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Additive Fabrication in Metallurgy - Case Study of Grey Cast Iron Valve Production

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Additive Fabrication technologies are well known from the last two decades. In that time Additive Fabrication technologies have evolved from strictly prototype part production into an option that can also be used to produce end-user parts. With development of Additive Fabrication machines capable of producing metal parts, a complete substitution of conventional metal casting technologies is possible. However, direct Additive Fabrication of metal parts is still not time/cost effective when producing large volume parts, and nowadays there is still lack of materials that can be used on those machines. This paper presents a method how a conventional sand casting process can be assisted by Additive Fabrication technologies. A sand mould pattern is produced by Selective Laser Sintering. Additive Fabrication is also used in direct manufacturing of cores.

Tehnologije dodavanja materijala u metalurgiji – Studija slučaja produkcije ventila iz sivog lijeva

Strukovni članak

Tehnologije sa dodavanjem materijala dobro su poznate od posljednja dva desetljeća. U to vrijeme tehnologije dodavanja su se razvije od tehnologija koje se upotrebljavaju strogo za brzo proizvodnju prototipnih dijelova, do tehnologija, sa kojima se može direktnu proizvodnju konačne produkte. Sa razvojem tehnologija za direktnu izradu metalnih dijelove, moguća je potpuna zamjena konvencionalnih tehnologija lijevanja metala. Međutim, direktna izrada dijelova još uvijek nije dovoljno ‘’cost efficient’’ kada su u pitanju komadi velikog volumna i danas još uvijek je samo nekoliko materijala , koji su testirani na strojevima za direktnu proizvodnju metalnih komada. Ovaj rad predstavlja metodu kako se mogu tehnologije dodavanja koristiti kao pomoć kod konvencionalnih lijevarskih procesa. Pješčani kalup izrađen je po postupku selektivnog laserskog sinteriranja pijeska, a postupci direktne proizvodnje su korišteni kod proizvodnje jezgra ventila.

1. Introduction

Despite the development of new technologies, manufacturing of cast part prototypes results in high production costs due to pattern preparation, core production and casting procedure itself. In the presented case study, a prototype series of ten valve housing with identical material and properties than an end-user part were required for functional testing. A combination of Additive Fabrication, CO2 sand forming and serial production casting [1-2] line was used in production of prototype grey cast iron valve housings. The production procedure can be completed in an extremely short period of time; ten finished parts were obtained in just ten working days from the final confirmation of the CAD model.

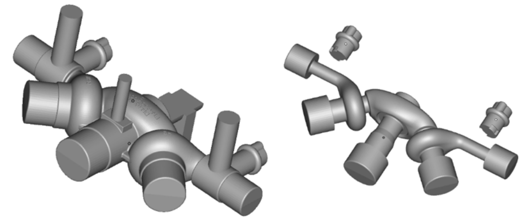

Figure 1. Left: CAD model of the valve with added attachments and feeders used for SLS (Selective Laser Sintering) manufacturing from polyamide. Right: CAD model of a valve’s core used for GSP (Generis Sand Process) manufacturing

Slika 1. Lijevo: CAD model ventila sa ljivarskim dodacima, koji se je izradio sa poliamida po postupku selektivnog laserskog sinteriranja. Desno: CAD model jedra ventila upotrebljen za izradu jedra po postupcu GPS (Generic Sand Process)

2. Pattern and core production

The basis for manufacturing by Additive Fabrication is a finished part's CAD model. Based on this CAD data and certain casting criteria [3], adapted valve housing and its core were modelled in SolidWorks CAD software (Figure 1). Feeders for material shrinkage during the cooling phase and core placement attachments were added. Additionally, a part of an inlet channel with pre-prepared position for later casting filter placement was also added to the valve housing model.

The CAD model of the valve with added attachments and feeders was used for SLS (Selective Laser Sintering) manufacturing of the pattern from polyamide with added glass fibres (PA 3200 GF) on EOS SLS machine [4].

When a core manufacturing is considered the main limitation is a required material (casting sand). Usually, sand cores are manufactured by CO2 sand forming with a pre-manufactured tool required. Nowadays, two possibilities of direct sand core production by Additive Fabrication exist [5, 6]. The first option is based on laser beam activation of an adhesive mixed with casting sand, developed by EOS company [7]. This technology is implemented by EOSINT S 750 (Figure 2) additive Fabrication machine that manufactures sand parts with 0,2mm layer thickness. The maximum part size is up to 720 mm x 380 mm x 380 mm with a building speed of up to 2,500 cm^3/h. Sand parts produced by this machine have good surface finish (average measured Ra of 10), but can also be somewhat fragile, presenting possible problems in industrial environment use.

