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THE INFLUENCE OF THE SHAPE OF GROOVES ON THE INTENSITY OF CLOSING AXIAL MATERIAL DISCONTINUITIES DURING ROLLING

WPŁYW KSZTAŁTU WYKROJÓW NA INTENSYWNOŚĆ ZAMYKANIA OSIOWYCH NIECIĄGŁOŚCI MATERIAŁOWYCH W PROCESIE WALCOWANIA

The article discusses the influence of rolling in the newly designed slitting-bending grooves on closing internal material discontinuities in continuous ingots. The defects located in the axial area of a strand, i.e. axial porosity and contraction cavity, were analysed. Numerical and experimental studies of the rolling process of flat bars for feedstock with marked materials discontinuities simulating actual defects occurring in an ingot were conducted. For comparison purposes, rolling of feedstock with discontinuities in traditional grooves was conducted. The numerical simulations were carried out using the Forge 2008®software programme. The experimental studies were conducted in a D150 laboratory rolling mill. In the research, the S355J2G3 structural steel and lead were used. Distributions of temperature, intensity of deformation and stress in a cross-section of strands after rolling were analysed. Changes in the surface areas of the discontinuities in feedstock after rolling in shape and traditional grooves were examined.

It was concluded that introduction of grooves with complex shapes may contribute to the improvement of internal quality of finished products. The complex shape of the tools has allowed for an almost 100% closure of the discontinuities located in the central part of a strand, already at the initial stages of the process, unlike in case of the traditional production method, where the discontinuities were transferred even until the final product. Applying the newly designed slitting-bending grooves enables utilisation of a smaller number of edge grooves at the initial stage of the rolling process, where reopening of freshly welded defects might occur.

Keywords: defect, discontinuity, numerical simulation, slitting grooves, bending grooves

W artykule omówiono wpływ walcowania w nowo zaprojektowanych wykrojach rozcinająco-przeginających na zamykanie się wewnętrznych nieciągłości we wlewkach ciągłych.Analizowano wady znajdujące się w części osiowej pasma – rzadziznę osiową i jamę usadową. Wykonano badania numeryczne oraz doświadczalne procesu walcowania prętów płaskich dla wsadu z naniesionymi nieciągłościami materiałowymi symulującymi rzeczywiste wady występujące we wlewku. Dla porównania przeprowadzono walcowanie w wykrojach tradycyjnych wsadówz nieciągłościami. Do symulacji numerycznych wykorzystano program komputerowy Forge 2008®. Badania doświadczalne przeprowadzono w walcarce laboratoryjnej D150. Do badań zastosowano stal konstrukcyjną S355J2G3, oraz ołów. Analizowano rozkłady temperatur, intensywności odkształceń oraz naprężeń na przekrojach poprzecznych pasm po procesie walcowania. Analizowano zmianę pól powierzchni nieciągłości we wsadach po walcowaniu w wykrojach kształtowych oraz tradycyjnych.

Stwierdzono, że poprzez wprowadzenie wykrojów o złożonym kształcie można wpływać na polepszenie jakości wewnętrznej wyrobów gotowych. Złożony kształt narzędzi pozwolił wprawie 100% zamknąć nieciągłości znajdujące się w części środkowej wsadu już w początkowych etapach procesu walcowania, w przeciwieństwie do tradycyjnej metody wytwarzania, gdzie wady przenoszone były nawet do końcowego wyrobu. Poprzez zastosowanie nowych wykrojów rozcinająco-przeginających możliwe jest zastosowanie mniejszej ilości wykrojów osadczych w początkowym etapie procesu walcowania, w których może wystąpić otwieranie się świeżo zgrzanych wad.

1. Introduction

The issues related to the process of closing material discontinuities in plastically deformed material were the subject of many studies conducted in the Institute of Metal Forming and Safety Engineering at Czestochowa University of Technology [1÷4]. On the basis of these studies, it was confirmed that the intensity of closure and welding of metallurgical defects in rolled strands is significantly influenced by the key technological parameters, such as rolling reduction, shape and order of applied rolling grooves, temperature of the deformed strand and location of the defects [1÷6]. Moreover, it is important that the initial processing of ingots, in which material discontinuities occurred after casting, was conducted in a way

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that enables closure of the discontinuities as soon as possible. Early closure of a discontinuity gives a bigger chance of welding it completely. Considering that, the most effective rolling variants are those that facilitate quick contact between the opposite surfaces of the discontinuities, what happens as a result of interaction between the compressive vertical and the tensile transverse components of normal stress. After closing a discontinuity, it is beneficial to use grooves and process parameters that will not contribute to reopening of the discontinuity [5].

