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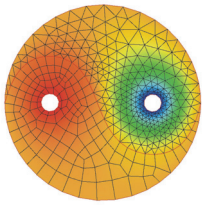

MODELLING OF FORMATION OF STOCK SURFACE AND SUBSURFACE LAYERS IN BREAKDOWN ROLLING OF ALUMINIUM ALLOY

MICHAL KRZYZANOWSKI[1], MICHAEL F. FROLISH[1], W. MARK RAINFORTH[1], JOHN H. BEYNON[2]

[1] Institute for Microstructural and Mechanical Process Engineering, The University of Sheffield S1 3JD, UK
(email: M.Krzyzanowski@Sheffield.ac.uk)
[2] Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

Abstract

Simulations of the reheating and breakdown rolling of the Al-Mg-Mn aluminium alloy AA3104 carried out using a two-high laboratory mill were supported by detailed numerical modelling of the stock surface layer formation. The model of the stock/roll interface is usually a micro-part of a more complex macro-finite-element model. Corresponding linking of modelling scales is a necessary stage for numerical analysis of fine mechanisms of the interface formation. This procedure allows for consideration of the fine mechanisms responsible for formation of the scale/metal interface while, at the same time, reducing the number of elements under consideration. It has been shown that a small amount of Mg (as oxides) was intermixed into the subsurface layer of a few microns depth by deformation during rolling. The mechanisms which led to the deformation and mixing of the oxide particles into the subsurface layer arose from slip at the roll/stock interface and the action of roll surface asperities on the stock surface.

Key words: simulation, rolling, stock surface, subsurface layers, multiscale modelling

1. EXPERIMENTAL PREREQUISITES

The mechanisms and processes involved in the formation of the surfaces and subsurface layers in hot rolled alluminium flat products are of considerable interest to the aluminum industry (Afseth et al., 2002; Scamans et al., 2002; Fishkis and Lin 1997). For example, hot rolling enhances filiform corrosion (FFC), which is known to be strongly related to the process history. It is interesting that similar layers induced by cold rolling do not enhance filiform corrosion rates to the same extent as by hot rolling. It is thought that the formation of the surface and near-surface layers depends on a range of factors, and particularly on the tribological conditions at the stock/roll interface. It has been shown by Scamans et al., (2002) that the high shear processing during hot rolling is involved in producing a highly deformed near surface layer. This is due to asperities which affect the contact conditions between the stock and the work rolls. There has not been a systematic investigation of the influence of rolling conditions on the formation of the surface and subsurface layers and the subsequent effect on properties.

According to Fishkis and Lin (1997), the surface region of a hot rolled aluminium alloy is characterized by a surface layer of continuous oxide 25–160 nm thick, and a subsurface layer of about 1.5–8 μm thickness. The subsurface layer is much dispersed and consists mainly of small grained metal with a grain boundaries pinned by small (about 3–30 nm) crystalline and amorphous oxides. The type and properties of the oxides depends on the stage of the process. MgO, γ-Al_2O_3, $MgAl_2O_4$ and amorphous Al_2O_3 are observed at the start of the process, while

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only MgO oxides were found at the end. Grain growth in this subsurface layer was retarded by Zener pinning by small oxide particles.

