metals

MDPI

Article

Effect of Die Angle and Frictional Conditions on Fine Grain Layer Generation in Multipass Drawing of High Carbon Steel Wire

Alexey Stolyarov [1], Marina Polyakova [2], Guzel Atangulova [1] and Sergei Alexandrov [3,4,*]

1 OJSC Magnitogorsk Hardware and Sizing Plant "MMK-METIZ", 5, Metiznikov, 455002 Magnitogorsk, Russia; Stolyarov.AY@mmk-metiz.ru (A.S.); sergei_alexandrov@hotmail.com (G.A.)
2 Mechanical Engineering and Materials Processing Institute, Nosov Magnitogorsk State Technical University, 38, Lenin Avenue, 455000 Magnitogorsk, Russia; m.polyakova@magtu.ru
3 Ishlinsky Institute for Problems in Mechanics, Russian Academy of Sciences, 101-1 Prospect Vernadskogo, 119526 Moscow, Russia
4 Federal State Autonomous Educational Institution of Higher Education, South Ural State University (National Research University), 454080 Chelyabinsk, Russia
* Correspondence: sergei_alexandrov@spartak.ru; Tel.: +7-495-434-36-65

Received: 12 October 2020; Accepted: 28 October 2020; Published: 31 October 2020

Abstract: Fine grain layers that generate near frictional interfaces in metal forming processes affect the quality of products. The present paper aims to contribute to the continuum-mechanics-based phenomenological approach for predicting such layers' properties. In particular, it studies the generation of fine grain layers in the process of multipass drawing of thin high carbon steel wires experimentally. The wires are drawn in three passes under different friction conditions. All three dies in each multipass process have the same semiangle. In total, two die semiangles are used, 4° and 5°. The effects of such processing conditions as the die semiangle, the number of passes, and the friction conditions on the thickness of fine grain layers are observed and discussed. The criterion for determining this thickness is based on the coefficient of anisotropy. Under soft friction conditions, the fine grain layer's thickness decrease occurs during the consequential passes independently of the die semiangle. On the other hand, in the case of hard friction conditions, the thickness may or may not be a monotonic function of the number of passes, and its general qualitative behavior depends on the die semiangle.

Keywords: friction; multipass drawing; thin wire; fine grain layer

1. Introduction

Many metal forming and machining processes generate a thin fine grain layer in the vicinity of frictional interfaces, for example [1,2]. This layer affects various properties of the products of these processes [3–7]. Therefore, it is crucial to develop an approach for designing metal forming and machining processes driven by the properties of the surface layer. To this end, it is necessary to determine the influence of the process parameters on parameters that characterize the properties of the surface layer.

Among metal forming processes, the generation of fine grain layers is most often studied in drawing and extrusion processes [4,6,8–10]. The thickness of this layer after the drawing process has been determined in [10,11]. Other issues related to the quality of the product after such processes have been investigated in [12–17], among many others.

The processes mentioned above are one-pass processes. Multipass drawing and extruding processes provide more possibilities for controlling the product's properties. The stress−strain properties of tough-pitch copper after multipass drawing and extruding have been studied in [18]. A design method for multipass drawing driven by the void index has been proposed in [19]. A process design system for the same process has been developed in [20]. This system can be installed in AutoCAD for calculating many process parameters.

The influence of the number of passes after multipass drawing on such material properties as tensile strength, yield strength, and percentage elongation has been revealed in [21,22]. The dependence of the axial surface residual stress on the number of passes in carbon steel wires during multipass drawing has been found in [23]. It is worthy of note that this paper emphasizes a high gradient of temperature in the vicinity of the friction surface. It is known that the temperature is one of the main contributory mechanisms responsible for the generation of fine grain layers [1]. In [24], the effects of the number of passes and heat treatment on the microstructure and texture of the drawn Ti-6Al-4V alloy bars have been demonstrated. The process of multipass drawing of microfibers has been studied in [25]. The diameters of these fibers are several tens of micrometers. The difference in the microtexture and microstructure between the core and periphery regions of the fiber has been found. The generation of microstructure, texture, and mechanical properties of VN3-1 alloy in the combined process of multipass drawing followed by isothermal annealing has been investigated in [26].

