MODELLING THE EVOLUTION OF CASTING DEFECT CLOSURE BY RADIAL SHEAR ROLLING

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ABSTRACT

This paper studies the behavior of a transverse through defect in an ingot during complex vortex flow of metal deformed by the radial shift rolling (RSR) method. The aim of the work was to investigate the applicability of the RSR method for the deformation treatment of oxide-dispersed strengthened steel (ODS-steel) ingots into a final semi-finished product. Vortex flow of metal promotes dispersion of alloying solid oxides and refinement of steel structure. However, the question of development or closure of possible casting defects of ODS-steel ingot remains open. For this purpose, an ODS-steel ingot with a through-hole modelling the defect was rolled according to the assumed process scheme. Also, to visualize the evolution of the defect in more detail during the rolling process, a simulation of the same defect development in an aluminum bar has been performed in 2 mm steps. The results of both rolls showed good correlation. Based on many cross-sections of the experimental bars, detailed 3D models of the defect evolution were built. An average reduction of 50 % in defect volume was found. Welding of the outer areas occurs immediately, but the central areas remain unclosed, stretching proportionally with the drawing of the rod during rolling. For this reason, RSR cannot be used with large cavity defects in the axial zone, but this method is guaranteed to weld surface defects even at low reductions.

Keywords: ODS steel, RSR, rolling, aluminum rod, defect evolution, 3D modelling.

INTRODUCTION

This work is part of a series of investigations on the production of ODS steels by liquid metallurgy methods. The steel used in the study of the possibility of injecting yttrium oxide nanopowder into the liquid melt of 12 % Cr steel during induction vacuum melting was taken as the basis of the experiment. ODS steel is one of promising materials for use in Generation IV+ nuclear power plants [1]. Solid refractory oxides (yttrium or titanium) penetrating into austenite grains during casting anchor them, playing the role of nickel in heat resistant stainless steels. Nickel decays to long-lived, dangerous radioactive isotopes when irradiated by neutrons, so it is important to find a substitute. In addition, highly dispersed oxide particles serve as runoff surfaces for radiation defects, reducing the irradiation damage to steel. The main problem is that such steel is reliably produced so far only by methods of mechanical alloying of powders, steel and oxides in mills followed by sintering by powder metallurgy methods. Of course, all the disadvantages of powder metallurgy also apply to the production of such steel.

The solution could be to produce ODS steel by conventional liquid metallurgy methods with remelting and large ingots suitable for mass production. However, even with the injection of alloying elements into the steel, it must be ensured that they are evenly spread in the volume of the material. This is only possible by applying very large deformations with non-monotonic metal flow. In addition, it is necessary to ensure that the normal casting defects that arise during the casting process are closed.

Steel ingots not subjected to additional pressure treatment can contain internal defects such as cracks, axial porosity, accumulation of microscopic gas bubbles and cavities in the steel volume. The worst-case scenario is that the defect is formed early in the process and remains unaccounted for in subsequent stages, resulting in the development of a defect in the steel [2, 3].

Traditionally forging has been used for defect closure and welding. There is a whole field of theoretical and experimental research devoted to intensifying the defect closure process [3, 4]. In most cases hot forging is used, with flat strikers [4]. Anvil stroke speeds in the range of 8 - 20 mm/s are used [4 - 6], with pattern compression of 15 - 20 % and temperatures of 1200^{o}C - 1250^{o}C [3 - 7].

The use of rolling as the main method for closing ingot imperfections is the least common, both in practice and in theory, due to the higher level of tensile stresses detrimental to defect closure [8, 9]. More often it is used to get rid of shrinkage voids and pores and blowhole occurring during casting of ingots [10 - 12].

In addition, these classic methods realize a monotonous flow of metal and lead to a significant reduction of the cross-section of the billet. This is not useful from the point of view of grinding and dispersing the alloying oxides embedded in the steel.

For these purposes it is planned to use the method of severe plastic deformation (SPD) treatment of the ingot at once. The method of Radial Shear Rolling (RSR) invented by Prof. Galkin [13, 14] is most suitable for these purposes in terms of realized metal vortex flow and favourable stress-strain state. The rolling scheme is shown in Fig. 1.