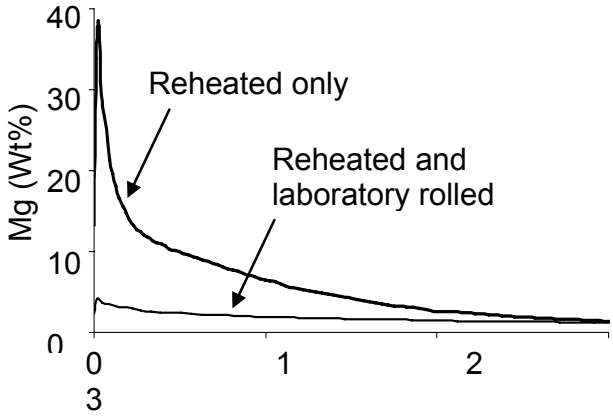

Fig. 1. *Distribution of Mg in the surface layer of aluminium alloy AA3104.*

Simulations of the reheating and breakdown laboratory rolling of the Al-Mg-Mn aluminium alloy AA3104 were carried out at the University of Sheffield (Frolish et al., 2005). Examination of the specimens using glow discharge optical emission spectrometry (GDOES) revealed that the reheating induced significant Mg enrichment in the surface and near surface regions and that Mg diffusion and oxidation continued throughout the reheating. The rate of oxidation decreased with time during the reheating process. As can be seen in the figure 1, the level of Mg in the near surface regions of the rolled specimen was an order of magnitude less than that observed in the reheated specimens (it peaked at about 40 wt%, ignoring the presence of oxygen). It has been shown that the subsurface layers obtained from the industrially hot rolled transfer bar and the laboratory rolled material were similar in terms of both thickness and microstructure. The particles seen in both subsurface layers are sufficiently small to provide Zener pinning to stabilise the fine structure of the layers. The scale of the subgrains in the laboratory specimens (about 50–350 nm) was similar to the transfer bar. Inspection of the work roll surfaces after the test indicated that, under the rolling conditions used, the fall in Mg content arose mainly due to the removal of some of the thin oxide layer by abrasion and adhesion to the work roll surface. In addition a small amount of Mg (as oxides) was intermixed into the subsurface layer by deformation during rolling. A focused ion beam (FIB) image illustrating the subsurface layer obtained in the industrially hot rolled aluminum alloy is presented in figure 2. It is thought that the mechanisms which led to the deformation and mixing of the oxide particles into the subsurface layer arose from slip at the roll/stock interface and the action of roll surface asperities on the stock surface. In both the industrially and laboratory rolled samples, the depth of raised magnesium content correlated well with the observed thickness of the subsurface particle layer.

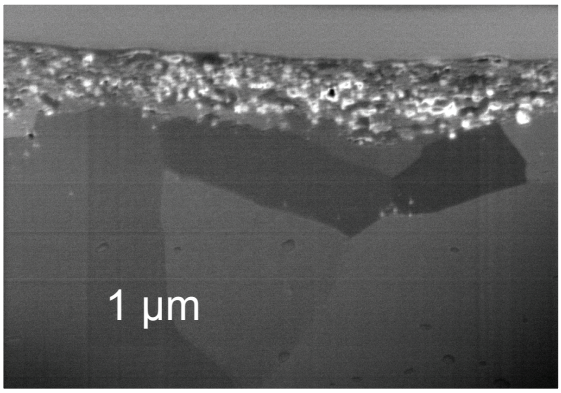

Fig. 2. *Cross section of the surface layer of the industrially rolled aluminium alloy AA3104.*

2. MATHEMATICAL MODELLING

One of the assumptions of this modelling approach is that the frictional force and wear result from the interaction of asperities on the contacting surfaces. The most widely used of all asperity deformation models is the adhesion model of Bowden and Tabor (1964). In this model the frictional force is derived from the force needed to shear the welded junctions formed by adhesion at the tips of contacting surfaces. However, it seems unlikely that the model can be applicable to the rolling conditions of aluminum alloys since the involvement of fracture in the process appears far more severe, in fact, according to the model, the welds formed even for the sliding of smooth lubricated surfaces over each other. The model does not depend on information about the asperities. This will not be the case where one surface is significantly harder than the other, a condition which is expected to apply in hot rolling of alluminium alloys. In this case the energy produced by sliding is dissipating mainly by plastic deformation of the surface layer, by shearing and failure that takes place near the surface. Other forms of energy dissipation such as those resulting from overcoming atomic and molecular forces acting between surfaces are relatively small for the metal surfaces and can be neglected. An approach to explaining mechanics of metallic sliding friction was developed by Kopalinsky and Oxley (1995). Schematic representation of the mechanical model developed on the

basis of they approach is presented in figure 3. The roll surface is significantly harder than the hot aluminum surface being deformed during a rolling pass. The hard roll asperities can form a wave of the underlying soft metal at the contact area, which can be removed in subsequent sliding or even by the chip formation during further shearing. Following this schematic representation the following assumptions has been made for the finite element (FE) model of the stock/roll interface in hot aluminum rolling: the elastic (or elastic plastic hard) roll with asperities or grinding defects on the roll surface; elastic plastic (soft) stock; friction is taken into consideration as the Coulomb friction model; no welded junctions were assumed at the tips of contacted surfaces; the thin continuous oxide scale was assumed only as a thermal barrier at the stock/roll interface. The assumed friction model is used for most applications with the exception of significant bulk deformations, for such application the shear friction model is more appropriate.