2. Purpose and scope of the study

The main purpose of plastic processing is obtaining, among other things, the required shape and the right internal quality of finished products. Defects occurring in feedstock can be transferred till the end of rolling process and they frequently contribute to deterioration in strength and plastic properties of hot rolled products. The difficulties in obtaining satisfying internal quality of feedstock inspired studies on the behaviour of internal material discontinuities during plastic forming processes. A new way of rolling of flat bars with forced widening in complex-shaped grooves was designed. Rolling of 200×20 mm flat bars from 160×160 mm feedstock was conducted in eight passes. Rolling in the first rolling stands has the biggest influence on closure of defects [1,7], therefore, the process was designed in a way that enables annihilation of discontinuities in the first three shaped groves. Figure 1 presents the three shaped grooves designed for rolling flat bars. After rolling in them, the strand was subjected to plastic forming, consecutively on flat barrels and in edge grooves.

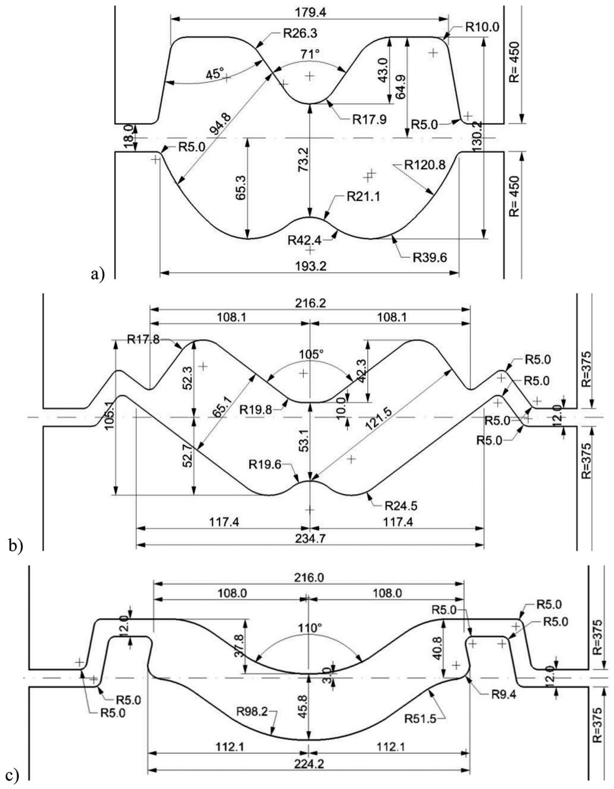


Fig. 1. Shaped grooves for rolling flat bars from a 160×160 mm feedstock: a) slitting groove; b, c) bending grooves

