDSS.

Materials and Methods

Welding neck flanges made of S32760 SDSS were manufactured in an industrial RARR mill of the company ULMA Forging. Under investigated conditions, some of the flanges showed problems associated to crack development in the internal diameter (ID) surface of the neck region, and fishtail defects. Fig. 1 shows the FE model of the industrial RARR mill, and the cracks and fishtail defects identified in some RARR flanges.



(a)

(b)

(c)

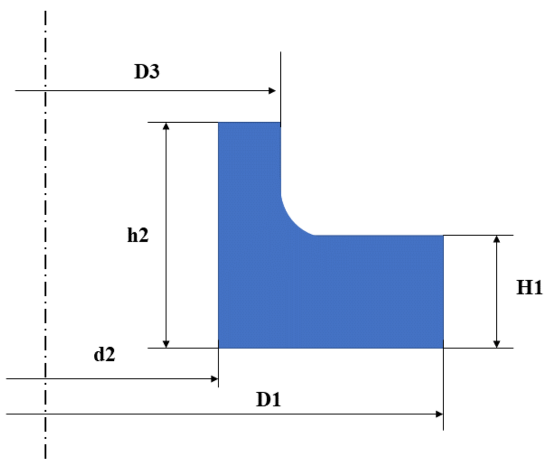
Fig. 1. (a) Fe model of the RARR mill of ULMA Forging, (b) cracks identified in the ID of the neck and (c) example of fishtail defect.

Materials Research Proceedings 28 (2023) 629-637 https://doi.org/10.21741/9781644902479-68

The software Forge NxT was used to simulate the RARR process. The finite element (FE) model counted with king-roll, both conical upper and lower rolls, mandrel, and the ring, whose geometry was generated from the prior state of the ring before the RARR (see Fig. 1a). The lateral guiding rolls were not included as the FE model has implemented the self-centering of the flange. All geometries were set up as rigid objects, while the flange material behavior was set as viscoplastic according to

$$\sigma = 28332 \cdot e^{-0.0051T} \cdot \varepsilon^{-0.1} \cdot \dot{\varepsilon}^{0.112} \cdot e^{\frac{-0.035}{\varepsilon}} \quad (1)$$

where σ is the flow stress (MPa), T is the temperature of the material (ºC), ε is the strain (-), and $\dot{\varepsilon}$ stands for strain rate (s^{-1}). The values of the material constants were obtained from a set of compression tests performed by Kang et al. [12]. The contact conditions with the elements were modeled using Coulomb limited to Tresca friction model [13], with friction coefficients of $\mu = 0.4$ and $m = 0.8$. Heat exchange between the flange and tools was modeled with a contact conductance HTC = 10.000 W/m^2K and free convection with ambient media was assumed. The mesh of the ring was structured into 48 parts with an element size of 20 mm, refined to 10 mm in the neck of the flange. The mesh of tools had an element size of 20 mm. All the kinematics of the model were set to the values used in the experiments performed in the RARR mill. First, in order to validate the model, axial and normal forces were adjusted to the values recorded from the mill, and the ring growth speed vs diameter was reproduced by the simulation. The geometry of the manufactured flange and dimensional tolerances in hot conditions are compared to the values obtained in the simulation in Fig. 2.



	Measure (mm)	Tolerance (mm)	Deviation (mm)	Error (%)
D1	1385.5	±10	-3.5	0.3
d2	1032.7	+14/-13	+4.2	0.4
D3	1102	+18/-9	-5.7	0.5
H1	113.1	+5 /-6	-0.9	0.8
h2	194.8	+16/-	+11.8	6.1

Fig. 2. Geometries of the flange in hot conditions compared to the simulated values.

The validated model was calculated using a king-roll rotational velocity of 25 rpm, a mandrel radial velocity of 3.03 mm/s, and a mandrel diameter of 170 mm. These were the selected variables to analyze their effect on the development of geometrical and crack defects. Then, a virtual design of experiments was carried out by simulating the RARR process. The conducted factorial analysis consisted of three levels and three factors. As a result, a total number of 27 simulations were carried out considering the conditions listed in Table 1.