The present paper mainly focuses on the effect of the number of passes in the process of multipass drawing of thin high carbon steel wires on the generation of a fine grain layer in the vicinity of the friction surface. It extends the results reported in [10], where the one-pass drawing process has been considered. A distinguishing feature of the process studied is that the ratio of the thickness of fine grain layers to the radius of the wires is relatively large as compared to other drawing/extrusion processes used for studying the generation of fine grain layers, for example, Refs. [8,9]. Therefore, the layer may affect the final product's local surface properties and its overall behavior under service conditions. The primary objective of this research is to find a correlation between the thickness of the fine grain layer and the process parameters. The coefficient of anisotropy is used for formulating a quantitative criterion that determines the thickness of the layer [10,27]. Another criterion based on metallographic observations has been proposed in [28]. The overall goal of this research is to incorporate experimental data in the approach for predicting the evolution of fine grain layers proposed in [29].

2. Material, Process and Methods

A high carbon steel wire of diameter 1.6 mm was reduced to a wire of diameter 1.15 mm by the process of multipass drawing through three conical dies. The nominal chemical composition of this steel is presented in Table 1.

Table 1. Nominal chemical composition of high carbon steel (mass fraction, %).

C	Si	Mn	Ni	S	P	Cr	Cu
0.72	0.19	0.52	0.05	0.03	0.03	0.10	0.10

The original wire was produced by drawing from a rod of diameter 5.5 mm. After drawing, the wire of diameter 1.6 mm was patented (heated to a temperature in the range between 980 °C and 1000 °C for 50 s and subsequently cooled in molten lead at 560 °C). The resulting microstructure was studied by an optical image analyzer "Thixomet" (Thixomet, St Petersburg, Russia). It was classified by equiaxial sorbite-like pearlite grains of a diameter in the range between 10 µm and 25 µm (Figure 1). The distribution of the microstructure was practically uniform over the entire cross-section of the wire.

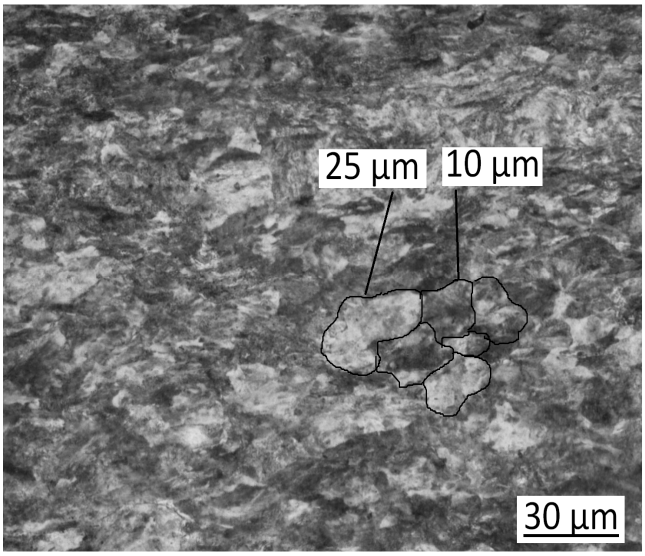

Figure 1. Microstructure of the wire material before multipass drawing, ×1000.

The process of multipass drawing consisted of three passes. The first pass reduced the original diameter of the wire to 1.45 mm, the second pass reduced the diameter from 1.45 mm to 1.3 mm, and the third pass reduced the diameter from 1.3 mm to 1.15 mm. A schematic diagram of the multipass drawing process is shown in Figure 2.

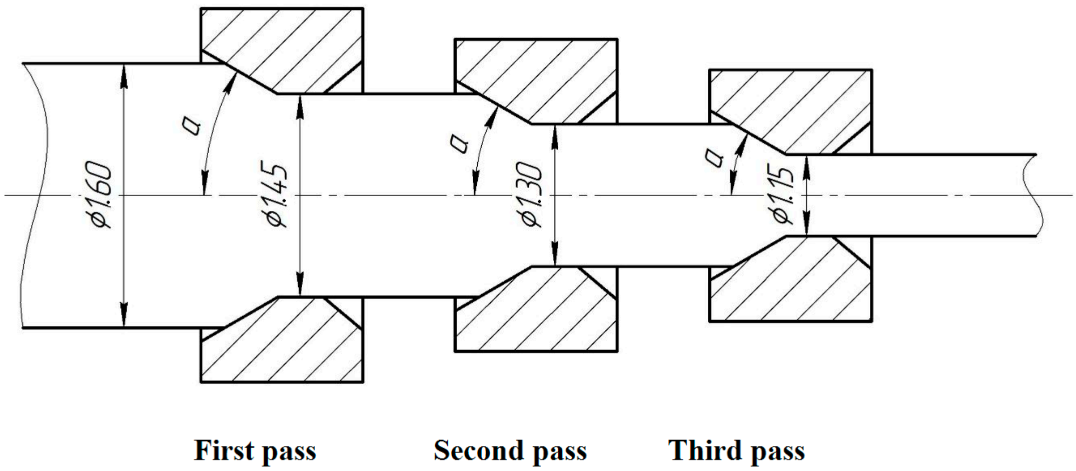

Figure 2. Schematic diagram of the multipass drawing process; unit: mm.