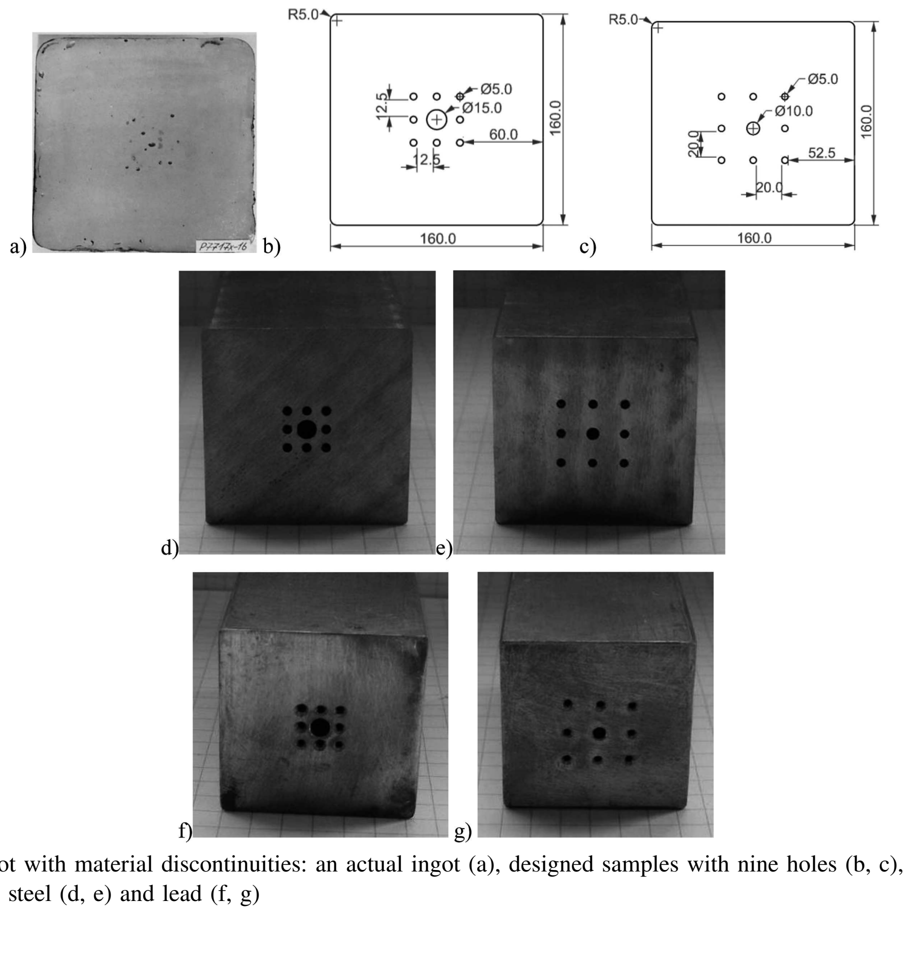


Fig. 2. Images of an ingot with material discontinuities: an actual ingot (a), designed samples with nine holes (b, c), and designed samples for experimental studies: steel (d, e) and lead (f, g)

The material used for the study was S355J2G3 construction steel and lead. Holes were placed in the sample so they could simulate real material discontinuities located in the axial part of a continuous ingot, i.e. axial porosity and contraction cavity. Figure 2 shows an image of an actual ingot with discontinuities (Fig. 2a), designed samples with nine holes (Fig. 2b, c), and samples (Fig. 2-c) for experimental studies: steel (Fig. 2d, e) and lead (Fig. 2f, g) with identically placed holes.

3. Numerical results

For the computer simulations of rolling of flat bars conducted in the Forge 2008®programme, the following rolling conditions were assumed: initial feedstock temperature prior to rolling – 1150°C for the S355J2G3 steel; temperature of the rolls – 60°C; friction coefficient – μ = 0.8, friction factor – m = 0.85; rotational speed of the rolls – 8.5 rpm. A rolling process of feedstock with placed axial discontinuities with the use of shaped grooves in eight passes was conducted. For comparison purposes, numerical studies for rolling in traditional grooves were carried out. Calibration was designed in a way that enabled obtaining the same final measurements for both of the processes (Table 1). Tables 1 and 2 present the measurements of the grooves and the key parameters for the rolling process in shaped and traditional grooves.

The data in Table 1 indicate that rolling feedstock in shaped grooves caused better elongation of the strand in the initial passes, compared to traditional rolling, which positively influenced the process of closing internal material discontinuities. The data in Table 2 indicate that introduction of rolling in shaped grooves may improve productivity of a rolling mills by reducing the number of passes from 14 to eight. Application of shaped grooves enables obtaining comparatively large relative unit reduction ε (about 35%) at the initial stage of rolling, which contributes to faster closure of internal material discontinuities. In case of traditional rolling, introduction of such deformation is impossible, because as a result of it the strand might become barrel-shaped, side surfaces of the strand might crack, and placing feedstock in a groove might be difficult. During rolling in shaped grooves introduced at the initial stage of the process, the number of edge grooves was also reduced, and edge grooves introduced at the initial stage of the process may contribute to reopening of freshly welded defects [7]. In the designed rolling process, the first edge groove was introduced only in the fifth pass.

TABLE 1

Measurements of the grooves and key parameters for rolling of 200×20 mm flat bars in shaped and traditional grooves

