Modelling of Fluidity during Hot Compaction of Ti-B System Synthesized Mass

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Abstract. Developing the scientific basis for making new materials with pre-planned, physical and mechanical properties by SHS (self-propagating high temperature synthesis)-compaction is a fundamental problem of modern metallurgy, which can be solved by imaginative modeling of the structural-phase state of materials. Among the many methods of obtaining metal-ceramic tiles, the ease of process management, cheapness, ecological cleanliness and the possibility of obtaining high-quality products are significantly distinguished by the innovative SHS electrical rolling process developed at the F. Tavadze Institute of Metallurgy and Materials Science, which, by maintaining the equilibrium velocities of the rolling and combustion fronts, ensures hot deformation of the hot viscous plastic mass in the deformation core under conditions of continuous compensation of heat losses Namicheishvili, 2016 [1] and Aslamazashvili, 2017 [2].

1. Introduction
In order to develop the technological schemes of the SHS- electrical rolling process developed to obtain large transverse dimensions and tiles of unlimited length, it is necessary to study the behaviour of the synthesized mass at the deformation core. Recent studies have shown that the basic technological parameters of the SHS-electrical rolling process (Figure 1) are undergoing more changes than expected. Although experimental studies of variable phenomena of thermodynamic processes and kinetics of material displacement in the SHS electro-rolling process have not yet been possible, some theoretical considerations and practical results can lead to tentative conclusions. For example, it is probably indisputable that in the process of SHS electro-rolling, in contrast to the rolling of compact metals, the stretching of viscous, hot billets is carried out not only in the rolling direction, but also in the opposite direction.
2. Experimental Investigations and Results

To determine this phenomenon and in order to define the regularity of the synthesized burden fluidity, the deformation core was imaginatively divided into sections of equal length along the entire length under the established process conditions. The anterior and posterior incisions of each site are considered as the incisions of the billet entering and exiting the deformation site (Figure 2).

In the process of deformation, the heated viscous plastic material in each area flows in three directions - in the vertical, transverse and longitudinal directions of compression. At the same time, the longitudinal deformation takes place in the direction of both rolling ("positive" stretching) and its opposite site ("negative" stretching.). This phenomenon is explained as follows: since the outflow is mainly in the direction of less resistance, in our case, the porosity of each previous precinct is greater than the porosity of the subsequent precinct. Some of the material flows in this direction, less resistance (Figure 3).

Along the core of the deformation, from the initial site to the last site, gradual hardening of the burden-material takes place, decreasing the so-called private Δhi shrinkage (site-operated stretching). The difference in material density (porosity) between the sections also decreases, therefore, the "positive" gradually increases and the "negative" stretch decreases. The sum of the "negative" private stretches causes the roller to be somewhat "negative". Hence, the total increment of the longitudinal direction of SHS electro-rolling process is the sum of the "positive" and "negative" shrinkage.

In the deformation core, the empirical formula is used to determine the hardening depending on the shrinkage (deformation) [2]:

\[ \rho_x = \rho_0 + (\rho_1 - \rho_0)\frac{\varepsilon}{\varepsilon}0,5 \]  

(1)
Where: $\rho_x$ - density in search section, g/cm$^3$; $\rho_0$ - initial density, g/cm$^3$; $\rho_1$ - rolling density, g/cm$^3$; $\varepsilon_x$ and $\varepsilon$ are the total relative deformations of the search section of the deformation core, %.

**Figure 3.** Fluidity of synthesized mass in imaginatively divided areas.

It is known that the main shrinkages in the rolling process, in our case the compaction of the porous material, are mainly carried out in the lag zone of the deformation center. The lag zone in SHS electro-rolling process, in contrast to the classic rolling of compact metal, is 77-82% of the total deformation core (Figure 4). Therefore, the process of compaction and material leakage, in particular the "negative" leakage process, is prolonged and consequently its impact is increased.

The epicenter of the less variable rolling velocities along the deformation core and rather variable velocities of the specimen show the values of the latency of the deformation core and the lengths of the forward zones (Figure 3).

**Figure 4.** Changing the rate of the horizontal rolling velocity adjuster (1) and the displacement of the specimen (2) along the deformation axis.