Conical dies made of sintered alloy H6F (tungsten carbide and cobalt) were used. All three dies used in the multipass drawing process had the same semiangle α. To vary the conditions at the friction surfaces, the experiment was carried out for two semiangles, $\alpha = 4°$ and $\alpha = 5°$. Moreover, special treatments of the friction surface and different lubricants were used for varying friction conditions in the multipass drawing process through the dies with $\alpha = 4°$ and $\alpha = 5°$. The different friction conditions at each semidie angle were denoted as the soft friction conditions, or (s), and the hard friction conditions, or (h). The rod from which the original wire for multipass drawing was produced was covered with a borate of soda (sodium tetraborate, U.S. Borax, Chicago, IL, USA) coating, and dry lubricant (sodium stearate, Lubrimetal, Via Moggio, Italy) was applied for the process of multipass drawing to get the soft friction conditions. The thickness of the coating was equivalent to 5 g/m^2. The coating did not cover the rod in the case of the hard friction conditions. Moreover, no lubricant was used, and the abrasive diamond suspension was injected in between the die and the wire in the process of multipass drawing. Table 2 presents the general plan of the experiment. In total, there were twelve series. Series 1.1, 1.2, 1.3, and 1.4 corresponded to the first pass, series 2.1, 2.2, 2.3, and 2.4 to the second pass, and series 3.1, 3.3, 3.3, and 3.4 to the third pass. Using different combinations of all the experimental results, one can reveal the effect of the die semiangle at the same friction conditions and the effect of the friction conditions at the same die semiangle on the thickness of fine grain layers.

Table 2. Plan of the experiment.

Series	Initial Diameter of Wire, mm	Final Diameter of Wire, mm	α, deg	Friction Conditions
1.1	1.6	1.45		
2.1	1.45	1.3	4	s
3.1	1.3	1.15		
1.2	1.6	1.45		
2.2	1.45	1.3	5	s
3.2	1.3	1.15		
1.3	1.6	1.45		
2.3	1.45	1.3	4	h
3.3	1.3	1.15		
1.4	1.6	1.45		
2.4	1.45	1.3	5	h
3.4	1.3	1.15		

The microstructure of the material after the multipass drawing was studied on samples cut from the longitudinal plane of symmetry of the wire. The samples were etched in 4% solution of nitric acid (Mendeleevskazot, Mendeleevsk, Russia) in ethyl alcohol (Kirov BioChemPlant, Kirov, Russia) by immersion of their polished surface into a bath with the reagent. An optical microscope with the magnification of × 500 supplemented with the image analysis software "Thixomet" (V3.0, Thixomet, St Petersburg, Russia) was used for the observation of the microstructure.

The criterion proposed in [27] was used for determining the thickness of the fine grain layers. This criterion is based on the coefficient of anisotropy of ferrite grains, denoted as A, that is automatically calculated using the "Thixomet" software. According to this criterion,

$$A < 0.7, \quad (1)$$

within the fine grain layer.

Three nominally identical initial wires have been tested in each series. The thickness of the fine grain layer was determined at six locations. Since the process was stationary, this thickness should have been the same at all locations for all three samples in an ideal case. Therefore, the arithmetic mean of these eighteen values was regarded as the thickness of the fine grain layer at the given die semiangle and friction conditions.

3. Results

3.1. Soft Friction Conditions

Figures 3 and 4 illustrate the distribution of microstructure in the vicinity of the friction surface after each pass of the multipass drawing process through $\alpha = 4°$ dies and $\alpha = 5°$ dies, respectively. In these figures, the thickness of fine grain layers is also shown at three locations.