Pass no.	Diameter of Rolls D, mm	Groove shape	Strand measurements, mm				Surface area of a cross section of a strand P, mm^2		Elongation factor λ	
			Traditional system		Shaped grooves		Traditional system	Shaped grooves	Traditional system	Shaped grooves
			h	b	h	b				
			160	160	160	160	25600	25600		
1	700/ 900	Barrel/ *Slitting*	134,51	71,57	73,30	189,40	22787,1	19659,2	1,12	1,30
2	700/ 750	Barrel/ *Bending*	101,74	88,76	53,60	212,30	19127,1	14202,2	1,20	1,38
3	700/ 750	Edge/ *Bending*	103,14	78,03	45,80	223,40	18058,4	10059,5	1,06	1,41
4	700	Barrel	85,33	87,05	30,00	248,94	15947,4	7359,0	1,13	1,36
5	700/ 500	Barrel/ *Edge*	70,04	92,68	35,39	207,96	13473,5	6635,6	1,18	1,11
6	600/ 500	Edge/ Barrel	71,88	89,22	24,14	214,34	13267,4	5157,3	1,02	1,28
7	600/ 500	Barrel/ *Edge*	46,08	202,78	24,53	199,97	9308,1	4913,4	1,42	1,10
8	600/ 430	Barrel	30,10	211,21	20,3	200,7	6438,8	4093,4	1,44	1,20
9	500	Edge	31,68	207,96	-	-	6293,5	-	1,02	-
10	500	Barrel	24,11	210,58	-	-	5072,7	-	1,24	-
11	500	Edge	25,76	203,74	-	-	4975,2	-	1,02	-
12	500	Barrel	21,62	208,68	-	-	4500,1	-	1,12	-
13	500	Edge	24,52	199,97	-	-	4418,5	-	1,02	-
14	430	Barrel	20,1	200,6	-	-	4039,4	-	1,10	-

TABLE 2

Key parameters for rolling of 200×20 mm flat bars in shaped and traditional grooves

Pass no.	Traditional system				Shaped grooves			
	Absolute reduction Δh, mm	Relative reduction ε	Reduction coefficient γ	Absolute widening Δb, mm	Absolute reduction Δh, mm	Relative reduction ε	Reduction coefficient γ	Absolute widening Δb, mm
1	25,5	0,16	0,84	11,6	56,2	0,35	0,46	29,4
2	32,7	0,24	0,73	17,2	19,7	0,27	0,73	22,9
3	10,7	0,06	0,94	1,4	7,8	0,15	0,85	11,1
4	17,8	0,17	0,83	9,0	15,8	0,34	0,65	25,5
5	15,3	0,18	0,82	5,6	5,4	0,18	0,84	5,4
6	3,5	0,02	0,98	1,8	11,2	0,32	0,68	7,0
7	25,8	0,36	0,64	13,6	10,5	0,05	0,96	2,9
8	15,9	0,35	0,65	8,4	5,3	0,19	0,82	4,1
9	3,2	0,02	0,98	1,6	-	-	-	-
10	7,6	0,24	0,76	2,6	-	-	-	-
11	6,8	0,03	0,97	1,6	-	-	-	-
12	4,1	0,16	0,84	6,8	-	-	-	-
13	8,7	0,04	0,94	2,9	-	-	-	-
14	4,4	0,18	0,82	0,6	-	-	-	-

On the basis of the conducted numerical simulations, temperature distributions (Fig. 3) in cross sections of particular strands after rolling in three shaping and traditional grooves were obtained.

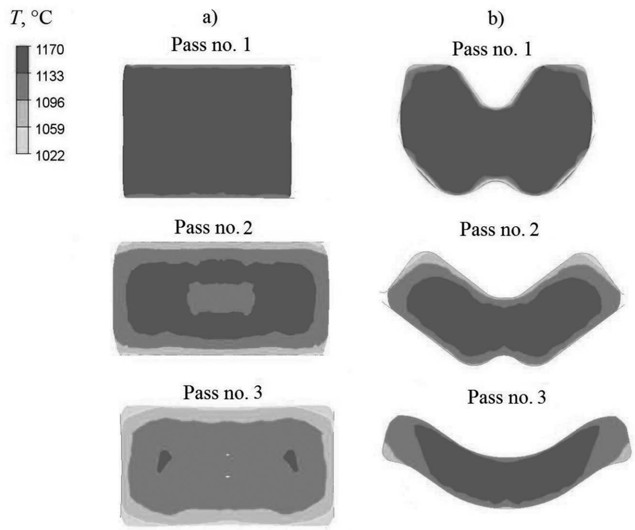


Fig. 3. Temperature T distributions on a cross section of a strand rolled in three passes in traditional (a) and shaped grooves (b)

The data in Figure 3 indicate that due to the shape of the first three shaped grooves, the temperature of the metal in the central part of the strand remains high (about 1170°C) for a longer period of time, and that causes better closure of internal material discontinuities in that area, compared to rolling in traditional grooves.

Moreover, an analysis of distribution of the intensity of stress σ_i (Fig. 4) and deformation ε_i (Fig. 5) during rolling of flat bars from the studied steel in the three first shaped and traditional grooves was conducted.