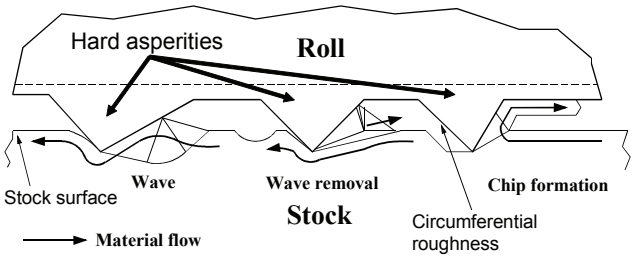

Fig. 3. *Schematic representation of the roll/stock interface model after Kopalinsky and Oxley (1995).*

model. Usually, the macro model consists of about 4000–5000 elements refined to the size of about 0.3 mm near the roll/stock interface. However, to be able to mimic the formation of the stock surface layer the size of the contact elements in the micro model should be about 2 μm and to have similar sizes to the roll elements. This would increase number of elements under consideration dramatically. The increment of load should also be adequate to the element sizes in contact. A too small increment of load might influence penetration while a too large increment of load influences formation of the non-positive stiffness matrix because of the large deformation. These factors require corresponding linking of the macro- and micro- scales of modelling. As can be seen in figure 4, the model is reduced to a small segment at the stock-roll interface. The boundary conditions for the small segment are taken from the macro-model. The FE mesh near the interface is then refined as required; the origin of coordinates is changed by tying it to one of the segment nodes and, finally, the surface layer is refined to the desired extent and oxide scale fragments can be introduced on to the metal surface (Krzyzanowski et al., 2003). This procedure allows for consideration of the fine morphological features of the surface layers and the scale/metal interface while, at the same time, reducing the number of elements under consideration. The approach also enables a thin film to be introduced on the both contact surfaces, which can also be defined as oxide scale. Both macro- and

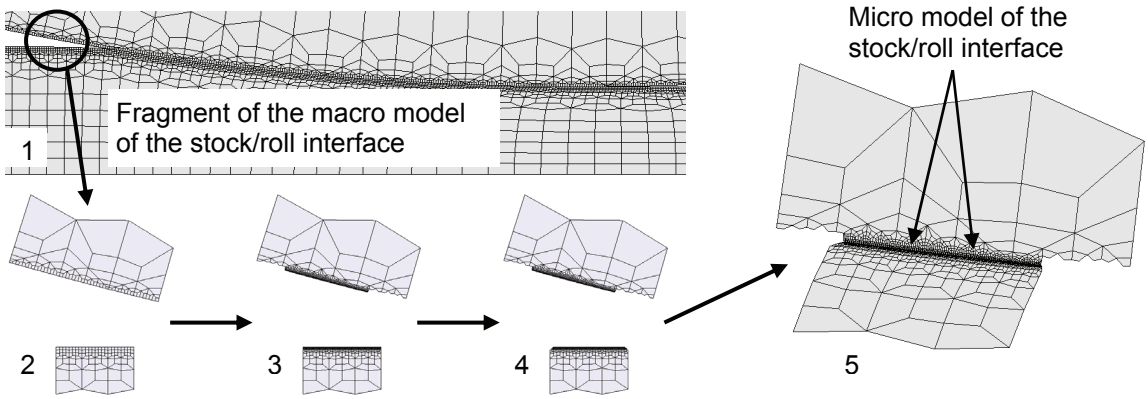

Fig. 4. *Linking modelling scales: 1 – macro model; 2 – reduction to characteristic size; 3, 4 – FE mesh refinement near the interface; 5 – change of coordinate origin and introduction of the roll asperities and grinding defects.*

When fine mechanisms of formation within a few microns thick surface layer during the rolling of aluminum alloys are under consideration, the FE model has to have the capacity to include very fine features of the scale/metal interface. The model of the stock/roll interface during rolling is usually a micro-part of a more complex macro-finite-element

micro- components of the FE model are rigorously thermo-mechanically coupled. Thus, all the mechanical and thermal properties are included as functions of temperature. The commercial MSC.Marc FE code and MSC.Mentat was used for solving the non-steady state two-dimensional problem of the metal flow, heat transfer, sliding and failure of the surface