Figure 2. The EOSINT S 750 is double laser-sintering system for the processing of Croning moulding material. Using the DirectCast method, the system builds cores and moulds for sand casting

Slika 2. EOSINT 750 je stroj sa dvoje laserima za proizvodnju Croning ljevarkih komada. Sistem upotrjebljava DC (Direct Cast) metodu za izrado pješčanih komada za lijevanje u ljevarski pijesak

Another procedure called Generis Sand Process (GSP) was developed by Voxeljet company [8] and currently marked by ProMetal RCT . It uses similar casting sands, but the method is based on selective addition of adhesive (epoxy resin or glass water) during manufacturing. Layer thickness is between 0,2 and 0,4 mm, but the process requires larger average grain size of sand used, resulting in a slightly rougher surface than with the previously described method (average measured Ra of 15) [9]. The main advantages of GPS are faster manufacturing and less fragile finished parts. Build Volume of ProMetal RCT S15 (Figure 3) is 1500 x 750 x 700 mm. Due to cost effectiveness and low surface quality demands, the majority of cores and inserts were manufactured by GPS procedure.

Figure 3. ProMetal S15 sand printer, that works with Generis Sand Proces (GPS)

Slika 3. ProMetal S15 pješčani 3D printer, koji radi na principu GSP (Generic Sand Process)

Another advantage of using additive fabrication for sand cores manufacturing is a possibility of making them hollow. This enables quick removal of gases produced by casting that can cause deficiencies in finished part from the core area. Manufacturing of hollow sand cores, especially with high geometrical complexity, by conventional methods is usually not possible.

3. Forming

For manufacturing of sand forms a conventional CO_2 sand forming technology was used (Figures 4 to 9). Forming is based on curing the casting sand with added glass water by CO_2 gas. For pattern, a polyamide model produced by SLS was used. The pattern was covered by a layer of casting sand that was cured by CO_2 gas. The sand used was type Termit with 3-5 % of added adhesive in the form of glass water (a silicate water solution). Chemical reaction of curing is presented by formula (1):

$$Na_2O \times nSiO_2 + nH_2O + CO_2 = \\ = Na_2CO_3 \times 10H_2O + nSiO_2 \times (n\text{-}10)H_2O \quad (1)$$

SiO_2 gel is used as an adhesive, while Na_2CO_3 has no adhesive properties.

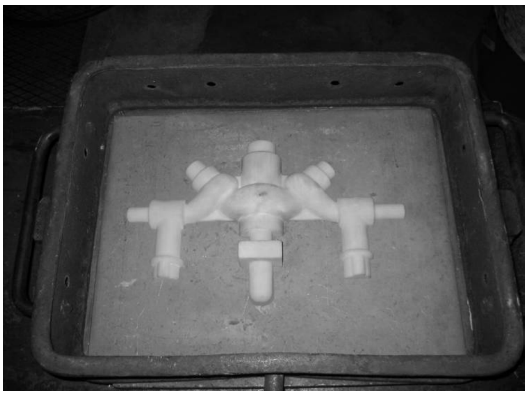

Figure 4. Form preparation starts with placing of one half of the pattern into the steel frame

Slika 4. Priprema forme vrši se sa plasiranjem jedne polovice forme (pramodela) u čelični okvir

Figure 5. The sand is then set and pressed. Used sand is Termit, as binder glass water (3 to 5 %) was used

Slika 5. Pijesak se sipa u okvir na formu i fiksira sa pritiskom. U našom slučaju je pijesak Termit sa dodanom staklenom vodu (3 do 5 %)