Table 1. Factors and levels considered in the factorial analysis.

Factors	**Level 1**	**Level 2**	**Level 3**
King-roll angular velocity (KAV)	15 rpm	25 rpm	35 rpm
Mandrel radial velocity (MRV)	2.64 mm/s	3.03 mm/s	3.57 mm/s
Mandrel diameter (MD)	120 mm	170 mm	220 mm

The response variables selected to analyze the effect of the factors listed in Table 1 were the material ductile damage, fishtail defect, and uniformity of both strain and temperature in the flange section.

Damage. The simulation of damage in the RARR process has been considered by implementing the Latham&Cockroft ductile damage model. The damage in the material D is estimated according to

$$D = \int_{\varepsilon_0}^{\varepsilon_f} \frac{\sigma_1}{\sigma_{eq}} \, d\varepsilon \tag{2}$$

where σ_1 is the first principal stress, σ_{eq} Von Mises equivalent stress, ε_0 and ε_f the initial and final deformation, respectively. In order to compute the accumulated damage in each simulation, three sensors have been set in the neck of the flange to estimate the maximum damage value at the end of the RARR process, as illustrated in Fig. 3.

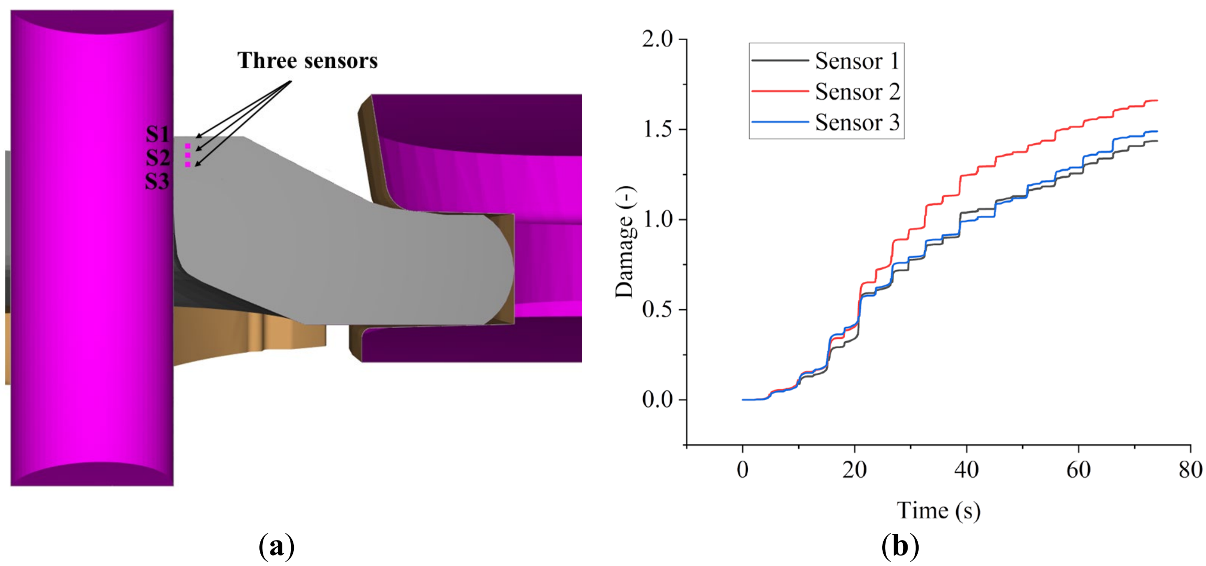


Fig. 3. Sensors to compute the ductile damage on the neck of the flange during RARR (a) Initial position and (b) evolution of damage computation KAV = 15 rpm, MRV=2.64 mm/s and MD = 170 mm.

Fishtail. The fishtail defect can be appreciated in Fig. 1c. In order to measure and quantify the severity of this defect, the depth of the depression in the flange surface region has been measured in the simulation.