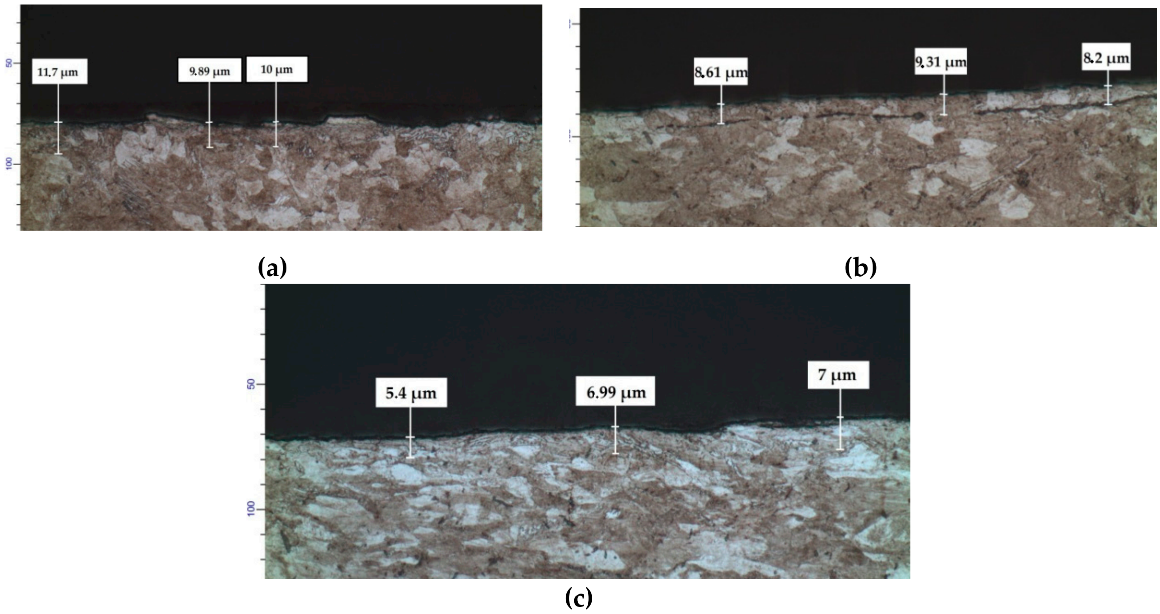

Figure 3. Thickness of fine grain layers after each pass of the multipass drawing process through $\alpha = 4°$ dies: (**a**) the first pass, (**b**) the second pass, (**c**) the third pass.

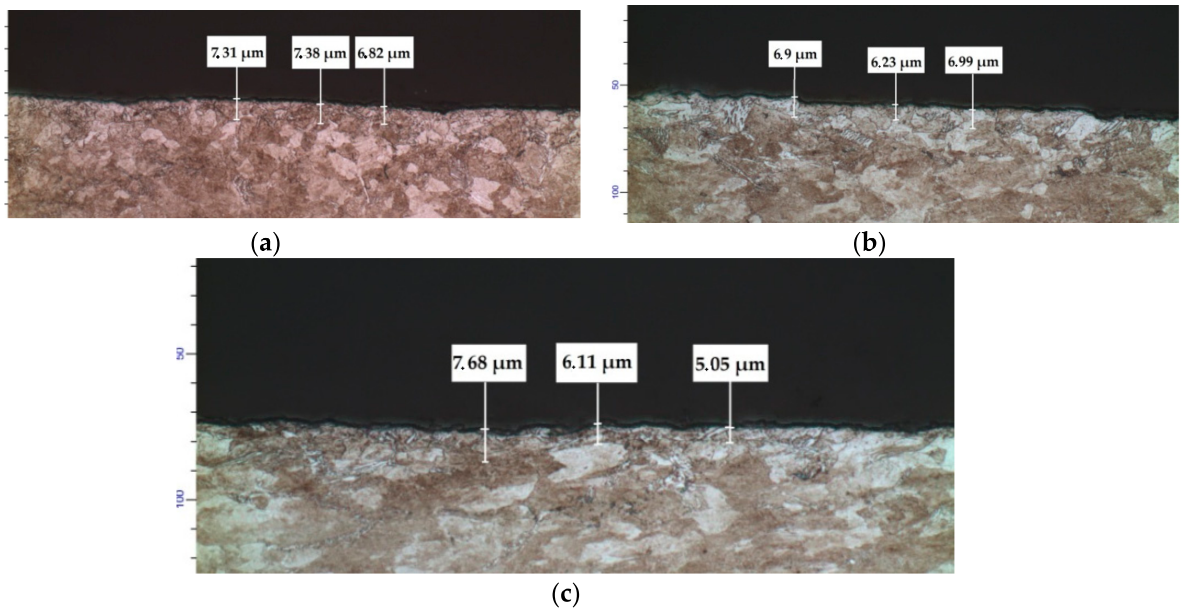

Figure 4. Thickness of fine grain layers after each pass of the multipass drawing process through $\alpha = 5°$ dies: (**a**) the first pass, (**b**) the second pass, (**c**) the third pass.

