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A COST-EFFECTIVE APPROACH TO THE RAPID FABRICATION OF FUNCTIONAL METAL PROTOTYPES

STROŠKOVNO UČINKOVIT NAČIN ZA HITRO IZDELAVO FUNKCIONALNIH KOVINSKIH PROTOTIPOV

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A quick response to the market is considered as one of the important factors to ensure a company's competitiveness. New products must be swiftly and cost-effectively developed, manufactured and introduced to the market. This work demonstrates a technology for the rapid manufacturing of the metal prototypes for a laptop hinge using both rapid-prototyping and rapid-tooling techniques. A small-batch production for the laptop hinge of about 20 pieces can be obtained economically via a silicone rubber mold using vacuum casting, without applying any plastic injection molding. The fabricated metal prototypes have excellent physical and mechanical properties, which can be used for functional tests. A cost reduction of 75 % and a time saving of 82 % can be achieved. This technology has considerable economic benefits and prospects for broad market applications.

Keywords: laptop hinge, metal prototype, silicone rubber mold, epoxy resin, surface roughness

Hiter odziv na zahteve trga je eden od ključnih dejavnikov za konkurenčnost podjetja. Novi proizvodi morajo biti hitro in stroškovno učinkovito razviti, izdelani in predstavljeni trgu. To delo predstavlja tehnologijo hitre izdelave kovinskih prototipov tečaja ohišja prenosnega računalnika s tehniko hitre izdelave prototipa in hitre izdelave orodja. Majhna proizvodna serija, okrog 20 kosov tečaja za prenosni računalnik, se lahko izdela s formo iz silikonske gume in z ulivanjem v vakuumu brez uporabe brizganja plastike. Izdelani prototipi iz kovine imajo odlične fizikalne in mehanske lastnosti ter so uporabni za funkcionalno preizkušanje. Doseže se lahko 75-odstotno zmanjšanje stroškov in 82-odstoten prihranek časa. Ta tehnologija ima velike ekonomske prihranke in možnosti široke uporabe na trgih.

Ključne besede: tečaj ohišja osebnega računalnika, kovinski prototip, forma iz silikonske gume, epoksi smola, hrapavost površine

1 INTRODUCTION

New market realities demand faster product development and a reduced time to market. They also require higher quality, cost reduction and greater efficiencies. To reduce the product development time and reduce the cost of manufacturing, rapid prototyping (RP)[1–3] has been developed, which offers the potential to completely revolutionize the process of manufacture. However, the features of the prototype do not usually meet the needs of the end product with the required material. Rapid-tooling (RT) technologies have been developed.[4–7] RT is regarded as a natural extension of RP, since it is a technology that uses RP technologies and applies them to the manufacturing of tool inserts. Since the importance of RT goes far beyond component performance testing, RT is regarded as an important method for reducing the cost and time to market in the development of a new product. Several RT technologies are commonly available in industry now. For the purposes of classification, RT is divided into soft and hard tooling as well as indirect and direct tooling. Soft tooling is easier to work with than tooling steels, because these tools are created from materials such as epoxy-based composites with aluminum particles, silicone rubber or low-melting-point alloys. It is well known that RT is capable of replacing conventional steel tooling, saving both costs and time in the manufacturing process. Indirect soft tooling is used more frequently in the development of new products, rather than direct tooling, because it is fast, simple and cost-effective.

It is a well-known fact that the silicone rubber mold is employed frequently because it has flexible and elastic characteristics, so that parts with a sophisticated geometry can be fabricated.[8] In addition, epoxy tools are frequently employed for intermediate tooling, because this material has acceptable mechanical properties and a high-temperature resistance.[9] Although some technologies, such as selective laser melting,[10] direct shell production casting,[11] direct metal laser sintering,[12] laser-engineered net shaping,[13] shape-deposition manufacturing,[14] metal injection molding[15] and high-speed machining[16] can be used to produce metal prototypes, the cost of the hardware is expensive. Thus, developing a low-cost method to manufacture a metal prototype is required. In this work, a cost-effective method for fabricating a functional metal prototype using RP and RT technologies is demonstrated to address this important issue. The surface roughnesses of the metal prototypes were measured using a white-light interferometry (WLI) technique. The