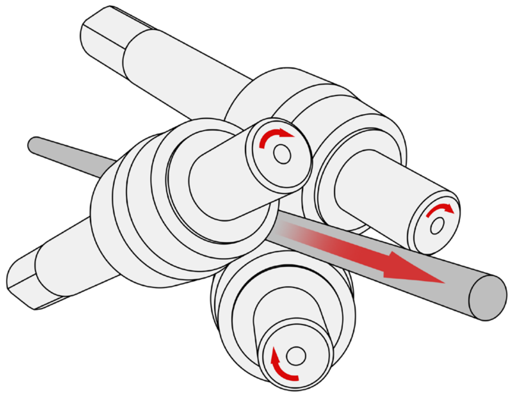

Fig. 1. Radial shear rolling scheme.

The three-roller RSR rolling scheme provides an extremely high level of deformation (more than 30 mm/mm). The stress-strain state of this process differs from conventional two-roll oblique rolling for pipe piercing [15]. RSR does not have a high level of tensile stresses in the central zone, they are balanced by compressive stresses. This fact, as well as the enormous level of accumulated strain, allows a significant change in the structure of the sample to the ultrafine grain state (UFG), which was demonstrated in [16]. This type of rolling was used for rolling austenitic steel ingots in [15]. However, no one has studied the behavior and closure of defects in the ingot by RSR.

To investigate this question, an experimental study of the evolution of a through transverse defect model (in diameter) in an ingot of stainless ODS steel with 61 % compression was carried out. Such a compression, according to the results of past studies, is enough for intensive mixing of the whole bar volume by vortex motion of metal and transformation of peripheral third of the bar radius into ultrafine grained state [16].

In order to visualize in more detail, the evolution of the through transverse defect, the evolution of the same defect in an aluminum bar was additionally simulated in 2 mm diameter increments (6 bars in total from 25 mm to 13 mm). It was decided to investigate transverse defects because the RSR process has a gradient strain level of the metal flow directions along the radius and this will most fully illustrate the processes occurring with defects at different depths along the radius.

EXPERIMENTAL

In defect research the most common method of defect characterization is X-ray tomography, which has a good ability to detect defects in a large volume of material [17, 18]. But this procedure requires expensive equipment [19], which is usually found in industrial plants with high material requirements in areas such as airspace, aircraft, medicine, etc. [20]. The most important disadvantage of this method in long-term use is considered to be the change of internal or surface properties of the material, such as texturing or plastic deformation as well as the accuracy of defect localization [21, 22].

The spatial resolution of most X-ray tomography instruments is limited to a low accuracy of more than 1 mm, while microscopic examination of metal sections containing the defect can characterize defects many times smaller in size and, most importantly, evaluate the defect metal joint in terms of microstructure at the defect welding points [23]. Therefore, we selected the method of examination of the defect by cutting the section with the defect into a number of cross-sections and visualization of the evolution of the defect by means of 3D modeling. Some of the most characteristic sections were examined with a microscope.

The experimental part was carried out on a radial shift rolling mill RSR-10/30. For the first part of the practical experiment, steel 12Cr with a diameter of 32 mm and a length of 150 mm was taken. The ingot was melted in an induction vacuum furnace UIPV-0.001. Before rolling, a through-hole was drilled in the cross-section of the ingot to simulate the defect. The diameter of the hole for modelling the defect was chosen to be 5 mm, which is 16 % of the ingot diameter.

The steel was rolled at 1200ºC and the aluminum was rolled at 400ºC. The steel ingot and aluminum bar were heated in a Nabertherm LH30/14 chamber furnace. In the case of steel, rolling was carried out in 6 steps with a reduction of 2 mm in diameter from 32 mm to 20 mm per heating step. The result of steel rolling is shown in Fig. 2.

For the second part of the practical experiment, an aluminum bar with a diameter of 25 mm was taken. The defect was artificially drilled into the cross section of the ingot with a diameter of 5 mm, which was 20 % of the diameter of the aluminum bar. Many similar studies are based on such limiting defect size ratios [4, 24, 25]. This approach has implications for generalizing the defect history for known experiments. Since in this case it was necessary to investigate the evolution of the defect in several intermediate states of its development, the experiment was optimized into a sequential rolling of 2 bars of 180 mm length with 3 identical holes with 5 mm diameter. The length of the bar was conditioned by the technical limitations of the equipment.