Table 3 displays the dependence of the thickness of the fine grain layers on the number of passes and α. The thickness is understood here as the arithmetic mean calculated as described in Section 2. In Table 3 and in what follows, this quantity is denoted as t.

Table 3. Dependence of t on the number of passes and α.

Die Semiangle	First Pass	Second Pass	Third Pass
$\alpha = 4°$	10.5 μm	8.8 μm	6.3 μm
$\alpha = 5°$	7.2 μm	6.8 μm	6.3 μm

It is seen from Table 3 that t was largest after the first pass and smallest after the third pass for both $\alpha = 4°$ and $\alpha = 5°$. In particular, it decreased from 10.5 µm to 6.3 µm in the process of drawing through $\alpha = 4°$ dies, and from 7.2 µm to 6.3 µm in the process of drawing through $\alpha = 5°$ dies. The value of t was practically the same after the third pass of each process.

3.2. Hard Friction Conditions

Figures 5 and 6 illustrate the distribution of microstructure in the vicinity of the friction surface after each pass of the multipass drawing process through $\alpha = 4°$ dies and $\alpha = 5°$ dies, respectively. In these figures, the thickness of the fine grain layers is also shown at three locations.

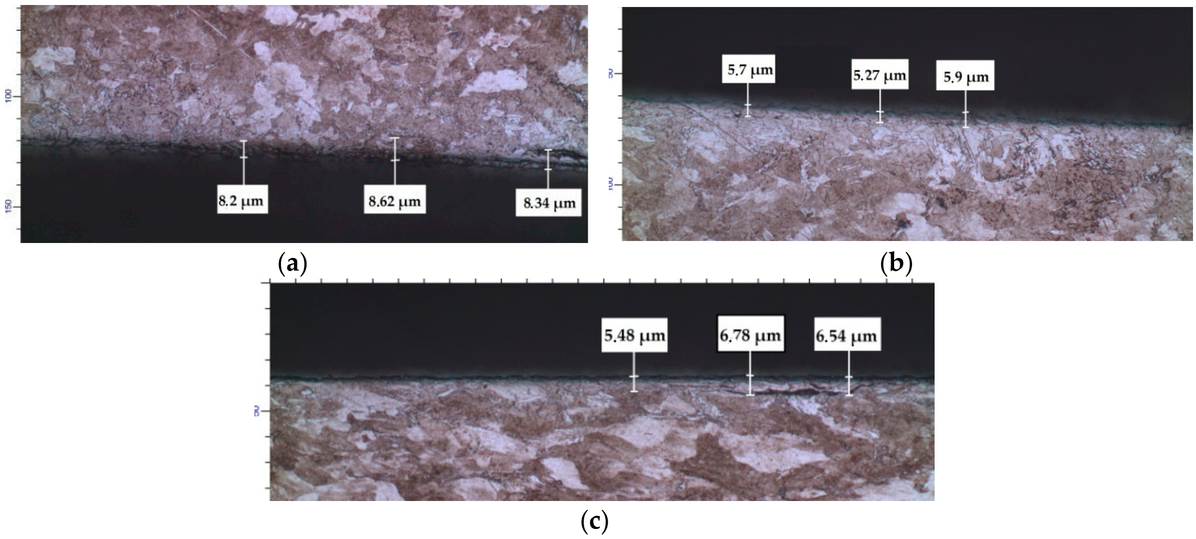

Figure 5. Thickness of the fine grain layers after each pass of the multipass drawing process through $\alpha = 4°$ dies: (**a**) the first pass, (**b**) the second pass, (**c**) the third pass.