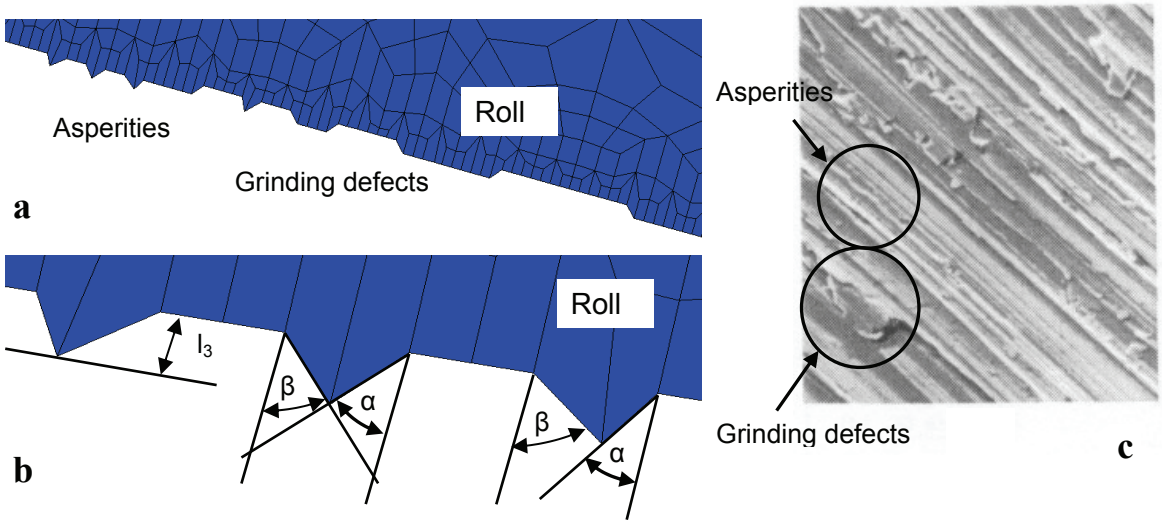

Fig. 5. *Asperities and grinding defects on the roll surface: FE model setup (a); SEM image (b).*

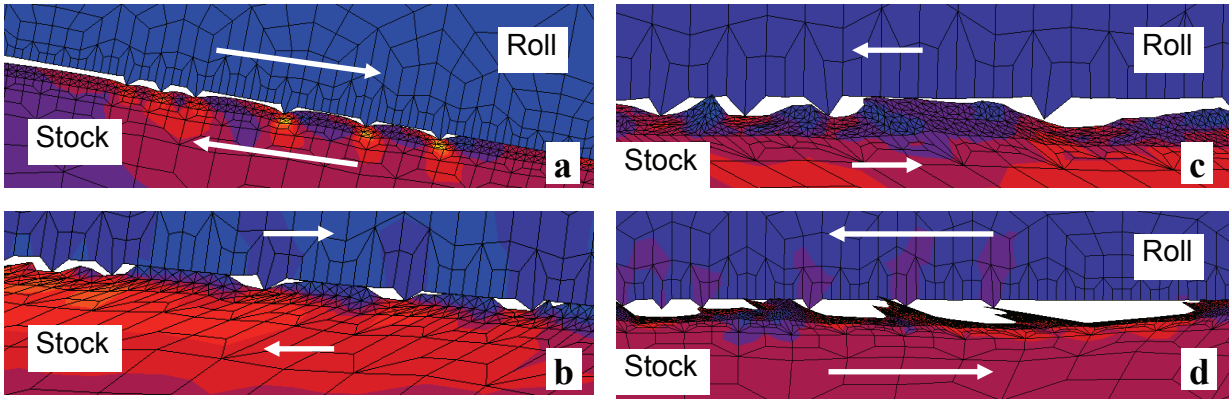

Fig. 6. *Deformation near the roll/stock interface predicted before (a, b) and after (c, d) the neutral zone. Backward/forward sliding is shown by arrows.*

layer during hot rolling. The thermal and mechanical properties were assumed to be similar to those used in rolling models.