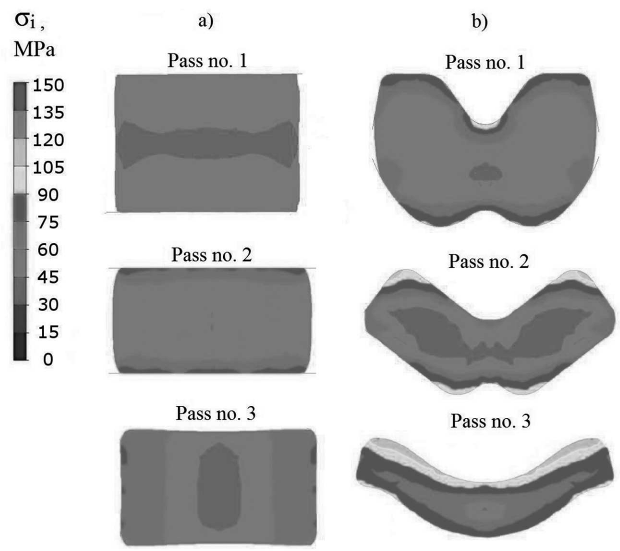


Fig. 4. Distributions of the intensity of stress σ_i on a cross section of a strand rolled in three passes in traditional (a) and shaped grooves (b)

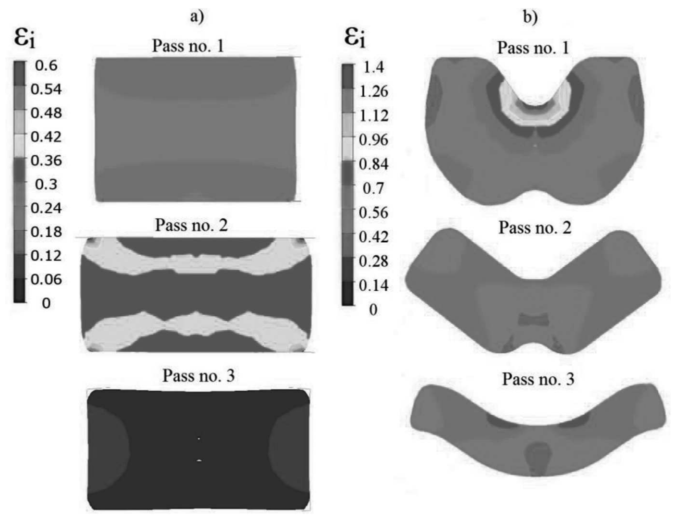


Fig. 5. Distributions of the intensity of deformation ε_i on a cross section of a strand rolled in three passes in traditional (a) and shaped grooves (b)

The analysis of the results of numerical modelling for rolling flat bars in shaped and traditional grooves presented in Figures 4 and 5 indicates that the average values for the intensity of stress σ_i in a cross section of the strand at the exit from the rolling gap were about 30% higher in case of rolling with the use of shaped grooves. The average values for the intensity of deformation ε_i in shaped grooves in a cross section of the strand rolled in the first three passes were about 60% higher compared to rolling in traditional grooves. The higher values of the intensity of stress and deformation contributed to better closure of axial discontinuities in the strand rolled in shaped grooves.

Thereafter, an analysis of average stress σ_m during rolling of flat bars from the studied steel in three traditional and shaped grooves was conducted. In order to determine the values of average stress σ_m in particular points, where discontinuities were located, the value of main stresses σ_1, σ_2, σ_3 was measured, and with the use of correlation (1) the average stress σ_m was defined.

$$\sigma_{m=}(\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{1}$$

Figure 6 presents calculated values for average stress σ_m in the places where axial defects occur, as well as in the places where no defects were observed in three shaped and traditional grooves.

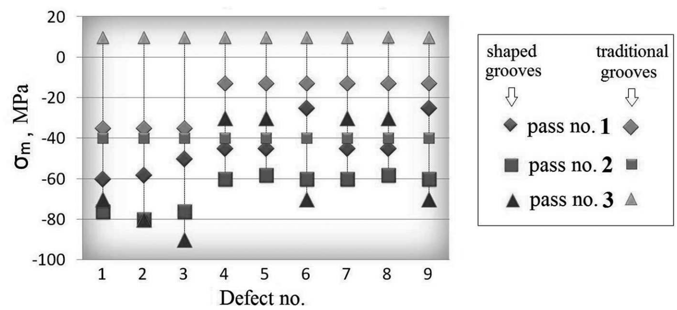


Fig. 6. Average stress σ_m in the places where particular defects are located within a strand rolled in shaped and traditional grooves, in three passes

The data in Figure 6 indicate that the average stress σ_m in shaped grooves at the core of the bar takes high negative values in between about -70÷-90 MPa, with a compressive character. Such values of average stress σ_m in the places where defects are located enabled closure of the defects already in the first three passes, e.g. the defects marked with numbers 1÷3. During rolling in traditional grooves, the values of average compressive stress σ_m were not high enough (about -40 MPa) to cause closure of the discontinuities in the first passes.