Aluminum was also rolled at the normal hot rolling temperature of this material of 400ºC. After each rolling step the aluminum was cooled down to room temperature, part of the bar with the defect was cut off, and the bar was heated further to the continued roll the remaining defects to appropriate dimensions along the route of 25 mm - 23 mm - 21 mm - 19 mm - 17 mm - 15 mm - 13 mm. At each point a piece of rod containing the defect was cut off to further characterize the current stage of development. The final diameter of the rolled aluminum was 13 mm, which is the smallest possible rolling diameter of the mill. The rolled aluminum specimens are shown in Fig. 3.

Each of the samples at the defect location was

Fig. 2. The final sample of rolled steel.

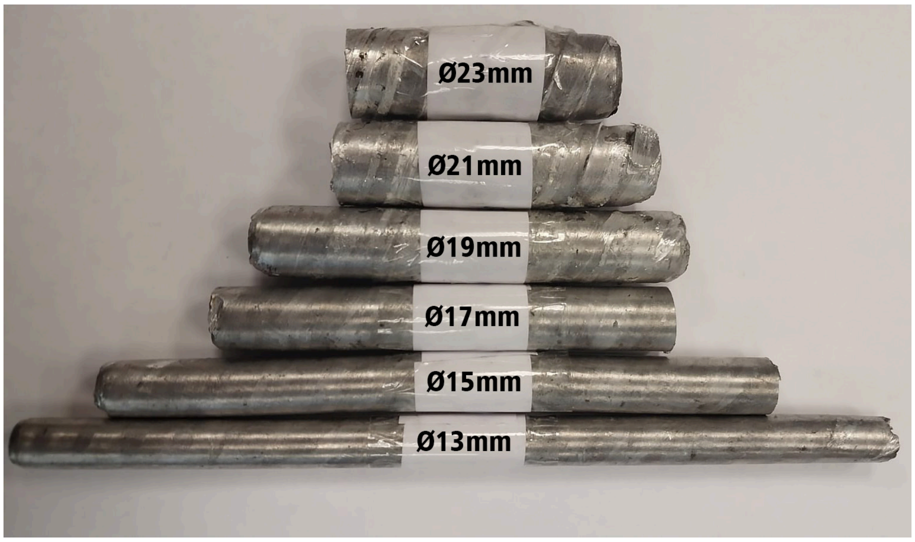

Fig. 3. Final aluminum rolling samples for the various stages of defect formation.

cut into 1 mm thick cross-sectional discs on a QATM Brilliant-220 precision cut-off machine, with a 0.6 mm thick disc. The steel cross section discs are shown in Fig. 4. Aluminum section discs are shown in Fig. 5.

The cut discs were numbered and scanned with a 1200 DPI scanner, and imported into CAD KOMPAS-3D (ASKON), to convert the drawings into vector graphics. Based on these sections, a 3D model of each defect was created to visualize the stage of evolution of its shape to determine how its volume changed.

Medium disc sections of 23 mm aluminum (first pass), 13 mm (last pass) and the last pass of steel were examined with a JSM IT-200LA scanning electron microscope (Jeol) and an accelerating voltage of 30 kV with a backscattered electron detector (BSE-C) image construction. The study was performed with pressed-on CitoPress-15 (Struers), ground and polished on Sapphire-220 (ATM). Metallographic etching was not performed as the grain structure was visualised by the back-reflected electron detector and etching would have damaged or masked cracks and traces of welding defects.

RESULTS AND DISCUSSION

Experimental rolling of an ODS steel ingot revealed incomplete and irregular closure of the defect, indicating challenges in achieving a uniform structure. The cross-sectional analysis vividly displayed variations in the direction of metal flow across the section, reflecting the complex dynamics during the rolling process. These observations underscore the need for further refinement in the rolling technique to enhance defect closure and attain a more homogeneous material structure. Understanding and optimizing the flow dynamics will be crucial in achieving desired material properties and structural integrity in ODS steel production. The defect volume decreased from 620 mm^3 to 380 mm^3. A visualization of the defect development after rolling is shown in Fig. 6.

A defect close to the outer layer is welded almost completely on one side, while the other side is partially welded or closed, forming a narrow crack without a joint from a through defect. This happened because the radial shear rolling process takes place most intensively at the peripheral part of the bar and the material deformation takes place there first of all. This makes it possible to predict the efficiency of the process in the presence of shallow asymmetrical surface defects up to one-third of the ingot radius.