Figure 6. Curing of the sand form with CO2 gas

Slika 6. Konsolidacija pijeska vrši se sa plinom CO2

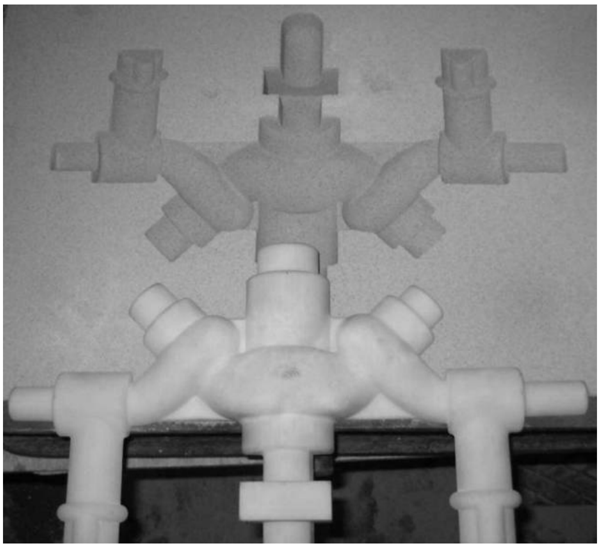

Figure 7. Cured sand form, with plastic pattern already removed. Other form half was manufactured in a similar manner.

Slika 7. Konsolidirana forma sa oduzetim plastičnim modelom (formo). Druga polovina bila je spremljena na jednaki način

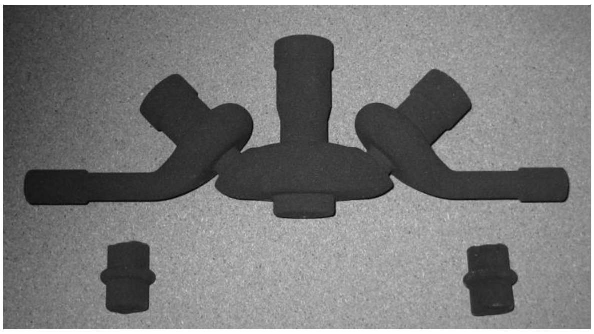

Figure 8. Sand cores made with Generis Sand Process on S 15 machine.

Slika 8. Pješčeno jedro proizvedeno sa GSP procesom na mašini ProMetal S15

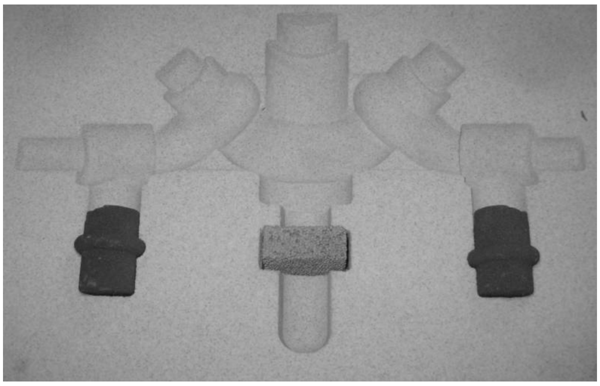

Figure 9. Inserting mould cores and filter.

Slika 9. Plasiranje jedra i filtera u lijevarsku formu

4. Casting

Casting (Figure 10) was performed on a line for serial production, resulting in minimal additional costs due to the melt quantity required in comparison to already prepared melt for serial casting. Casting temperature of used GJL 200 Grey cast iron was between 1420 and 1440 ºC.

Chemical analyses review:

C - 3.30 to 3.45 %

Si - 2.20 to 2.30 %

Mn - 0.65 to 0.70 %

P - 0.20 to 0.35 %

S - max 0.10 %

Cr max 0.20 %

Ni max 0.07 %

Sn max 0.03 %

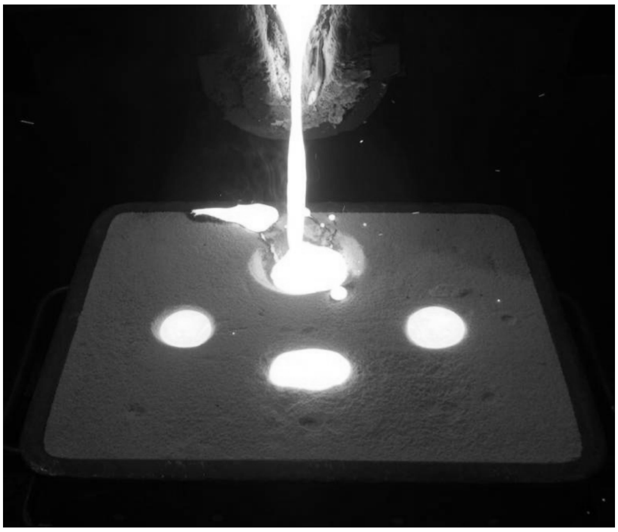

Figure 10. Grey cast iron casting into a finished form. Casting is completed once the melt pours out of the feeder openings