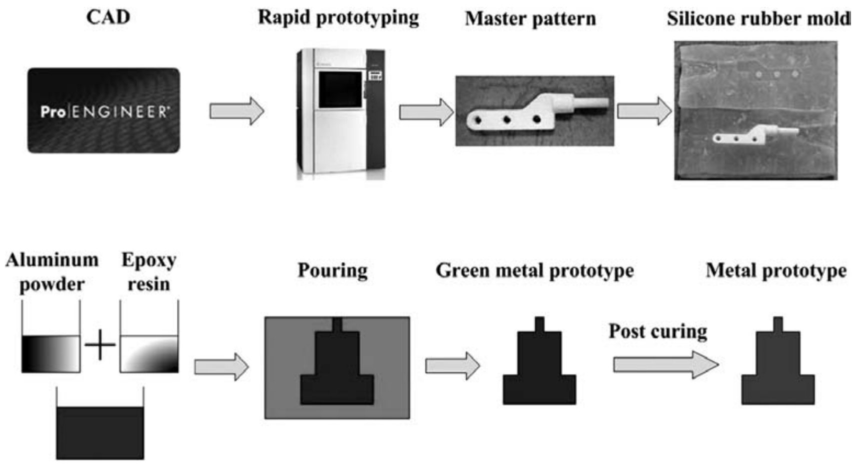

Figure 1: Schematic illustration of the process flow for this work
Slika 1: Shematski prikaz poteka postopka

properties of the fabricated metal prototypes were also discussed, as well as the advantages of this method.

2 EXPERIMENT

Figure 1 shows a schematic illustration of the process flow for this work. The master pattern model for this work is a laptop hinge, which was designed using Pro/ENGINEER software. The master pattern model was fabricated using an RP system (Z Printer 310; Z Corporation, Inc.). A silicone rubber mold was fabricated from the master pattern model. **Figure 2** shows a schematic illustration of the fabrication process for a silicone rubber mold in detail. The base compound (KE-1310ST; ShinEtsu, Inc.) and the hardener (CAT-1310S; ShinEtsu, Inc) were mixed thoroughly to fabricate the silicone rubber mold. The amounts of base compound and hardener were calculated by multiplying the desired volume of the silicon rubber mold to be made by the density of silicone rubber (1.07 g/cm^3 at 23 °C). In general, the curing agent and the silicone rubber in a mass ratio of 10 : 1 were mixed thoroughly with a stirrer. The properties of the silicone rubber mold, such as durability and mold life, are significantly affected by the relative amounts of curing agent and silicone rubber, because it will affect the cross-linking of the silicone rubber.[17,18] Thus, calculating the weight of the base and the curing agent precisely is crucial before mixing. To reduce the level of human error, a user-friendly, man-machine interface was developed using the Visual Basic program. A vacuum machine was used for generating a vacuum atmosphere, which provides the function of the degassing process to remove the air bubbles derived from the mixing process of the silicone rubber and the hardener. Depending on the extent of the air bubbles in the mixture, the degassing process can range from 25 min to 60 min. After this degassing process, the pressure inside the vacuum machine was changed by breaking the vacuum atmosphere. Thus, a silicone rubber mold can be fabricated without the defects caused by the air bubbles derived from the mixing process.

It is a well-known fact that epoxy-resin composite materials are frequently used for making rapid tooling. Epoxy resin (C1; Devcon, Inc.) was used to fabricate metal prototypes of the laptop hinge. The epoxy resin used is usually aluminum filled to enhance the mechanical or physical properties. The amount of epoxy resin required was calculated by the size of the master pattern. The hardener and base compound (70 % aluminum powder and 30 % liquid epoxy resin) in a weight ratio of 1 : 112 were mixed thoroughly with a stirrer. The mixing process of aluminum powder and epoxy resin is very important because a uniform distribution of the aluminum particles in the epoxy resin has a great effect on the mechanical property of the RT. Depending on the extent of the air bubbles in the mixture, the degas process can range from 30 min to 80 min. A stepwise post-curing cycle for the fabricated metal prototypes was performed in a convection oven (DH400; Deng Yag, Inc.) to ensure the completion of the curing reaction of the composite materials. **Figure 3** shows the temperature profiles used