The results of investigation of stage-by-stage evolution of through defect in aluminum bar rolling at every 2 mm of diameter reduction are shown in Fig. 7.

In aluminum samples the defects on the surface are welded completely, forming a cavity only in the center, as in steel samples. The cavity stretches according to the direction of metal flow in the central area of the rod. This is due to the pulling of the sample along the rolling, and the lack of active deformation in the central zone,

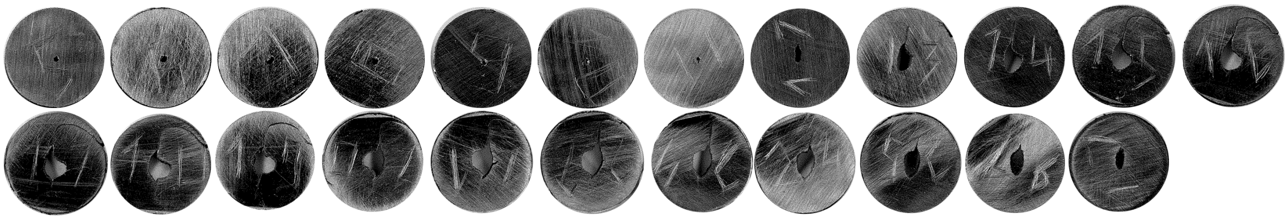

Fig. 4. Cut steel discs.

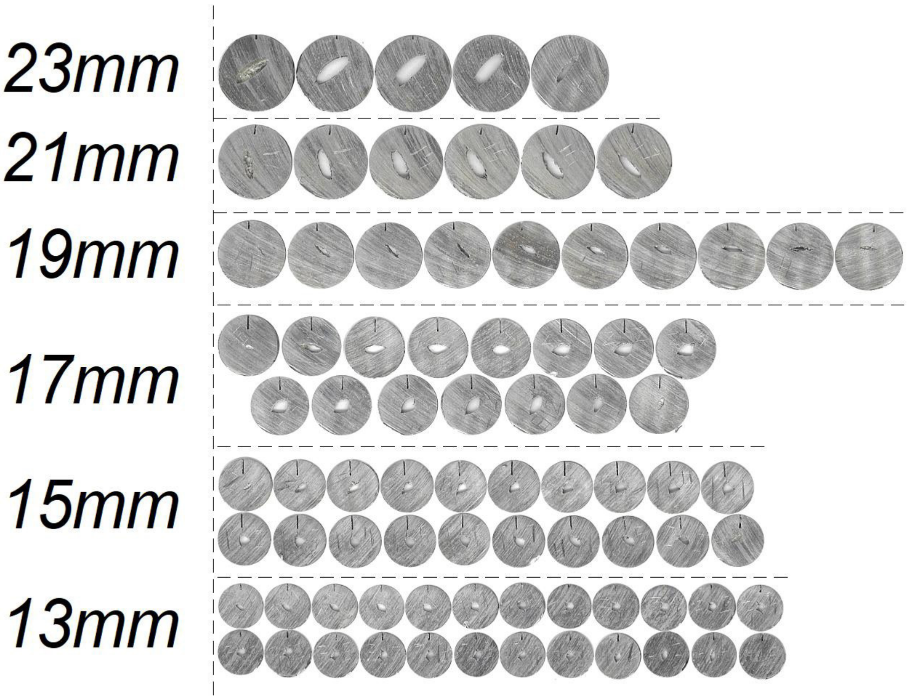

Fig. 5. Cut aluminum discs.

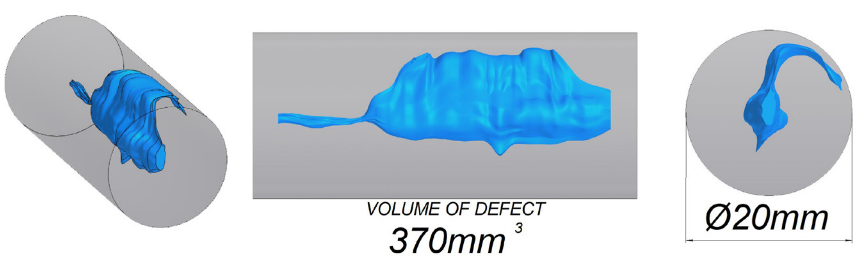

Fig. 6. Visualization of the development of a transverse through defect in a steel ingot after radial shear rolling at 61 % compression.