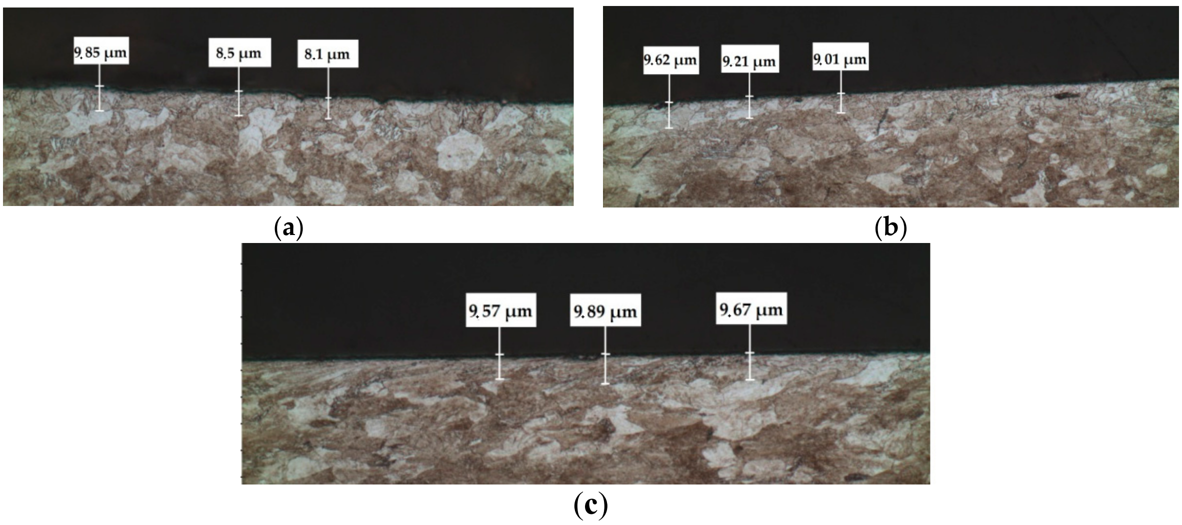

Figure 6. Thickness of the fine grain layers after each pass of the multipass drawing process through $\alpha = 5°$ dies: (**a**) the first pass, (**b**) the second pass, (**c**) the third pass.

Table 4 displays the dependence of t on the number of passes and α. It is seen from this table that the effect of the number of passes and α on the fine grain layer thickness under the hard friction conditions was qualitatively different from that under the soft friction conditions (Table 3). In particular, the thickness monotonically increased with the number of passes from 8.8 µm to 9.7 µm in the process of drawing through $\alpha = 5°$ dies. This dependence was nonmonotonic in the process of drawing through $\alpha = 4°$ dies, and the thickness attained a minimum of 5.6 μm after the second pass.

Table 4. Dependence of t on the number of passes and α.

Die Semiangle	First Pass	Second Pass	Third Pass
$\alpha = 4°$	8.4 μm	5.6 μm	6.3 μm
$\alpha = 5°$	8.8 μm	9.3 μm	9.7 μm

The experimental results obtained in this work are summarized in Table 5. The sample range R is also presented in this table.

Table 5. Summary of the experimental results.

α deg	Pass	(s)		(h)	
		t, μm	R, μm	t, μm	R, μm
4	1st	10.5	1.9	8.4	1.4
	2nd	8.8	1.2	5.6	1.0
	3rd	6.3	1.4	6.3	1.1
5	1st	7.2	2.7	8.8	1.0
	2nd	6.8	1.1	9.3	1.3
	3rd	6.3	1.0	9.7	1.9

4. Discussion

The effect of the die's semiangle, the number of passes, and the friction conditions on the thickness of fine grain layers generated by the process of multipass drawing has been studied experimentally. The criterion (1) has been adopted for determining this thickness.

Under soft friction conditions, the decrease of the fine grain layer thickness was found to have occurred during the consequential passes. It could be attributed to the highest surface roughness of the original wires drawn in the first pass of the multipass drawing process. Probably, one of the mechanisms of fine grain layer generation in the drawing process is the interaction of profile peaks and irregularities with the die. During the subsequent passes, gradual smoothing of the wire surface profile irregularities occurred, and the effect of these irregularities on fine grain layer generation diminished. It has also been observed that the fine grain layer's final thickness was independent of the die semiangle.

Under hard friction conditions, the dependence of the fine grain layer thickness on the drawing process's parameters was as follows. The fine grain thickness layer monotonically increased from the first pass to the last pass in the case of the 5° dies. However, this dependence is nonmonotonic in the case of the 4° dies, and the thickness attained a minimum after the second pass. It is worth noting that the fine grain layer's final thickness was significantly affected by the die semiangle, in contrast to the soft friction conditions.

The partition of deformation in three passes affected the generation of fine grain layers, but the tendency was not clear (Table 5). In particular, the layer's thickness monotonically decreased with the passes in drawing through both the 4° and the 5° dies under soft friction conditions. However, the thickness varied much more in the case of the 4° dies. On the other hand, the layer's thickness monotonically increased with the passes in drawing through 5° dies under hard friction conditions. This dependence was not monotonic in the case of drawing through the 4° dies. As under soft friction conditions, the thickness varied much more in drawing through the 4° dies. This vagueness with the effect of the number of passes on the subsurface layer's properties requires further research in this direction. On the other hand, the variety of effects observed shows there is much scope to design the process of drawing of thin wires driven by these properties.