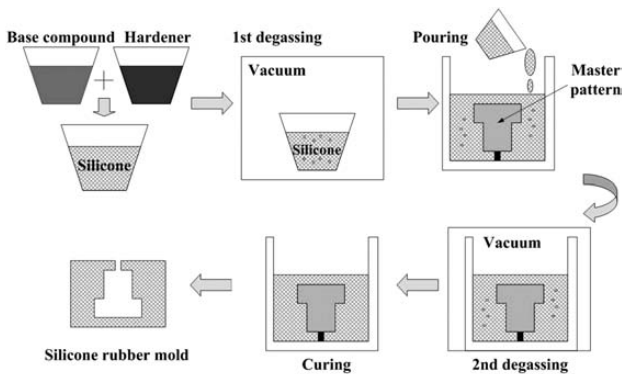

Figure 2: Schematic illustration of the fabrication process for a silicone rubber mold using vacuum casting
Slika 2: Shematski prikaz postopka izdelave forme iz silikonske gume z ulivanjem v vakuumu

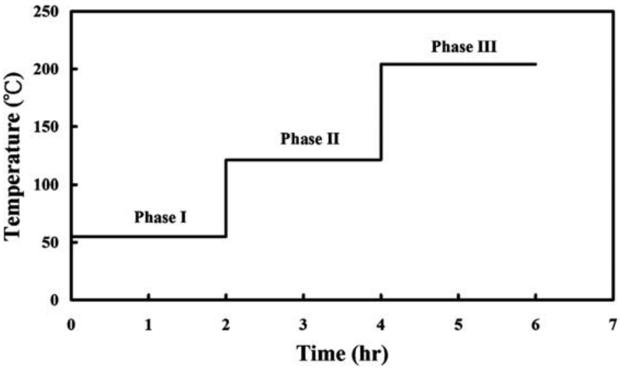

Figure 3: Temperature profiles used for post-curing the metal prototype of a laptop hinge
Slika 3: Temperaturni profil, uporabljen za utrjevanje po strjevanju kovinskega prototipa ležaja ohišja prenosnega računalnika

for post-curing the metal prototype of the laptop hinge. This temperature profile consists of three phases. In the first phase the green part is heated to 55 °C and remains at a constant temperature for 2 h to reach a suitable temperature for the cross-linking of epoxy resins. In the second phase the temperature was increased from 55 °C to 121 °C, and then remains at a constant temperature for 2 h to enhance the mechanical properties of the metal prototypes. In the third phase the temperature was increased from 121 °C to 204 °C and remains constant for 2 h to cure the metal prototypes fully. The surface roughnesses of the metal prototypes were measured using a WLI (vertical resolution 0.1 nm, horizontal resolution 0.5 µm, Chroma 7502). The sampling area was chosen to be 50 µm × 50 µm. The arithmetic average roughness value (R_a) was used to quantify the surface finish. The R_a values represent the average displacement of the peaks and valleys measured with respect to a mean line.

3 RESULTS AND DISCUSSION

Figure 4 shows the master-pattern models of the male and female parts of the laptop hinge. The fabricated master pattern models required further processing, because of their relatively poor surface roughness, which results from the layered structure inherent in the building method.[19] In this work, hand finishing was used to improve the stair-step surface texture inherently in the fabricated master-pattern models.[20] **Figure 5** shows the silicone rubber molds for the male and female parts of the laptop hinge. The cured silicone rubber block was cut along the parting line and the master pattern was removed. It is clear that the surfaces of the silicone rubber molds have the desired surface finish. In addition, the silicone rubber mold enables the master-pattern models to release without breakage or damage.[21,22]