According to the references [8], the biggest air gaps, considering their volume, appear in the axial part of an ingot. Therefore, in order to eliminate those discontinuities, high average compressive stress σ_m must be forced in the central part of the strand, which is difficult in case of traditional rolling. However, it can be easily obtained by introduction of shaped grooves.

Relative changes in surface areas of the axial discontinuities (contraction cavity – batch no. 1, axial porosity – batch no. 2) were also analysed within the scope of the study, based on numerical modelling for rolling flat bars in shaped and traditional grooves (Fig. 7). The surface area of cross sections of the defects in the sample before rolling amounted to 331.4 mm^2 in the first case, and 233.6 mm^2 in the second case.

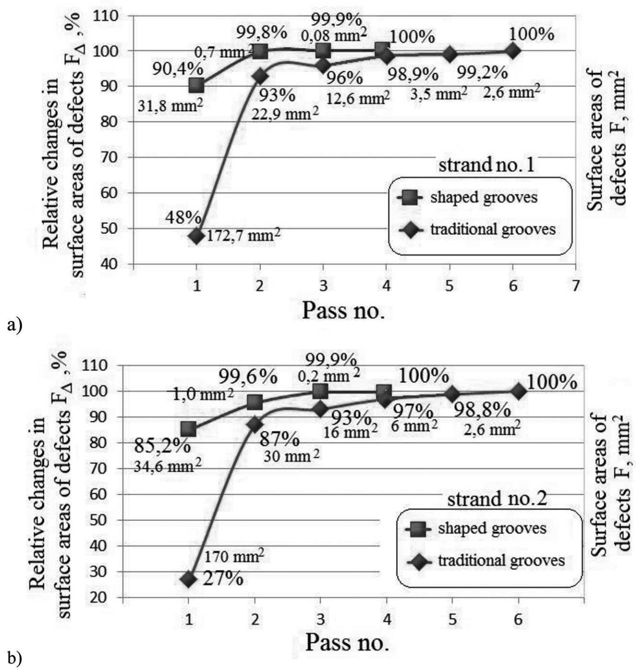


Fig. 7. Relative change in the surface areas of defects during rolling in particular passes in feedstock with discontinuities in the form of: a) contraction cavity; b) axial porosity

The data presented in Fig. 7 indicate that the closure of discontinuities was more successful during rolling in shaped grooves, compared to rolling in traditional grooves. During rolling in shaped grooves complete closure of discontinuities (100%) took place in the fourth groove, while in case of traditional rolling only in the sixth one. In case of shaped grooves, the discontinuities closed in the first groove in 88% on average, in the second groove in 99.7%, in the third groove in 99.9%, and in the fourth one in 100%. In case of traditional grooves, the discontinuities closed in the first groove only in 37% on average, in the second groove in 90%, in the third groove in 94%, in the fourth groove in 98%, in the fifth groove in 99%, and reached 100% only in the sixth one. The total surface area of the discontinuities was reduced almost 10 times already in the first groove during rolling in shaped grooves, compared to traditional rolling where the discontinuities were reduced only two times.

Additionally, discontinuities located in the central part of the feedstock in the form of defects with a diameter of 15 and 10 mm (Fig. 8) were analysed.