The specimens after the multipass drawing process were not heat-treated. However, it is known from the literature that some material properties of the sub-surface layer can be improved by heat treatment [30].

5. Conclusions

From this work, the following conclusions can be drawn:

(1) The thickness of fine grain layers generated in the multipass drawing process is qualitatively affected by friction conditions.
(2) Under soft friction conditions, the fine grain layer thickness decreases during the consequential passes for both die semiangles, 4° and 5°.
(3) Under hard friction conditions, the thickness may or may not be a monotonic function of the number of passes, and its general qualitative behavior depends on the die semiangle.

Author Contributions: Writing—original draft preparation, S.A.; methodology, A.S.; drawing, M.P.; microscopy, G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was made possible by the grant 18-19-00736 from the Russian Science Foundation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Griffiths, B.J. Mechanisms of White Layer Generation with Reference to Machining and Deformation Processes. *ASME J. Tribol.* **1987**, *109*, 525–530. [CrossRef]
2. Sanabria, V.; Mueller, S.; Reimers, W. Microstructure Evolution of Friction Boundary Layer during Extrusion of AA 6060. *Procedia Eng.* **2014**, *81*, 586–591. [CrossRef]
3. Griffiths, B.J.; Furze, D.C. Tribological Advantages of White Layers Produced by Machining. *ASME J. Tribol.* **1987**, *109*, 338–342. [CrossRef]
4. Kim, Y.-T.; Ikeda, K. Flow Behavior of the Billet Surface Layer in Porthole Die Extrusion of Aluminum. *Metal. Mater. Trans.* **2000**, *31A*, 1635–1643. [CrossRef]
5. Warren, A.W.; Guo, Y.B. Numerical Investigation on the Effects of Machining-Induced White Layer during Rolling Contact. *Tribol. Trans.* **2005**, *48*, 436–441. [CrossRef]
6. Kajino, S.; Asakawa, M. Effect of "Additional Shear Strain Layer" on Tensile Strength and Microstructure of Fine Drawn Wire. *Mater. Process. Technol.* **2006**, *177*, 704–708. [CrossRef]
7. Choi, Y. Influence of a White Layer on the Performance of Hard Machined Surfaces in Rolling Contact. *Proc. Inst. Mech. Eng. Part B J. Eng. Manufact.* **2010**, *224*, 1207–1215. [CrossRef]
8. Hwang, Y.-M.; Huang, T.-H.; Alexandrov, S. Manufacture of Gradient Microstructures of Magnesium Alloys Using Two—Stage Extrusion Dies. *Steel Res. Int.* **2015**, *86*, 956–961. [CrossRef]
9. Alexandrov, S.; Jeng, Y.-R.; Hwang, Y.-M. Generation of a Fine Grain Layer in the Vicinity of Frictional Interfaces in Direct Extrusion of AZ31 Alloy. *ASME J. Manuf. Sci. Eng.* **2015**, *137*, 051003. [CrossRef]
10. Stolyarov, A.; Polyakova, M.; Atangulova, G.; Alexandrov, S.; Lang, L. Effect of Frictional Conditions on the Generation of Fine Grain Layers in Drawing of Thin Steel Wires. *Metals* **2019**, *9*, 819. [CrossRef]
11. Kharitonov, V.A.; Stolyarov, A.Y.; Lataev, A.P. Determining the Depth of the Layer of Additional Shear Deformation in Drawing of Thin Wire. *Steel* **2012**, *12*, 45–47.
12. Rubio, E.M.; Camacho, A.M.; Perez, R.; Marin, M.M. Guidelines for Selecting Plugs Used in Thin-Walled Tube Drawing Processes of Metallic Alloys. *Metals* **2017**, *7*, 572. [CrossRef]
13. Medvedev, A.; Arutyunyan, A.; Lomakin, I.; Bondarenko, A.; Kazykhanov, V.; Enikeev, N.; Raab, G.; Murashkin, M. Fatigue Properties of Ultra-Fine Grained Al-Mg-Si Wires with Enhanced Mechanical Strength and Electrical Conductivity. *Metals* **2018**, *8*, 1034. [CrossRef]
14. Martinez, G.A.S.; Santos, E.F.; Kabayama, L.K.; Guidi, E.S.; Silva, F.A. Influences of Different Die Bearing Geometries on the Wire-Drawing Process. *Metals* **2019**, *9*, 1089. [CrossRef]