To evaluate the validity of the fabricated silicone rubber mold, some wax patterns were replicated from the elastomeric mold. **Figure 6** shows that the wax patterns of the laptop hinge were replicated from the silicone rubber mold because of the low interfacial free energy and the chemically inert surface.[23] It is clear that the laptop hinges made of wax were successfully transferred from the silicone rubber mold by vacuum casting. The detailed appearance of the laptop hinges was faithfully replicated. This means that the silicone rubber mold fabricated can be used to replicate metal prototypes of the designed laptop hinges. The use of epoxy resin is often the fastest way to complete short runs of functional prototypes manufactured by vacuum casting. **Figure 7** shows the green part of a male laptop hinge fabricated

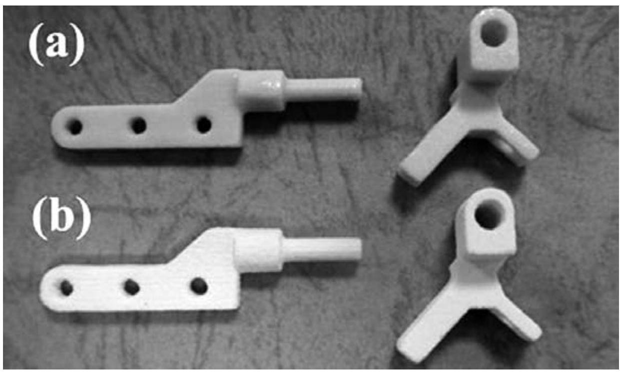

Figure 4: Master-pattern models of: a) male and b) female parts of a laptop hinge
Slika 4: Modeli: a) moškega in b) ženskega dela tečaja za ohišje prenosnega računalnika

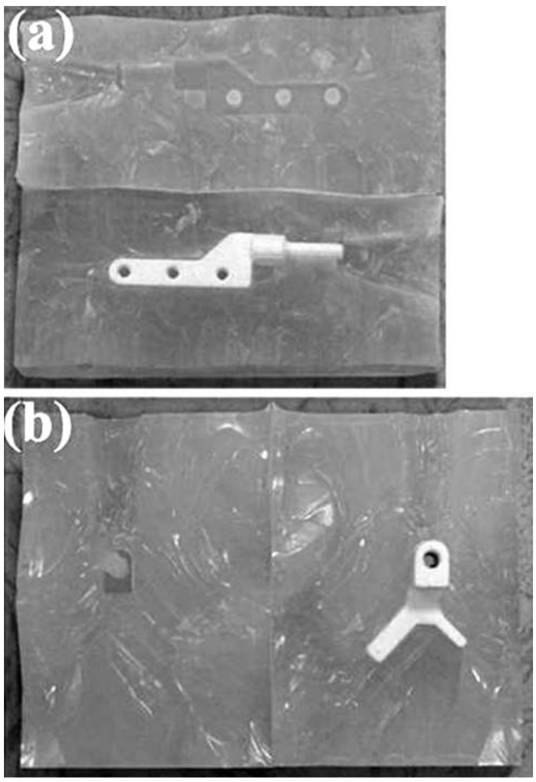

Figure 5: Silicone rubber molds for: a) male part and b) female part of a laptop hinge
Slika 5: Forma iz silikonske gume za: a) moški del in b) ženski del tečaja za ohišje prenosnega računalnika

using a silicone rubber mold. It can be observed that the metal prototype of the male laptop hinge was fabricated faithfully. The life of a silicone rubber mold depends to a large extent on the surface finish of the fabricated laptop hinges. In general, a silicone rubber mold will reproduce up to 20–30 parts with a gradual deterioration of the surface quality under normal operating conditions. After the post-curing process, metal prototypes of the laptop hinge were shown in **Figure 8**. Thus, a small-batch production of the metal prototype can be obtained economically via a silicone rubber mold using vacuum casting without applying any plastic injection molding. According to the specification provided by the epoxy-resin composite supplier, the fabricated metal prototypes have excellent physical and mechanical properties (tensile strength ASTM D 638, compressive strength ASTM D 695, and cured hardness ASTM D 2240). A tensile strength of 35439 kPa (5140 psi) can be achieved, which can be used for a functional test. **Figure 9** shows the WLI image of a metal prototype. The average roughness of the metal prototype is approximately 114 nm. This result shows that the fabricated metal prototype has the desired surface finish. As described above, this method is a viable alternative for the fabrication of metal prototypes.[24] **Table 1** shows the time needed to manufacture metal prototypes of a laptop hinge. **Table 2** shows the cost needed to manufacture metal prototypes of a laptop hinge. The estimated cost and time for manufacturing the metal prototype of a laptop hinge was NT$ 683 and 19.5 h, which represents a cost reduction of 75 % and a time saving of 82 % compared to the traditional manufacturing method (NT$ 2730 and 108 h)[25] using a metal injection molding process.[26–28] This method provides a