Uniformity of Plastic Strain (*SDP*) and Temperature (*SDT*). The uniformity of plastic strain and temperature in the section were analyzed through the calculation of the standard deviation according to

$$SDP = \sqrt{\textstyle\sum_{i=1}^{N} (\varepsilon_i - \varepsilon_a)^2 / N}. \tag{3}$$

$$SDT = \sqrt{\sum_{i=1}^{N} (T_i - T_a)^2 / N} \quad (4)$$

Where N is the total number of analyzed points (12 in the neck of the flange), ε_i and T_i are the strain and temperature at a point, and ε_a and T_a stand for the average values of strain and temperature in the region analyzed. The position of these 12 sensors in the neck of the flange is provided in Fig. 4.

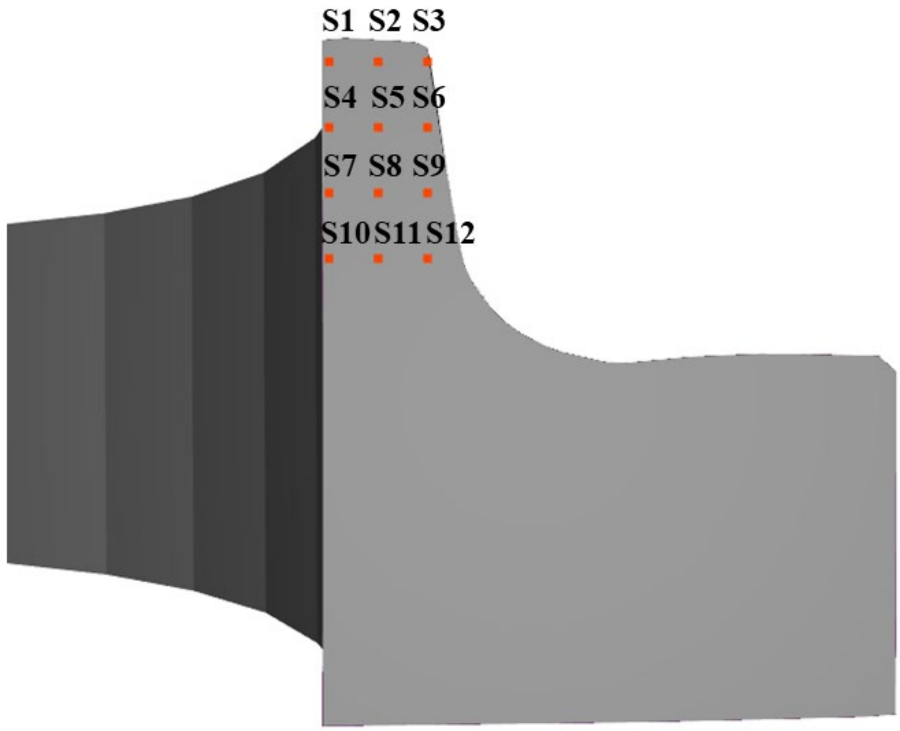
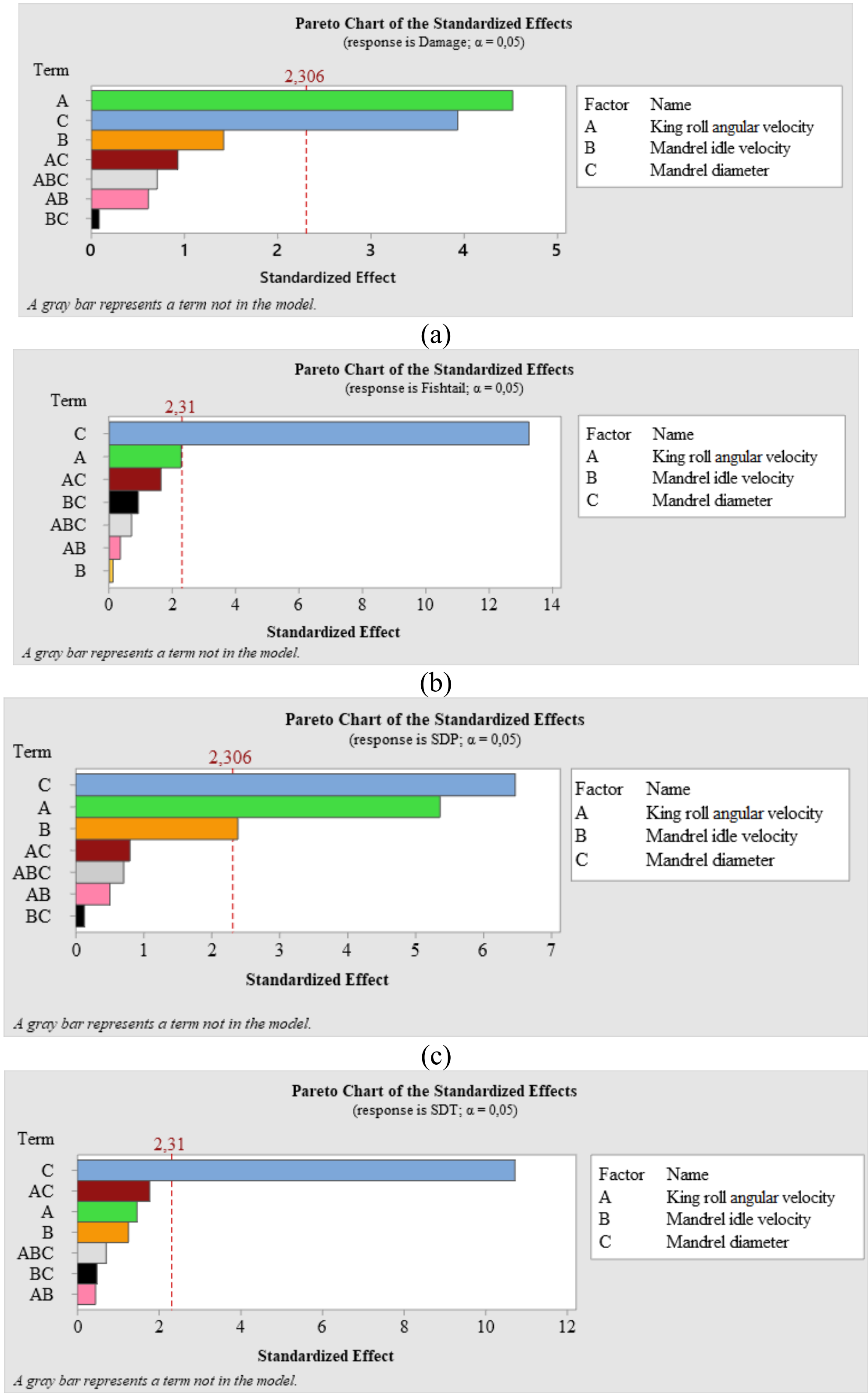