During the SHS electro-rolling process, the last section of the rolled stock (about 10% of the total length) was broken, or it was cut from the main body. This is undoubtedly explained by the fact that the "negative" drain changes billet’s electro-rolling temperature regime. The "negative" high-temperature (synthesized) burden will penetrate into the charge combustion zone located in front of the biting intersection, which will lead to a slight increase in its density and additional heating of the so-called "preheating zone" of the recently ignited mass. A similar effect is exerted by the high-temperature gas accumulated in the pores, which in the filtration mode is intensively applied to these non-flammable parts of the billet. This facilitates the ignition process of the next bite of burden, which increases the speed of movement of the combustion front[3]. The combustion front gradually moves away from the biting intersection, at the same time the end of the billet moves towards the intersection biting i.e they move in meeting directions and at the intersection of their meeting the synthetic
combustion ceases, this last section of the product no longer receives additional heat energy, begins its accelerated cooling and before reaching the biting intersection it manages to cool below the SHS phase formation temperature. The material becomes non-deformable, fragile and further deformation causes cracks in it and even breakage of the product.

Due to the above, the main reason for the failure of the rolling mill’s last section is the violation of the synchronization of the rolling velocity and the velocity of the movement of the burden’s combustion front, in particular, the lag of the rolling rate.

In order to synchronize the rolling speed of the combustion front of burden with the rolling speed, a new adjustment of the rolling mode is required - selecting the rolling speed so that the last section of the billet reaches the hub of the blast in a heated viscous plastic state.

To determine $\Delta h_i$ shrinkage dependent on the total tension at certain sections of the deformation core, a formula is obtained based on the geometry of the deformation core, which allows the analysis of the hardening process:

$$\Delta h_i = \frac{2i+1}{n^2} \Delta h$$

(2)

Where: $n$ is the number of conditionally divided precincts; $i = 0 ÷ (n-1)$; $\Delta h$ – total shrinkage.

For private case: Deformation center $L = 32$ mm with evenly divided 1 mm increments, $n = 32$, $i = 0$-31. Private and total shrinkage was calculated for each site (Figure 5, 6)

![Figure 5. Private (1) and total (2) shrinkage along the deformation core length.](image1)

![Figure 6. Change in relative shrinkage along the length of the deformation core.](image2)
Since the deformation center is not a large area and the structural formation of the synthesized mass takes place in a small amount of time, the mass in the viscous plastic state undergoes multifaceted displacement. Therefore, in order to increase the degree of compaction, we choose rolling in the gauge, during which the transverse movement is limited. When TiB06 and TiB2 burdens are rolled on the basis of Ti-B system, the dimensions of the initial sample are b0xh0l0 = 70x24 mm, and the dimensions of the strip obtained by SHS electro-rolling are b1xh1 = 75x10 mm, the length of the deformation core is 32 mm.

The starting specimens are cold pressed burden briquettes of the same composition of different compaction grades. For each precinct, the following are defined: individual shrinkage, intersection volumes, densities, masses of synthesized burdens required for the corresponding solidifications (compaction) according to precincts, and the difference between these masses, which is then divided by the length of the roll. The theoretical report data are given in Table 1 and Figure 7 and 8.

**Table 1. Influence of initial density on TiB2 / TiB06 casings when compacting**

| Sample | 1 | 2 | 3 | 4 |
|--------|---|---|---|---|
| corresponding initial size of the deformation core, mm | 70x24x32 | | | |
| corresponding final size of the deformation core, mm | 75x10x32 | | | |
| Length of the deformation core, mm | 32 | | | |
| Volume of the deformation core, cm³ | 35,1 | | | |
| Initial density, g/cm³ | 2,5/2,59 | 2,59/2,8 | 2,7/3,0 | 2,8/3,2 |
| Density of the rolled plate, g/cm³ | 4,49/4,95 | 4,55/4,98 | 4,59/5,01 | 4,65/5,05 |
| corresponding initial mass of the deformation core, gr | 144,0/149,2 | 149,2/161,1 | 155,5/172,8 | 161,3/184,3 |
| Mass of the compact plate in the deformation core, gr | 139,8/152,4 | 142,0/154,8 | 144,1/157,7 | 146,6/160,5 |
| Mass difference, gr | 4,2/3,2 | 7,2/6,7 | 11,4/15,1 | 14,7/23,8 |
| Size of the initial billets, mm | 70x24x320 | | | |
| Rolling dimensions, mm | 75x10x398/75x10x375,1 | 75x10x408/75x10x403 | 75x10x421,6/75x10x429,2 | 75x10x431,6/75x10x454,2 |
| L₀=320mm Rolling billet elongation, mm | 78,8/55,1 | 88/83 | 101,6/109,2 | 111,6/134,2 |
| "Positive and negative" elongation, mm | -61,5/+17,3 /-43; +12,1 | -68,6/+19,4 /-64,7; +18,3 | -79,2/+22,4 /-85,2; +24,0 | -87,0/+24,6 /-104,7; +29,5 |
| Increase in the rate of the synthesis mm/sec, (initial.16,5/16 mm/sec) | +2,7/1,9 | 2,9/2,7 | 3,3/3,4 | 3,5/4,0 |
Figure 7. When rolling a TiB₂ burden, the mass required for compaction in sections along the deformation core is 1-ρ₀=2.5 g/cm³; 2-ρ₀=2.59 g/cm³; 3-ρ₀=2.7 g/cm³; 4-ρ₀=2.8 g/cm³.