Figure 6: Wax patterns of the laptop hinge were replicated from the silicone rubber mold
Slika 6: Voščeni modeli tečaja za ohišje prenosnega računalnika, izdelani z uporabo forme iz silikonske gume

Figure 7: Green part of a male laptop hinge fabricated using a silicone rubber mold
Slika 7: Surovec moškega dela tečaja za ohišje prenosnega računalnika, izdelan v formi iz silikonske gume

Table 1: The time needed to manufacture the metal prototype of a laptop hinge
Tabela 1: Čas izdelave kovinskega prototipa tečaja za ohišje prenosnega računalnika

Manufacturing process	Rapid prototyping of a laptop hinge	Silicone rubber mold	Metal prototype of a laptop hinge
Time (h)	0.5	8	11

Table 2: The cost needed to manufacture the metal prototype of a laptop hinge
Tabela 2: Stroški izdelave kovinskega prototipa tečaja za ohišje prenosnega računalnika

Manufacturing process	Rapid prototyping of a laptop hinge	Silicone rubber mold	Metal prototype of a laptop hinge
NT$	141	444	98

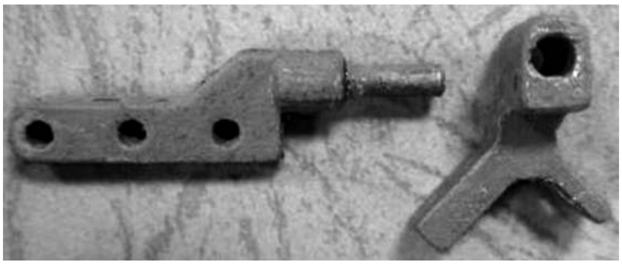

Figure 8: Metal prototypes of the laptop hinge after the post-curing process
Slika 8: Kovinski prototipi tečaja za ohišje prenosnega računalnika po postoku utrjevanja

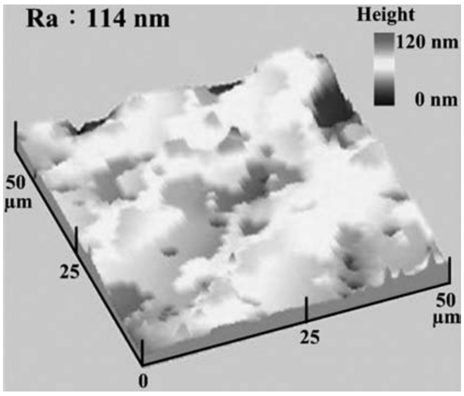

Figure 9: WLI image of a metal prototype
Slika 9: WLI-posnetek kovinskega prototipa

low-cost method to fabricate the functional metal prototype with the desired mechanical properties for the functional test. A major contribution of this work is that this method is a simple and cost-effective method for fabricating metal prototypes of a laptop hinge with high yield.

4 CONCLUSIONS

Manufacturing industry is currently under increasing pressure due to international competition. New products must be developed more quickly and cheaply, and then manufactured and introduced to the market. A procedure for fabricating metal prototypes with the desired surface finish and accuracy has been demonstrated in this work. The research results reported in this study have industrial application values because this is a simple and effective method in terms of cost and time reductions. This process has considerable economic benefits, which can be employed to fabricate metal prototypes for a functional test in the first development phase of a new product. In addition, this process has the potential to be extended to other fields of applications with the development of casting materials, such as ceramics, low-melting-point alloys, or some functional polymers.

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