Figure 5a and 5b illustrate asperities and grinding defects being introduced on the roll surface. They originate from observation of the roll surface used for hot rolling of aluminum (Smith et al., 1997), which is illustrated in figure 5c. The sizes, shape and distribution of the surface defects along the roll surface can be different depending on the preparation of the roll surface. When the roll surface comes into the contact with the stock, it forms waves in the relatively soft surface layer of aluminum due to indentation of the roll surface imperfections. The roll surface moves faster than the surface of the stock at entry into the roll gap. As can be seen in figure 6, the waves of the deformed material are pushed in the rolling direction due the relative movement. After the neutral zone along the arc of contact the relative movement of the roll and stock surface is reversed causing the highly deformed near surface layers of the stock to be pushed in the direction opposite to the rolling direction. This kind of backward and forward slip at the roll/stock interface can result in churning out of the soft aluminium surface layer that leads to mechanical mixing near the interface.

The preliminary results suggested that the mechanical mixing occurs due to forward and backward slip at the roll gap. There are many factors that can have an influence on the mechanical mixing in the area. One of them is aspect ratio of the rolling pass *AR* defined as a ratio between the projected length of contact and the mean thickness of the material in the pass:

$$AR = \frac{\sqrt{(h_o - h_f)R}}{0.5(h_o + h_f)} \qquad (1)$$

where: R is the roll radius; h_o and h_f are the initial and final thickness of the material. A typical AR range for industrial aluminium breakdown rolling is 0.15 – 3.75, and it was simulated in the laboratory conditions by changing the stock thickness. The relative velocity between the chosen point on the stock surface and the surface of the roll during the rolling pass for the different aspect ratios is shown in figure 7. It can be seen that the relative velocity is higher at entry into the roll gap and reduces towards the exit. The maximum forward slip at the exit from the roll gap was about -2.58 mm/s during the rolling pass with AR = 1.4 while it was only -1.64 mm/s for AR = 3.7 under the same rolling conditions. Thus, for other than very low aspect ratios (AR < 1.0), it is thought that decrease of AR will increase the churning effect at the surface layer. As it has been mentioned earlier, the profile and distribution of the surface defects along the roll surface can be different depending on preparation of the roll surface or the history of the roll use. It is thought therefore that the micro profile of the roll surface will also affect the formation of the stock surface. Figure 8 illustrates how the relatively "sharp" asperities can cause damage to the surface of the stock. The mechanical properties of this very thin surface layer of the stock can be significantly different from the bulk properties of the material and this effect to be the subject to further research. It has been shown by modelling, for example, that changes of the yield stress in the area can significantly affect deformation and failure at the surface layer. The lower the assumed yield stress of the surface layer, the less is the probability of churning, which has been predicted for higher values of the yield stress.

3. CONCLUSIONS

A combination of experiments and finite element analysis linking macro- and micro-level of model-

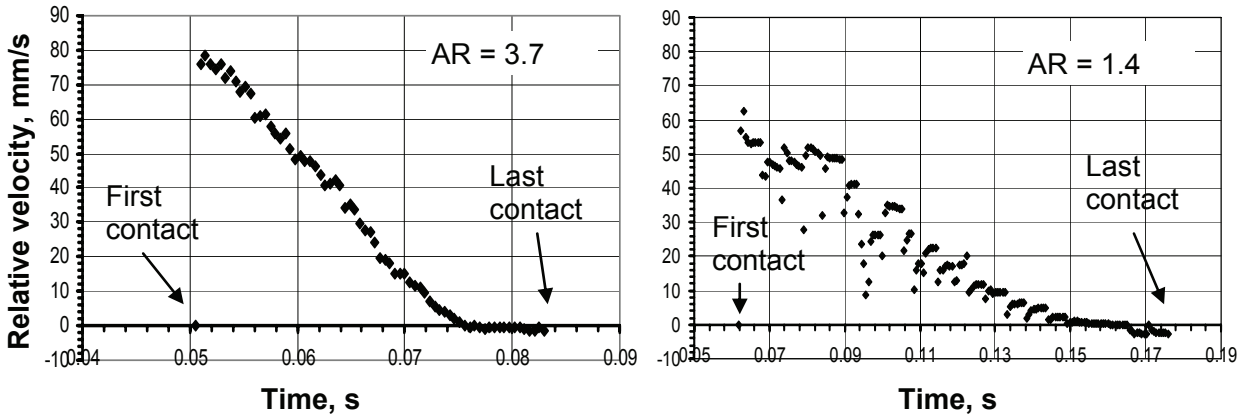

Fig. 7. Relative velocity between the stock and the roll surface predicted for the different AR and the following rolling parameters: roll radius 69.7 mm; strain 0.4.