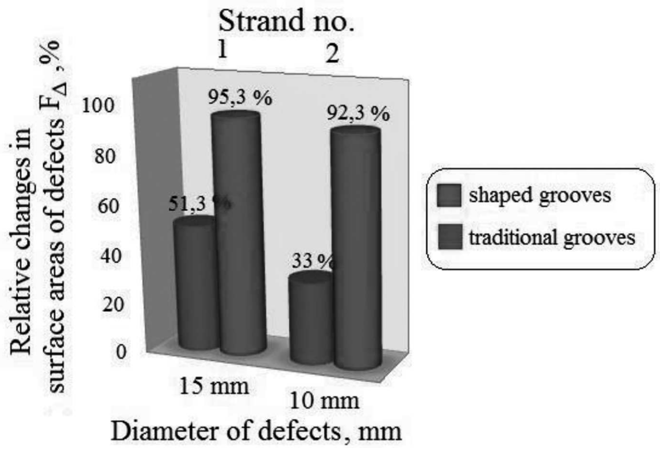


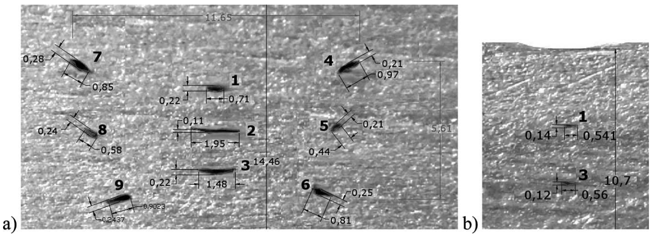
Fig. 8. The diagram of closing discontinuities with 15 and 10 mm in diameter in the central part of feedstock, after rolling in the first groove

Figure 8 indicates that the discontinuities in the central part of the feedstock were also closing more successfully in shaped grooves, compared to traditional grooves. In the first pass, the discontinuities in shaped grooves were closing in 94% on average, while in traditional grooves only in 42%. In the second pass, the discontinuities in shaped grooves were closed completely (100%), while in traditional grooves they were carried on even until the fifth pass.

4. Experimental study

During the first phase of experimental studies, rolling of feedstock with discontinuities took place in a D150 mm rolling mill owned by the Institute of Metal Forming and Safety Engineering at the University of Technology in Częstochowa. Grooves and samples used for the research were appropriately scaled for the purpose of laboratory studies. Moreover, numerical studies for the downsized feedstock were conducted for later comparison with the results of experimental studies.

The initial model material was lead, which enabled rolling of bars at ambient temperature. Further studies were conducted with the use of S355J2G3 steel as feedstock. The placement of holes in the samples was the same as in case of numerical simulations. After rolling, lead samples were scanned and edited in the AutoCad®programme, and then surface areas of the discontinuities were determined (Fig. 9).



a) b)

Fig. 9. An image of axial defects in a template from a lead sample after rolling in a) the first groove; b) the second groove

Then, the relative change in surface areas of axial discontinuities (contraction cavity – batch no. 1, axial porosity – batch no. 2) in lead samples after rolling in three shaped grooves were analysed (Fih. 10).

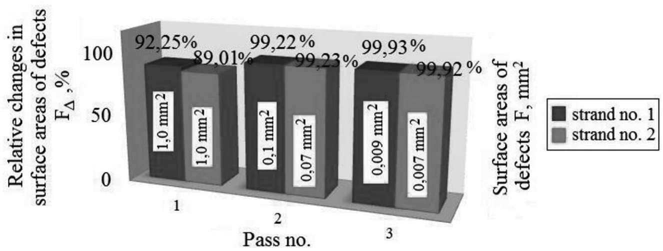
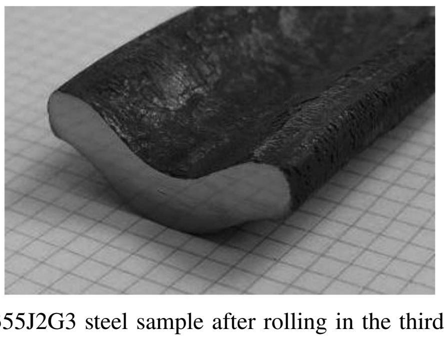


Fig. 10. Relative change in the surface areas of axial defects during rolling of lead samples in three shaped grooves

The data in Figure 10 indicate that during rolling of lead samples in shaped grooves, axial discontinuities were closing in the first groove in 91% on average, in the second groove in 99%, and complete closure (100%) was obtained in the third one. The difference in closure of discontinuities during laboratory and numerical studies was small and did not exceed 1%.