Slika 10. Sivi lijev lio se u konačnu formu. Lijevanje je gotovo, kad se višak materiala prolije kroz otvor za hranjenje jedra

5. Finished casting

After the cooling-down phase, the rough machining of the casting followed. This includes the cutting of inlet channel and feeders, the latter followed by sand blasting. For milling, some new techniques were used as described by dr. Balic in his recent work [10]. Mass of the machined casting was 3,045 kg with measured hardness of 210 to 225 HB. Castings were later sent for final machining by CNC machines in order to prepare them for functional testing (Figure 11).

Figure 11. Casting after final machining

Slika 11. Ventil nakon finalnog strojnog tretmana na CNC postrojenju

6. Research findings

During the production process, several problems occurred, partly as a consequence of introducing new technologies and also due to differences between sand casting procedure and other casting technologies usually used in Rapid Tooling [11-12]. Hollowed cores caused core breakings at most loaded areas, resulting in bad castings, due to the core being lifted by the melt to form a wall (Figure 12).

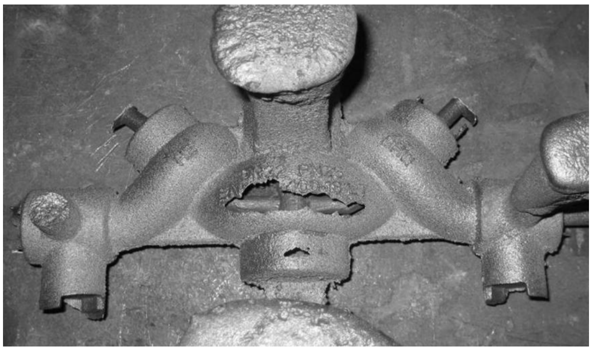

Figure 12. Hole in the casting, caused by lifting of the broken core

Slika 12. Rupa na ventila, koja je nastala zbog podizanja jedra, koje se u procesu lijevanja slomilo zbod sile uzgona

Due to systematic problem of core breaking (Figure 13), the rest of the hollow cores were reinforced by inserting a metal wire inside the cavity.

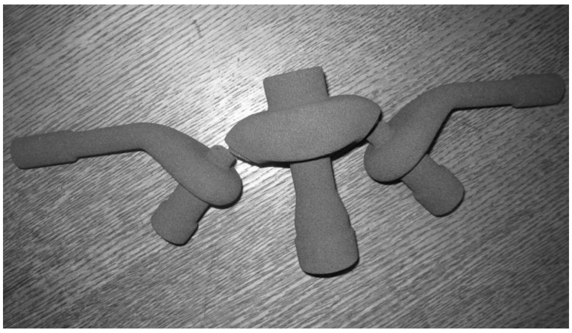

Figure 13. Core breaking on part with smallest core thickness

Slika 13. Jedro ventila slomilo se na području najmanje debljine jedra

The cavity was later filled with casting sand that was cured by CO2. After the core reinforcements there were no more visual errors on the finished castings. But as they were sent for a final CNC machining, a small vertical core movement was nevertheless discovered. This resulted in an extremely thin upper valve wall (Figure 14) and valve openings no longer being coaxial (Figure 15).

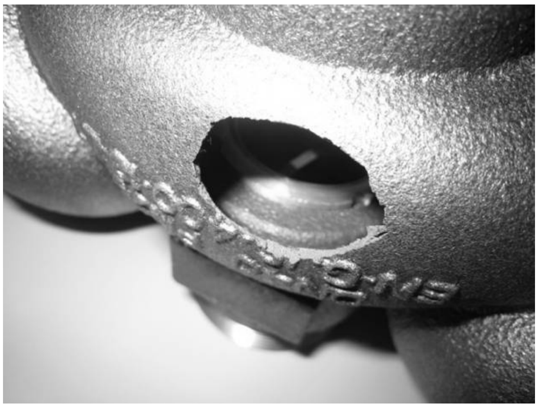

Figure 14. Thin upper wall caused by vertical core movement

Slika 14. Vrlo tanak gornji zid ventila kao uzrok vertikalnog guranja jedra u procesu lijevanja

