Rapid tooling of tyre tread ring mould using direct metal laser sintering

Jelena Milovanovic*, Milos Stojkovic, Miroslav Trajanovic
Faculty of Mechanical Engineering Niš, A. Medvedeva 14, 18000 Niš, Serbia

Received 04 May 2009; accepted 26 October 2009

Paper outlines a feasibility study of using direct metal laser sintering (DMLS) for rapid tooling (RT) of tread ring of tyre vulcanization mould. Lead time and costs for rapid tooling with DMLS is acceptable for small mould segments (1/64 of tread ring). RT strategy that utilizes DMLS appeared to have significant advantages concerning lead time and costs as compared to conventional tooling of tyre mould including CNC-HSM engraving. Simplicity of tread ring tooling by DMLS makes new tyre development and test easier and faster.

Keywords: DMLS, Rapid prototyping, Rapid tooling, Tyre mould

Introduction

Direct metal laser sintering (DMLS) is an additive manufacturing process, in which high-power laser sinters fine layers (20 µ each) of metal powders layer-by-layer from bottom up until build is complete1. Fabricated tool inserts may be applied in die-casting, injection molding and a variety of other applications2,3. Geometrical and mechanical properties of parts produced by DMLS are comparable to those machined or produced by investment casting4. Tyre vulcanization mould is a very specific and complex type of tread ring mould, which is characterized by inverse tyre tread geometry (Fig. 1). Complexity of tread ring mould is manifested primarily by its toroidal shape containing different kind of ribs5-10 (circumferential, lateral, spines or lamellas and esthetic). Conventional manufacturing process of tread ring mould involves complex (4- or 5-axis) machining and precise die-casting making tooling process very intricate, time consuming and expensive11-13. A preliminary study14 has shown that rapid prototyping (RP) and rapid tooling (RT) seems to be promising technologies for manufacturing of complex shapes. RP and RT include applications of LOM (Laminated object manufacturing)15, FDM (Fused deposition modeling), SLA (Stereolithography), 3DP (3D printing), SLS (Selective laser sintering), DMLS (Direct metal laser sintering) and SLM (Selective laser melting)16 technologies and their immanent RT procedures17.

In present study, most suitable RP technology (DMLS) was identified for optimal rapid tooling solution concerning main manufacturability parameters of quality, time and costs.

DMLS Technology for Manufacturing of Tread Ring Segments

Feasibility study of DMLS includes: i) Direct-metal sintering of tread ring segment (study was conducted with one-pitch-segment (1/128 of tread ring mould) by testing the most important utilization features of segment (geometrical and dimensional accuracy, surface roughness (SR), hardness, density and porosity, temperature and pressure endurance, thermal conductivity and chemical reactivity)); ii) Time and costs consideration; and iii) Identification of optimal rapid tooling procedure to employ DMLS in the production of tread ring mould.

Tread Ring Segment Prototype

DMLS one-pitch segment was manufactured by EOSINT M270 machine (with Yb fibre laser 200W). Material used for making tread ring segment was Direct Steel H20 (composition: Cr, Ni, Mo, Si, V, and C), which is a very fine grained steel-based metal powder.
Geometrical Accuracy

Accuracy of sintered segment was diagnosed in two ways: i) First approach was based on geometry comparison between native CAD model for RP machine, and healed CAD model [CAD model was reversely designed (i.e. healed) from scanned DMLS segment. Healed CAD model is consisted of series of cross-section curves, while input CAD file of segment was given in STEP and/or STL format. Critical areas of DMLS segment are located near connection curves between two segments in mould assembly (connection curves in radial direction at lateral junctures of segments and connection curve in circumferential plane at circular junctures of segments near to central rib or near to end of the tread). Deviations of central rib radius could affect mould accuracy largely, causing radial run-out of a tool.]; and ii) Second approach of geometrical accuracy analysis employs Steinbichler optical measurement system. Geometrical accuracy of DMLS segment is 0.05 mm (Fig.2).

Surface Roughness (SR)

SR directly affects on tyre appearance, wear resistance, mould durability and its maintenance costs. SR measured (Mitutoyo surftest SJ-301) values for one-pitch segments are as follows: Ra ≈ 3.78-5.60 µm; Rz ≈ 16-25 µm after shotpeening; and Ra ≈ 1 µm after polishing.

Hardness

Hardness (HRC, 34; HRB, 319) is measured using Rockwell and Brinell device.

Density

Density of DMLS segment, measured by using test cubes, is 99.5% in skin parameters.

Other Utilization Features

For other utilization features of DMLS segment (temperature endurance, pressure endurance, thermal conductivity and chemical reactivity), a test tread ring mould, in which one of its segments was DMLS segment, was assembled. Test-mould was exposed to real conditions in standard vulcanization process cycle. Test shows that DMLS one-pitch-segment meets set of utilization features (temp. endurance, >180°C; thermal conductivity, 18 W/mK; pressure endurance, 21 bar).

Manufacturing and Post Processing Time

Manufacturing and post processing time to determine competitiveness of DMLS technology are 14 h and 30 min respectively.

Results and Discussion

Strengths of DMLS (Advantages)

Greatest strength of DMLS is certainly possibility to create any shape that can be found on tread ring mould.
In addition, simplicity of digital model preprocessing for RP takes 10% of CAM preprocessing time that precede CNC machining. Considering that time for RP depends on the volume of model, a proper design optimization (small-volume optimized models, thin or surface-like models) can not only save a lot of time, but also material costs.

Weaknesses of DMLS (Limitations)

There are limitations in size of mould segments that can be sintered by these systems. Concerning maximal part building area of DMLS chamber (250 mm x 250 mm x 215 mm), largest segment of tread ring mould for passenger tyre 205/60 R15 is 1/8 segment (diam, 630 mm; L<242; W<200). In addition, larger segment takes more metal powder and more production time that finally increase production costs.