Fig. 4. Position of the 12 sensors in the neck of the flange to measure the uniformity of strain and temperature in the region where cracks are developed.

Results and Discussion

The results of the multivariate factorial analysis are provided. The Pareto chart with the standardized effects of each of the factors on the analyzed response variables is depicted in Fig. 5. In each of the charts, the factors are ordered from the highest to lowest standardized effect value.



(d)

Fig. 5. Pareto chart of standardized effects of factors on (a) Damage, (b) Fishtail defect, (c) SDP, and (d) SDT.

The results shown in Fig. 5 put into evidence which factors contribute more to the variability in the response variables. Lenth's method was used to check which effects are significant (red dotted line). It is an objective method to test the effects of unreplicated factorial designs [14]. According to the results, KAV velocity shows a significant effect on Damage and uniformity of deformation. The MRV only provides a significant effect on the uniformity of deformation, but lower compared to the rest of the considered factors. Finally, the MD is the factor that shows a clear significant effect on all the considered response variables, namely, damage, fishtail, and uniformity in both, temperature and strain in the flange section. One interesting aspect to discuss is the interaction between the king-roll rotational speed and mandrel radial velocity, which has not shown any significant effect on the analyzed variables. In addition, the statistical significance of the model coefficients was determined by the P value. The P value less than 0.05 (95% confidence level) indicates that the model terms are significant [15]. After the revision of the results, it was confirmed the significance of the effects identified in the Pareto. Furthermore, the analysis of residuals confirmed that they were randomly distributed and had near-constant variance. Then, the main effects of the factors that showed significance in the previous analysis are presented in Fig. 6. No interaction between the analyzed factors has been identified.