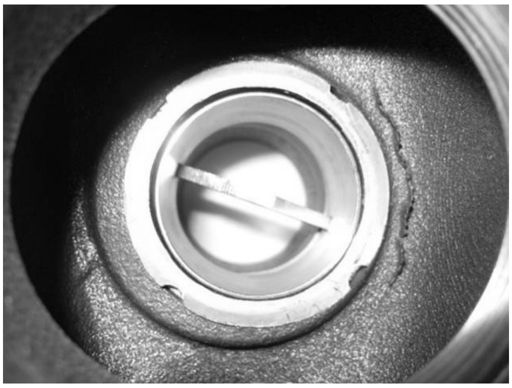

Figure 15. Problems of CNC machining due to valve opening not being coaxial

Slika 15. Problematični strojni tretman sa CNC mašinama zbog nekoaksijalne rupe ventila

It has been proved that in spite of the reinforcing and additional curing, cores crack during the casting resulting in a small misalignment of valve openings (2-3 mm). In the next phase new designs of cores were tested without the hollowed out inner channels, presuming that this type of core will withstand the force caused by lifting of the melt. Unfortunately, even these cores broke during casting. Therefore, a more conventional approach to using a mould for core production was used. The mould was also manufactured from polyamide by EOS Formiga P100 Additive Fabrication machine (Machine on Figure 16 and mould on Figure 17).

Figure 16. The FORMIGA P 100 laser-sintering machine with a built envelope of 200 mm x 250 mm x 330 mm, the FORMIGA P 100 produces plastic products from polyamide or polystyrene

Slika 16. Formiga P100 mašina za lasersku sinteriranje plastičnih materijala ima radni volumen 200 mm x 250 mm x 330 mm. Moguća je priprema plastičnih modela sa poliamida ili polistirena

Based on the problems revealed by fine machining additional holding marks were added to the core design. The mould construction also enabled additional reinforcing achieved by adding a steel wire inside a core. Cores were produced by conventional CO_2 curing of the casting sand inside a polyamide mould.

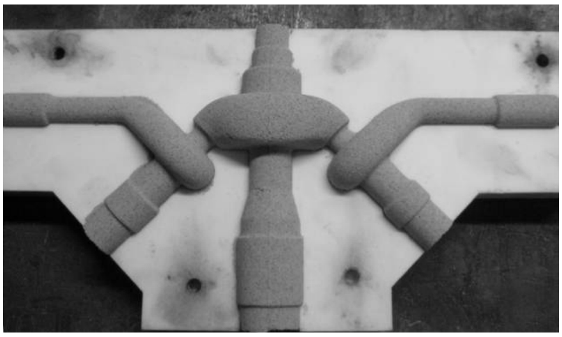

Figure 17. Polyamide mould for core manufacturing. A wire was added prior to CO_2 curing in order to reinforce the core

Slika 17. Model za proizvodnju jedara iz poliamida. U jedru se stavilo dodatnu armaturu u oblici čelične žice i nakon toga utvrđivalo sa CO2 plinom, kako bi jedro moglo, da se zoperstavi silama kod lijevanja

Sand cores with croning procedure (Figure 17) were made after all the trouble with different core production procedures. Re-modelled cores were made on EOSINT S 750 sand laser sintering machine with a shape modification (additional support on crucial side was added), which was more resistant to torsion strength.

The quality of finished cast parts was the same as that needed for serial production parts. After final inspection made with comparison of original CAD model to a model obtained with 3D scanning method, some deviations compared to CAD model were established. Interior of the cast was perfect, but since in our case the frame for forming was hand-prepared, with closing mechanism tolerance of 1 mm, a deviation of 1 mm with regard to the upper vs. the lower side of the product was found.

7. Conclusion

The presented case study shows the possibilities of using Additive Fabrication technologies in prototype casting production. Development of Additive Fabrication machines capable of manufacturing part from casting sand opened a way for implementing these technologies in the casting industry.

However, in our case of a 10 valve series, manufacturing of all individual forms and cores directly on an Additive Fabrication machine was not such a cost effective solution as the approach of just manufacturing a polyamide pattern, later used in conventional sand forming. Additionally, a problem of core breaking occurred due to rather unfavourable geometry, which was not previously checked with some simulation/analysis program like Ansys. Again, an indirect approach of using SLS for core mould manufacturing proved a viable solution, due to the possibility of additional reinforcing. This approach can be cost effective also in a somewhat larger series of prototype test part production.

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