Figure 8. When rolling TiB₂ burden, the difference between the supplied and compacted masses in the areas along the deformation core

Table 1 show that the process of SHS electro-rolling (mass flow, compaction, shrinkage, etc.) is greatly influenced by the density of the pre-cold pressed burden. Increasing of the latter leads to an improvement in the quality of compaction.

Density of the burden increases from the initial cross-section of the deformation hub to the last cross-section, similar to the change in total shrinkage (density is proportional to the relative deformation), and the mass value required for each site increases initially and then decreases. The increase in the initial stage is caused by an increase in the volume of the precinct, and the latter
depends on the lateral expansion as a result of the shrinkage. After filling the gauge, the width of the product is unchanged and the value of the mass decreases at the cost of reducing the volume.

3. Results and discussions
The synthesized burden is supplied to the deformation core with a certain constant density, and because the volumes of the evenly divided initial areas of the deformation center decrease and the degree of compaction increases, in the process of compaction, a mass deficit is observed at the initial stage, and then an excess. The contact between the rolls and the container from the beginning to the end of the deformation core causes the temperature of the latter to decrease, while the thermal field is maintained in the central part.

In the peripheral zones of the billet, by the forces of friction, the rolls disperse the mass in the direction of its movement. Due to the lower density of the previous layers in the central zones and consequently less resistance, the mass moves in the opposite direction because the density of the previous precinct is less than that of the next precinct (Figure 3). Eventually, the mass delivered from the deformation core corresponding to the length of the deformation exceeds the mass required to compact the deformation core, and a large portion of this excess mass flows in the form of a negative shrinkage and a small portion in the form of a positive shrinkage. The redistribution of the absolute values of the positive and negative shrinkage corresponds to the ratio of the lag and forward areas to the length of the total deformation core. (Depending on the velocity curves for a particular case from Figure 4 78, +22%).

"Negative" shrinkage, or the fluidity of masses against the motion of the product, causes the combustion center to move and, consequently, to increase the rate of synthesis. Based on the example under consideration, for TiB$_2$ the nominal $V_{\text{synth}} = 16$ mm/s, this increase represents 16-21%, the velocity increase is 2.6-3.4 mm/sec, and the maximum final velocity will be increased up to 18.6-19.4 mm/sec.

Thus, during the electrical rolling process of the synthesized mass, it is necessary to change the rolling speed, taking into account the technological parameters (geometric, high-speed and power), so as not to infringe the speed balance.

4. Conclusions
The work discusses the TiB$_2$ and TiB$_{06}$ SHS electro-rolling process selected to obtain metal-ceramic wear-resistant, wood-resistant and corrosion-resistant tiles based on the Ti-B system, in particular, the flow analysis of the synthesized burden.

In the case of electrical-rolling of a synthesized mass, based on experimental observations and theoretical reports, it is established that both "positive" and "negative" shrinkage occur. Depending on the magnitude of the latter, the speed of movement of the combustion front varies.

For each area evenly divided by the imaginary deformation core, the calculation formula for the values of the private shrinkage is derived on the basis of mathematical analysis.

For a particular case, a report is made and diagrams are given for the cold-pressed samples of different density samples at the imaginary divisions of the deformation core at the density change and mass distribution, and the average mass supplied to the volumes of these areas is compared.

High-speed mode balance values are calculated. An increase in the length of the billet under the influence of "negative" shrinkage is shown, which leads to an increase in the speed of the combustion front and the delay time before rolling, intense heat loss, and disconnection of the cooled last part from
the product during rolling. It is therefore necessary to adjust the rolling velocities by calculating the high-speed and thermal balances.

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