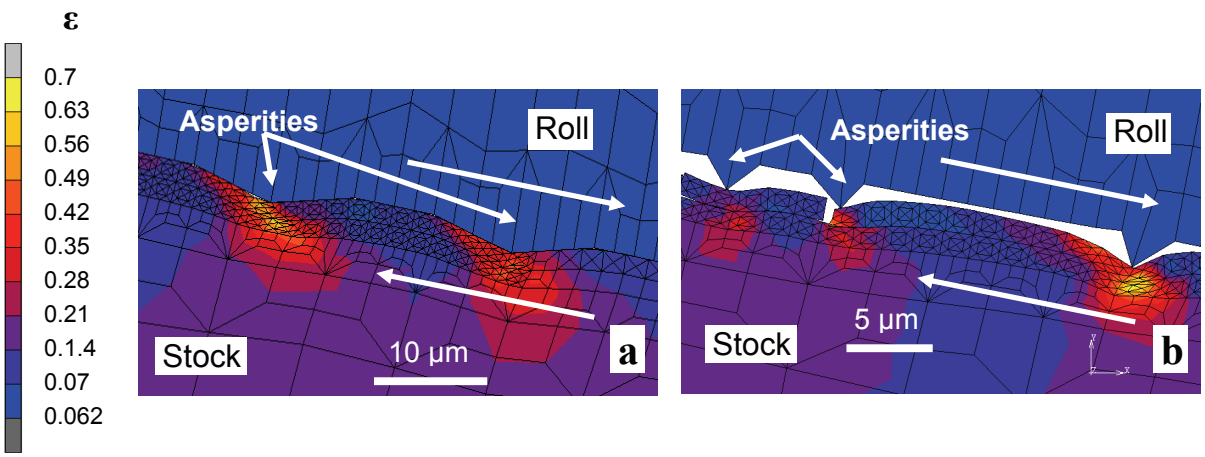

Fig. 8. Equivalent total strain predicted in the material near the roll/stock interface for the different shape of asperities: "shallow" (a) and "sharp" (b).

ling has been applied to represent formation of the stock surface layer in hot rolling of alluminum alloy AA3104. Adoption of the mechanical model of metallic sliding friction allowed for numerical representation of a wide range of the phenomena responsible for formation of the stock surface layer during hot rolling of aluminium arising from slip at the roll/stock interface and the action of roll surface imperfections on the stock surface. It is possible to investigate the influence of a range technological parameters, for example, rolling direction, aspect ratio, roll roughness and rolling speed on mechanical mixing in the area using the developed FE model.

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SYMULACIA KSZTAŁTOWANIA SIĘ WARSTWY POWIERZCHNIOWEJ WYROBU PODCZAS WALCOWANIA WSTĘPNEGO STOPU ALUMINIOWEGO

Streszczenie

Symulacja ponownego nagrzewania oraz walcowania wstępnego stopu aluminium AA3104, zawierającego Al, Mg oraz Mn, została wykonana w oparciu o badania doświadczalne, stosując laboratoryjną walcarkę duo (dwuwalcową). Badania doświadczalne były ściśle połączone z modelowaniem numerycznym kształtowania się warstwy powierzchniowej wyrobu. Model powierzchni rozdziału pomiędzy walcem i wsadem zazwyczaj rozpatruje się jako część "mikro-" bardziej skomplikowanego modelu "makro-" opartego o metodę elementów skończonych. W tym przypadku odpowiednie połączenie skal modelowania jest procedurą niezbędną dla dokładnej analizy numerycznej mechanizmów kształtowania powierzchni rozdziału. Taka procedura pozwala na rozpatrywanie dokładnych mechanizmów odpowiadających za kształtowanie powierzchni rozdziału walec/wsad, obniżając jednocześnie liczbę rozpatrywanych elementów. W pracy wykazano, że podczas walcowania mała ilość tlenków magnezu wtrąca się w warstwę powierzchniową wsadu na głębokość około kilku mikronów. Mechanizm odpowiadający za kształtowanie oraz mechaniczne wtrącenie się cząstek tlenkowych w warstwę powierzchniową wsadu łączy się z oddziaływaniem chropowatej powierzchni walca na powierzchnię wyrobu oraz z poślizgiem wzdłuż powierzchni rozdziału: walec/wsad.

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