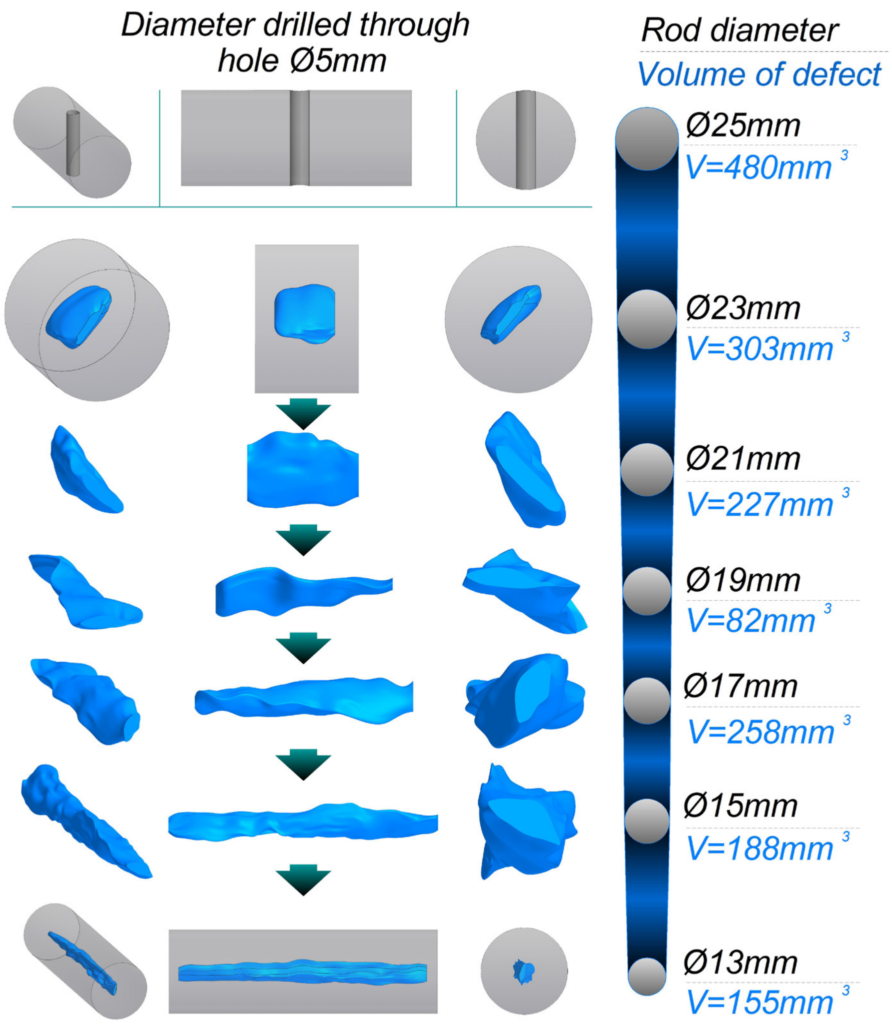

Fig. 7. Visualization of the evolution of a transverse through defect in aluminum rolling with a rolling step of 2 mm in diameter.

as actively occurs in the periphery due to the contact of the bar with the rolls of the mill. At the same time, there is a noticeable twisting of the cavity at its outer edges according to the rotation of the billet and the eddy current vectors of the metal at these points of the rod radius. FEM-study of the stress-strain state of the bar and the flow of metal at RSR was conducted earlier in [16]. Apparently, despite the predominance of compressive stresses during rolling of solid rod as in the known sources, their balance is very fragile and monotonic flow of metal in the very axial part of the rod predetermines the stretching of defect cavity.

Particularly notable is that the closure of surface defects occurs already in the first rolling pass with only 2 mm (15 %) compression, leaving only the axial defect, but reducing its diameter along the radius of the bar, and increasing it along the axis.