Then, the discontinuities placed in steel samples were analysed. An optical microscope – Nikon Eclipse MA-200 – was used for observation. Figure 11 presents an image of one of the samples after rolling in the third shaped groove, while Figures 12÷14 present examples of traces of the discontinuities in samples after rolling, with magnification of 50 and 200x. Next, the size of each defect was determined and relative changes in surface areas of axial discontinuities (contraction cavity – batch no. 1, axial porosity – batch no. 2) in steel samples after rolling in the third shaped groove were analysed (Fig. 15).



a)

Fig. 11. A S355J2G3 steel sample after rolling in the third groove

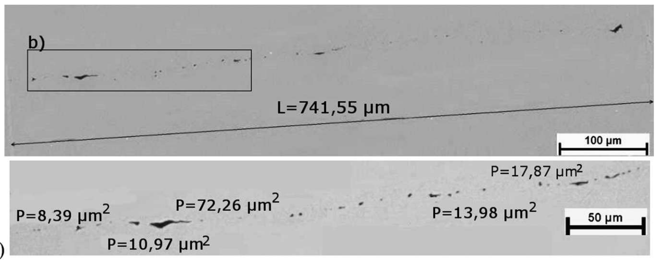


Fig. 12. Remains of the defect 2 after rolling in the 3^{rd} groove: a) general view of the defect, magnification of 50x; b) parts of the defect, magnification 200x

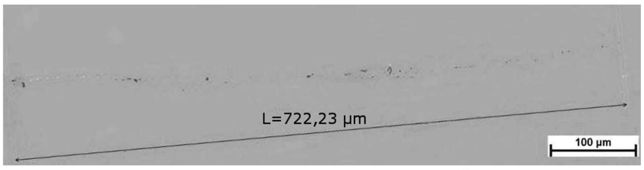


Fig. 13. Remains of the defect 3 in the sample after rolling in the 3^{rd} groove: a) general view of the defect, magnification of 50x

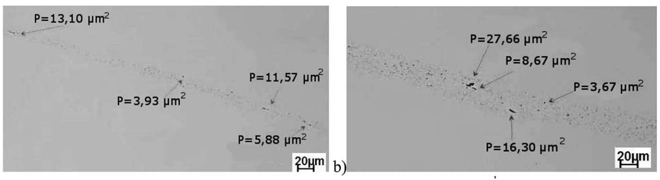


Fig. 14. Remains of the defects 8 and 9 in the sample after rolling in the 3^{rd} groove: a) part of the defect no. 8, magnification 200x; d) part of the defect no. 9, magnification 200x

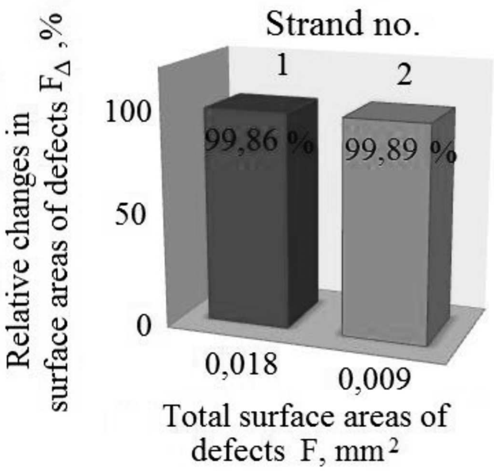


Fig. 15. Relative change of the total surface areas of defects in two batches with axial discontinuities after rolling in the 3^{rd} groove

The data in Figure 15 indicate that all the discontinuities were closing in about 99.8% on average. Most of the defects in the sample closed completely. The remains of discontinuities were only traces of closed defects, and most of the discontinuities can be considered as completely closed, because they show no signs of possible reopening in the future. The difference in surface areas of the discontinuities in the samples after numerical and laboratory studies was minor and did not exceed 0.1%.

5. Conclusions

The numerical and experimental examinations carried out within this study found the following:

- Closure of internal axial discontinuities is mostly influenced by the applied reduction and the shape of a rolling gap;
- Introduction of new slitting-bending grooves contributed to faster closure of discontinuities in the central part of feedstock in the first groove, where they were closing in about 94%, while in the second one they already reached complete closure, without leaving any traces. In case of traditional rolling, the discontinuities were closing only in 42% in the first groove, and complete closure took place in the sixth groove;
- Application of appropriately large reduction in the initial shaped grooves enables easy elimination of material discontinuities in continuous ingots, and thus improvement of the quality of finished products;
- In case of traditional rolling, all axial discontinuities in feedstock were carried on event until the sixth pass, while in case of rolling in shaped grooves, the discontinuities were completely closed already in the fourth pass;
- During rolling in shaped grooves, the average compressive stress σ_m at the core of the strand amounted to -70MPa, which contributed to closure of material discontinuities already in the first grooves;
- Replacing traditional calibration of a 200×20 mm flat bar from a 160×160 mm feedstock with calibration with shaped grooves enables rolling in a smaller number of passes, which should reduce the rolling time and the costs associated with operation of rolling mills.

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