15. Belov, N.; Murashkin, M.; Korotkova, N.; Akopyan, T.; Timofeev, V. Structure and Properties of Al–0.6wt.%Zr Wire Alloy Manufactured by Direct Drawing of Electromagnetically Cast Wire Rod. *Metals* **2020**, *10*, 769. [CrossRef]
16. Santana Martinez, G.A.; Qian, W.-L.; Kabayama, L.K.; Prisco, U. Effect of Process Parameters in Copper-Wire Drawing. *Metals* **2020**, *10*, 105. [CrossRef]
17. Prisco, U.; Martinez, G.A.; Kabayama, L.K. Effect of Die Pressure on the Lubricating Regimes Achieved in Wire Drawing. *Prod. Eng.* **2020**. [CrossRef]
18. Thomsen, E.G. Stress-Strain Properties of Tough-Pitch Copper After Multi-Pass Drawing and Extruding. *ASME J. Eng. Mater. Technol.* **1983**, *105*, 178–181. [CrossRef]
19. Kuboki, T.; Abe, M.; Neishi, Y.; Akiyama, M. Design Method of Die Geometry and Pass Schedule by Void Index in Multi-Pas Drawing. *ASME J. Manuf. Sci. Eng.* **2005**, *127*, 173–181. [CrossRef]
20. Lee, S.-K.; Lee, I.-K.; Lee, S.-Y. Development of a Multi-Pass Drawing Process Design System for Steel Profiles. *Materials* **2018**, *11*, 2446. [CrossRef]
21. Luksza, J.; Majta, J.; Burdek, M.; Ruminski, M. Modelling and Measurements of Mechanical Behavior in Multi-Pass Drawing Process. *J. Mater. Process. Technol.* **1998**, *80*, 398–405. [CrossRef]
22. Luksza, J.; Burdek, M. The Influence of the Deformation Mode on the Final Mechanical Properties of Products in Multi-Pass Drawing and Flat Rolling. *J. Mater. Process. Technol.* **2002**, *125*, 725–730. [CrossRef]
23. Lee, S.-K.; Kim, D.-W.; Jeong, M.-S.; Kim, B.-M. Evaluation of Axial Surface Residual Stress in 0.82% Carbon Steel Wire During Multi-Pass Drawing Process Considering Heat Generation. *Mater. Des.* **2012**, *34*, 363–371. [CrossRef]
24. Hu, M.; Dong, L.; Zhang, Z.; Lei, X.; Yang, R.; Sha, Y. Effects of Multi-Pass Drawing Strain and Heat Treatment on Microstructure, Texture and Properties of Ti-6Al-4V Alloy. *Mater. Sci. Eng.* **2019**, *A757*, 70–83. [CrossRef]
25. Huang, S.-J.; Chang, L.; Shyr, T.-W. Characterization of Microtexture of 316L Stainless Steel Fiber after Multi-Pass Drawing by Electron Backscatter Diffraction. *Mater. Character.* **2018**, *141*, 338–347. [CrossRef]
26. Lei, X.; Dong, L.; Zhang, Z.; Liu, Y.; Hao, Y.; Yang, R.; Zhang, L.-C. Microstructure, Texture Evolution and Mechanical Properties of VT3-1 Titanium Alloy Processed by Multi-Pass Drawing and Subsequent Isothermal Annealing. *Metals* **2017**, *7*, 131. [CrossRef]
27. Stolyarov, A.; Kamalova, G.; Polyakova, M. Investigation of Grain Anisotropy on Surface Area between Carbon Steel Wire at Drawing. *Mater. Sci. Forum* **2019**, *946*, 253–257. [CrossRef]
28. Alexandrov, S.; Sidjanin, L.; Vilotic, D.; Movrin, D.; Lang, L. Generation of a Layer of Severe Plastic Deformation Near Friction Surfaces in Upsetting of Steel Specimens. *Metals* **2018**, *8*, 71. [CrossRef]
29. Goldstein, R.V.; Alexandrov, S.E. An Approach to Prediction of Microstructure Formation near Friction Surfaces at Large Plastic Strains. *Phys. Mesomech.* **2015**, *18*, 223–227. [CrossRef]
30. Wu, X.; Yang, M.; Yuan, F.; Wu, G.; Wei, Y.; Huang, X.; Zhu, Y. Heterogeneous Lamella Structure Unites Ultrafine-Grain Strength with Coarse-Grain Ductility. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 14501–14505. [CrossRef]