Rapid Tooling Strategies

i) Fully-direct Rapid Tooling Strategy

This production strategy anticipates direct laser sintering of tread ring mould large segments or one-pitch-segments. Mould segments that are sintered by DMLS fulfill all utilization features of tyre curing mould. In addition, this RT strategy appears to be simplest and most flexible. Low speed of volume sintering (1650 mm³/h) makes RT strategy economically unacceptable for particular case of tread ring volume. Results from case study showed that DMLS system can make 16 one-pitch-segments for 150 work hours. Considering that one tread ring mould usually includes 128 one-pitch-segments, fully-direct RT strategy needs 1200 h of DMLS.

In order to be competitive to CNC-HSM direct engraving, fully direct RT should be faster process (no more than 240 h), and costs should not exceed the costs of production mould (12000 $). Another important shortcoming of fully-direct RT strategy is high price of H20 steel powder. Material costs of H20 increase total production costs cumulatively. In the case of rapid tooling of prototype mould by DMLS, economic indexes are better.

ii) Semi-Direct Strategy

With the application of semi-direct RT strategy, DMLS is used for sintering the form of tyre tread segments, so called master models, which are used as inserts for die casting of AlSi tread ring mould segments. DMLS provides a suitable shape and dimensional accuracy as well as all other features (hardness, roughness, etc.). In this tooling strategy, tread ring mould is assembled from AlSi one-pitch-segments; utilizing features of tread ring moulds are produced by conventional
manufacturing procedures. After post processing (removing from platform, cleaning and shot peening), master model is used as an insert in die-casting mould. Next step is die-casting of aluminum one-pitch-segment of the mould. After casting one-pitch-segment of the mould, it is necessary to post-process it by removing the gates, runners and burrs. Finally, one-pitch-segment can be used to assemble tread ring of tyre curing mould.

**Limitations on Semi-direct RT Strategy**

Considering that tread ring of tyre curing mould is of toroidal shape, it is very difficult to cast larger segments of ring. If segments are large (like 40° or 1/9 segments), surfaces of ribs that are presented at tread ring mould are more slanted. This can cause opening of mould impossible. Another constraint, which prevents from casting larger segments of tread ring mould, is very specific disposition of so-called pitches of tyre tread. Usually, tyre tread has 3 or 5 different types of pitches that are characterized by slightly different geometry\(^5\)\(^\text{-}^{10}\). These different pitches are repeated on tyre tread by very specific disposition. Actually, this disposition has crucial influence on tyre vibration and noise\(^18\). Thus, it is economically inappropriate to cast several different larger segments that include different combination of pitches. Optimal solution is tread ring mould assembled from one-pitch-segments, where each mould segment corresponds to appropriate tyre tread pitch.

**Time and Costs Consideration**

Time and costs in semi-direct RT strategy are more reduced as compared to fully-direct strategy. In the case of 5 different pitches, DMLS system sinters them for about 50 work hours (Table 1). After post processing of 5 master models, that takes 3 h; 5120 of AlSi-alloy segments (128 jigsaw puzzles ´ 40 moulds) is moulded in fast die casting process (Table 2). Duration of die casting process depends on number of nests in die as well as on number of available die-cast machines. Thus, semi-direct RT strategy could make significant savings as compared to CNC-HSM engraving strategy, and conventional CNC-three-step-casting strategy.

**Conclusions**

Feasibility study of using DMLS for rapid tooling of tread ring mould indicates that just small and thin pieces

---

**Table 1—Time and costs for direct metal sintering of one-pitch-segments**

<table>
<thead>
<tr>
<th></th>
<th>Sintering of 1 one-pitch-segment</th>
<th>Post-processing time for 1 one-pitch-segment</th>
<th>Set of 5 one-pitch-segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, min</td>
<td>600 (10 h)</td>
<td>30</td>
<td>3150 (52.5 h)</td>
</tr>
<tr>
<td>Processing* cost, $</td>
<td>120</td>
<td>30</td>
<td>750</td>
</tr>
</tbody>
</table>

* Processing cost does not include H20 material costs

**Table 2—Time and costs for die-casting of series of mould segments**

<table>
<thead>
<tr>
<th></th>
<th>1 segment ( V » 21 cm(^3))</th>
<th>Segment post-processing (removing the gates, runners and burrs)</th>
<th>128 segments (one mould set)</th>
<th>5120 segments (set for series of 40 production moulds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, min</td>
<td>0.35 *</td>
<td>1.45</td>
<td>230</td>
<td>9200</td>
</tr>
<tr>
<td>Processing cost, $</td>
<td>≈ 6000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Time for die-casting of 5 puzzles is 22 s in tool that has 5 nests
(small volume and mass) with high complexity of geometry should be considered. Only one-pitch-segment of tread ring mould can be suitable for using DMLS. DMLS technology meets a whole set of utilization features of tread ring mould. Moreover, while fully direct RT strategy shows limitations considering time and costs, semi-direct RT strategy is applicable in the case of manufacturing tread ring mould. In comparison to conventional tooling processes, semi-direct RT strategy is more direct, faster, simpler, more accurate and cheaper. At the same time, semi-direct RT strategy that utilizes DMLS technology is most flexible procedure for manufacturing of prototype tread ring where design changes are usually frequent.

Acknowledgements
This study was co-financed by Ministry of Technology and Development of Government of Republic of Serbia and Rubber Products Company TIGAR-TYRES a.d. (incorporated in MICHELIN Co.). Authors are grateful to numerous experts from Research and Development Department of Rubber Products Company TIGAR-TYRES, for cooperation.

References