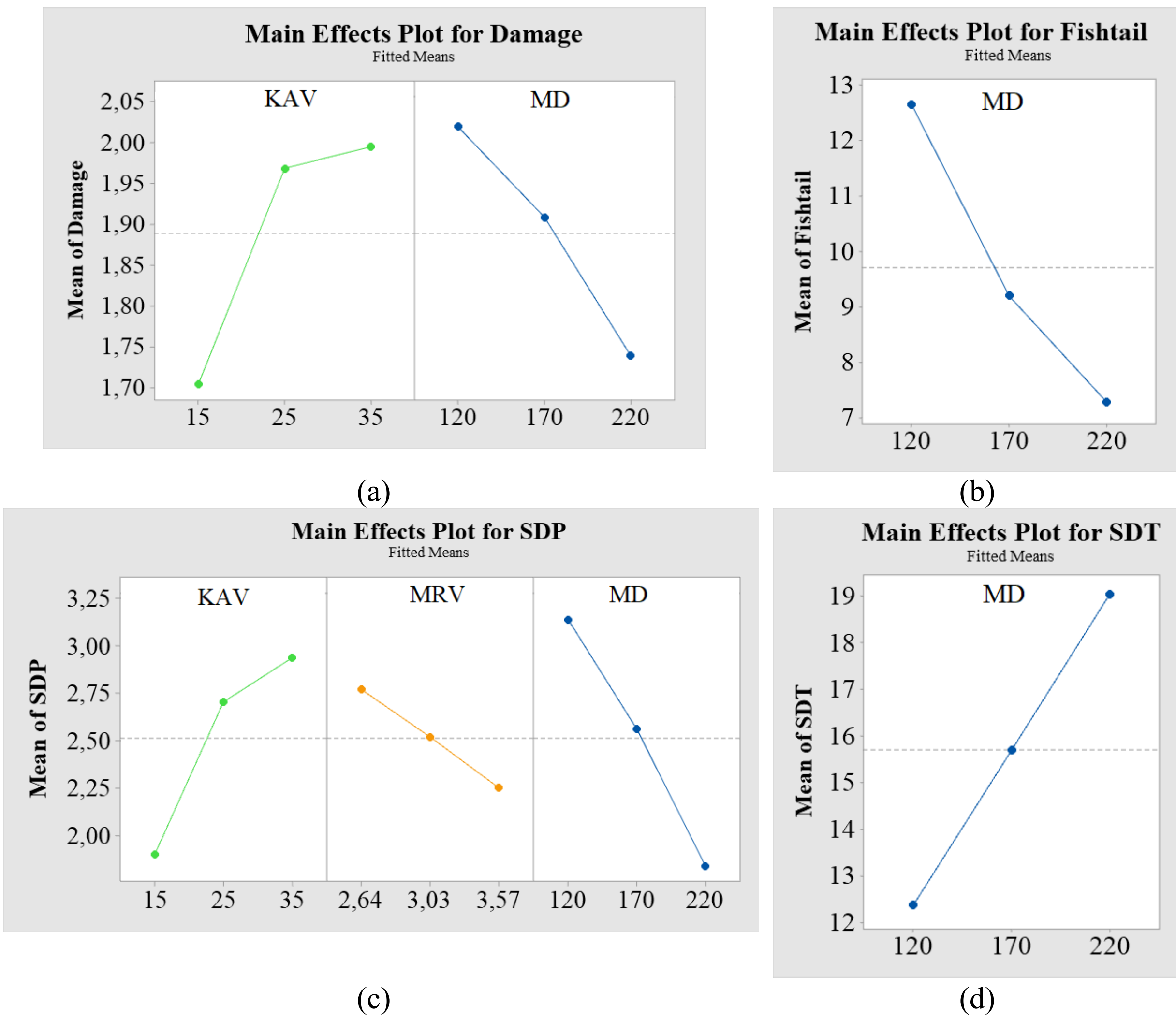


Fig. 6. Main effects of factors on (a) Damage, (b) Fishtail defect, (c) SDP, and (d) SDT.

According to the results of Fig. 6, the reduction in ductile damage in the neck of the flange could be achieved by reducing the KAV or increasing the MD. Regarding the fishtail defect, the MD shows a strong effect, reducing the fishtail the higher the MD. The uniformity of temperature in the neck of the flange depends on the effect of the MD, showing a higher deviation the higher the diameter of this element. In the case of uniformity of plastic strain, a decrease of KAV increases the uniformity, while an increase of the MRV or MD is associated with better uniformity of plastic deformation in the analyzed region of the flange.

From the analysis of the main effects, it is concluded that reducing the KAV presents a positive effect not only on the ductile damage but also on the fishtail defect and uniformity of plastic strain in the neck of the flange. However, the dimensions of the king-roll and flange should be considered given that material flow in the section of the flange depends on the combined effect of flange rotation, and mandrel and axial rolls displacement. A similar material flow could be obtained with higher KAV if the diameter of the king-roll or flange is reduced.

In the case of the MD, it is important to highlight that shows a significant effect on all the analyzed variables. However, the effect of the diameter of this tool on SDSS damage during the process or fishtail defect is not clear in the literature. A higher diameter is associated with lower values of fishtail, lower values of ductile damage, and better uniformity of plastic strain. The only drawback is a lower uniformity of temperature in the neck of the flange, which is expected given that the contact region with the ID of the flange is increased and there is a higher thermal exchange with the mandrel. A further thermo-mechanical study could provide insightful information about the impact of mandrel diameter on the stress state in the section of the flange and the material flow.