The volume of the defect is significantly reduced from 480 mm^3 to 155 mm^3. This is more than 67.7 % of the original defect volume and is greater than for steel rolling (40.3 %), although the general pattern of defect development is quite obvious. The difference is probably due to the known dynamic instability of the radial shear rolling process and the possibly thicker scale layer on the steel specimen. Although, the lower part of the defect is fully welded. Microscopic examination can provide

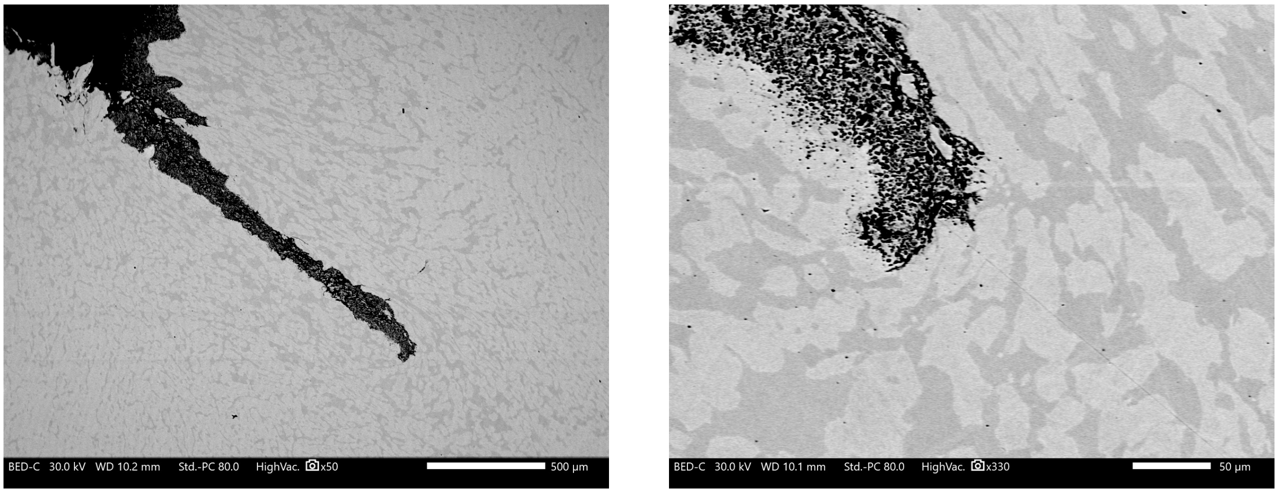

Fig. 8. Welding point for a through cross-sectional defect in final steel specimen.

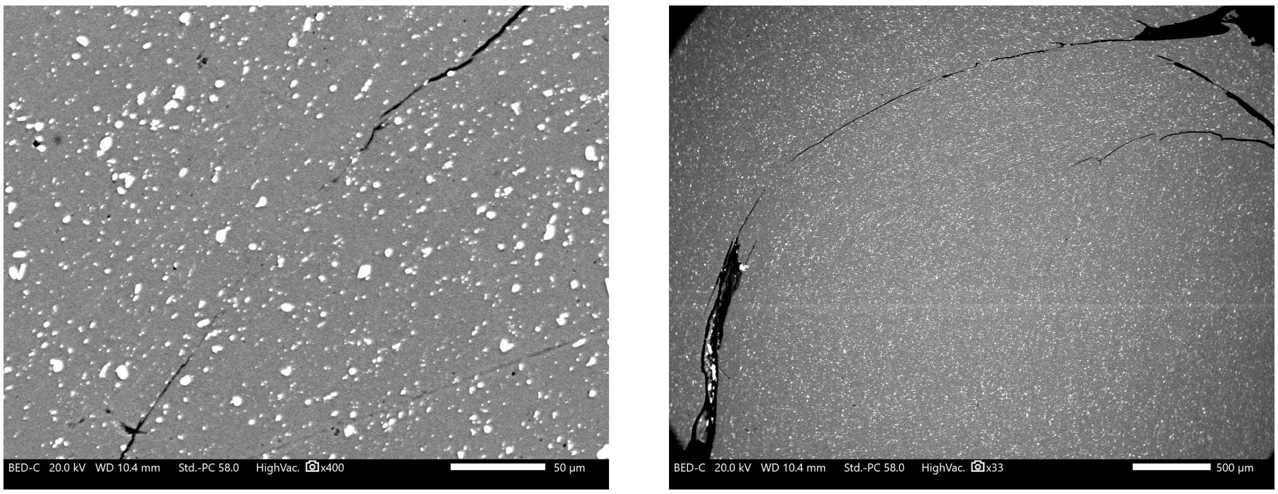

Fig. 9. Welding point for a through cross-sectional defect in first pass aluminum specimen.

more definite answers.