Summary

A study of forming defects and failure occurrence in the RARR of SDSS flanges has been proposed. First, a FE model of the RARR industrial process has been developed and validated. Then, some determinant process parameters, such as KAV, MRV, and MD, have been modified and simulated. The effect of modifying these process parameters on the development of cracks and fishtail defects has been assessed by means of a multivariate factorial analysis. From this study, the flowing conclusions have been drawn:

- The increase in mandrel diameter reduces underfilling defects and also the development of failures due to ductile damage in the ID of the flange neck. Nevertheless, it leads to an increase in forces in the early stages of the process. In addition, the higher contact area with the mandrel leads to a low temperature in the flange ID during the process, which could favor the precipitation of intermetallic phases that reduce SDSSs hot workability.
- The reduction of king-roll angular velocity hinders the development of cracks in the ID of the flange neck and improves the strain distribution on the flange section.
- The mandrel radial velocity doesn't show a significant effect on the development of cracks or fishtail defects. It only shows a slight effect on the strain distribution of the flange section, leading to better uniformity at higher values.

References

[1] A.P. Kölblinger, S.S.M. Tavares, C.A. Della Rovere, A.R. Pimenta, Failure analysis of a flange of superduplex stainless steel by preferential corrosion of ferrite phase, Eng. Fail. Anal. 134 (2022) 106098. https://doi.org/10.1016/j.engfailanal.2022.106098

[2] F. Khoshnaw, C. Marinescu, A. Sofronia, C. Munteanu, M. Marcu, L.E. Barbulescu, C. Ciobota, E.M. Cojocaru, S. Tanasescu, A. Paraschiv, Microstructural and thermoanalytical characterization of super duplex stainless steel - UNS S32760-F55, Mater. Today Commun. 28 (2021) 102644. https://doi.org/10.1016/j.mtcomm.2021.102644