Electron microscopy techniques were used to examine mid-disk sections of 23 mm aluminum (first pass), 13 mm (last pass) and the last pass of steel. A snapshot of the defect weld location is shown in Fig. 8.

Upon welding, the defect was effectively closed, resulting in a seamless and homogeneous mass of metal where recrystallization was observed, indicating a successful fusion of the material. However, upon close inspection, it was evident that a portion of the defect exhibited a narrow crack, measuring less than a millimeter in width. This crack narrowed down to a few tens of microns at specific points and slightly widened towards the surface. The narrowest region of the crack extended to a depth of approximately one millimeter.

Comparing the welding defect in the final aluminum sample, which was 13 millimeters in size, to the defect in the steel depicted in Fig. 8, both exhibited similar characteristics. Notably, the cracks in the aluminum were symmetrical in length and were completely welded, mirroring the closure achieved in the steel, albeit slightly more than a millimeter away from the central cavity. This similarity in defect behavior in different materials highlights the possibility of using RSR rolling to achieve stable defect closure and structural integrity. Further investigations are warranted to optimize welding processes and mitigate the formation of these narrow cracks.

Microscopic examination of an aluminum sample after the first rolling pass with a welded defect revealed a visually inconspicuous incomplete closure of the defect on one side. The area is shown in Fig. 9.

This figure most fully illustrates the defect evolution process at RSR. The greatest metal movement occurs from a depth of 1 mm to a depth of 3 mm. These data are in excellent agreement with the RSR structure refinement gradient data carried out on zirconia and with the cumulative strain gradient according to simulations [26]. The upper uncovered millimeter of the defect can be explained by a zone of constrained deformation from the interaction with the tool. Local undercutting of the uppermost layer of the contact surface at the time of contact with the tool is also likely to have an effect. As can be seen from the evolution of the defect, these defects also close, but the closing process begins at a depth of 1 - 3 mm from the edge. The defect is welded simultaneously over several millimeters of the radius. A recrystallized joint of short length is found in two places at once.

Here it is also very important to note the asymmetry of defect closure similar to that observed in steel. Here it is less pronounced, but the systematic nature of this effect cannot be denied. Most likely, this asymmetry is due to the dynamic instability of the radial-shear rolling process and the features of the flow of metal between the three rolls and the symmetry of the defect, which pushes the entire metal in one direction from the axis. Surely these same features are responsible for the helical shape of the axial defect in the last stages of rolling and helical crest on the surface of the billets after rolling, clearly visible in Fig. 2 and Fig. 3. An answer to this question may be given by an experiment examining the stages of closure of asymmetrical noncircular defects of various depths. It is likely that they will all be welded to a depth of about 30 % of the radius.

CONCLUSIONS

The experimental rolling process has revealed a distinct pattern in defect closure dynamics. Predominantly, the closure of defects primarily occurs at the peripheral regions of the bar. Notably, the most intensive welding activity is observed at a depth of 1 to 3 millimeters from the edge, a phenomenon evident even from the first pass of rolling. During this process, the defect undergoes a noticeable shift, transitioning from a transversal position to a more central one.

Remarkably, the defect undergoes a significant reduction in volume, averaging around 50 %, as it moves towards the central part of the bar. This reduction is attributed to the welding and fusion of the defect with the surrounding material, effectively incorporating it into a more homogeneous structure. However, it is noteworthy that the central part of the defect remains unwelded; instead, it undergoes tapering and elongation, aligning with the billet material's flow and drawing during the rolling process.

These findings illuminate the intricate dynamics of defect closure during rolling, underscoring the significance of understanding how material flow and the rolling process itself influence defect behavior and ultimately impact the structural integrity of the final product. Further exploration and optimization of these processes hold potential for enhancing defect closure and improving the overall material quality.

The defect weld locations are homogeneous and recrystallized without metallographic traces of the joint, according to microscopy results. However, because the process is dynamically unstable, significant asymmetry is found in the closure of symmetrical defects, where one part is welded without a trace and the other remains as a thin crack extended along the radial flow of the metal without joining the halves. This will probably have no effect during rolling real defects, which are always asymmetrical.

Three-roll radial shear rolling is very effective in closing surface defects up to 30 % of the radius, but is strictly not recommended for machining ingots containing axial defects.

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