[3] N. Serban, V.D. Cojocaru, M.L. Angelescu, D. Raducanu, I. Cinca, A.N. Vintila, et al, High temperature deformation behaviour of an industrial S32760/1.4501/F55 super duplex stainless steel (SDSS) alloy, Metall. Ital. 111 (2019) 41-48.
[4] Z.W. Wang, S.Q. Zeng, X.H. Yang, C. Cheng, The key technology and realization of virtual ring rolling, J. Mater. Process. Technol. 182 (2007) 374-381. https://doi.org/10.1016/j.jmatprotec.2006.08.020
[5] L. Liang, L. Guo, J. Yang, H. Zhang, Formation mechanism and control method of multiple geometric defects in conical-section profiled ring rolling, J. Mater. Process. Technol. 306 (2022) 117628. https://doi.org/10.1016/j.jmatprotec.2022.117628
[6] L. Giorleo, E. Ceretti, C. Giardini, Speed Idle Roll Law Optimization in a Ring Rolling Process, Key Eng. Mater. 651–653 (2015) 248-253. https://doi.org/10.4028/www.scientific.net/KEM.651-653.248
[7] J. Zhou, X.T. Gong, X.B. Yang, W.J. Xu, Effect of Drive Roll Rotation Speed on Ring Rolling Process, Adv. Mater. Res. 189-193 (2011) 2586–2592. https://doi.org/10.4028/www.scientific.net/AMR.189-193.2586
[8] G. Allegri, L. Giorleo, E. Ceretti, C. Giardini, Driver roll speed influence in Ring Rolling process, Procedia Eng. 207 (2017) 1230–1235. https://doi.org/10.1016/j.proeng.2017.10.875
[9] W. Shen, F. Wang, Z. Yang, C. Li, P. Lin, X. Zhu, Investigation of the Crack Initiation and Propagation in Super Duplex Stainless Steel During Hot Working, in: Z. Peng, J.-Y. Hwang, J.P. Downey, D. Gregurek, B. Zhao, O. Yücel et al. (Eds.) 11th International Symposium on High-Temperature Metallurgical Processing, Cham: Springer International Publishing, 2020, pp. 157-67. https://doi.org/10.1007/978-3-030-36540-0_15
[10] G. Zhou, L. Hua, J. Lan, D.S. Qian, FE analysis of coupled thermo-mechanical behaviors in radial–axial rolling of alloy steel large ring, Computat. Mater. Sci. 50 (2010) 65-76. https://doi.org/10.1016/j.commatsci.2010.07.008
[11] W. Meng, G. Zhao, Y. Guan, The Effects of Forming Parameters on Conical Ring Rolling Process, The Scientific World Jo. 2014 (2014) 235656. https://doi.org/10.1155/2014/235656
[12] J.H. Kang, S.J. Heo, J. Yoo, Y.C. Kwon Hot working characteristics of S32760 super duplex stainless steel, J. Mech. Sci. Technol. 33 (2019) 2633-2640. https://doi.org/10.1007/s12206-019-0511-y
[13] A. Murillo-Marrodan, E. Garcia, F. Cortes, A Study of Friction Model Performance in a Skew Rolling Process Numerical Simulation, Int. J. Simul. Modell. 17 (2018) 569-582. https://doi.org/10.2507/IJSIMM17(4)441
[14] K.Q. Ye, M. Hamada, Critical Values of the Lenth Method for Unreplicated Factorial Designs, J. Qual. Technol. 32 (2000) 57-66. https://doi.org/10.1080/00224065.2000.11979971
[15] G. Vairamani, T.S. Kumar, S. Malarvizhi, V. Balasubramanian, Application of response surface methodology to maximize tensile strength and minimize interface hardness of friction welded dissimilar joints of austenitic stainless steel and copper alloy, Trans. Nonferrous Metal. Society of China 23 (2013) 2250-2259. https://doi.org/10.1016/S1003-6326(13)62725-9