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FIRST APPROACH TO GENERATE COMB LINKED PARTS BY LASER MELTING

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ABSTRACT

In micro range, the balance between gravitational forces and forces related to the surface of a body are oppositional compared to macro range. Downsizing the geometry of a body leads to faster decrease of forces related togravitation compared to the decrease of forces related to the surface.At a certain stage, the effect of surface tension exceeds gravitational force. A benefit of this behavior is applied by the laser melting process where the top surface area of a rod is molten by laser beam energy. The resulting sphere sticks to the rod and can be formed after cooling in a secondary process step. In this article the robustness of the laser melting process is investigated and a method is shown creating a comb linked part which enables better handling of the micro parts.
Key words: *Laser based free form heading, laser melting, size effect, micro preform, microforming*

1. INTRODUCTION

Compared to some decades ago, both, capabilities and main characteristics of products have gone through a huge change. Nowadays, newly invented products have to have an increased functionality by the same size or at least the same amount of functions by a decrease in outer geometries. These boundary conditions, which base on the expectations of customers, are flanked by a steady pressure on the market because of prices. The result is that products are subject to function compaction. This can be seen in many fields of technology, such as automotive electronics and telecommunication.
As soon as an existence for a great market is most probable, the individual cost per product unit decreases with increasing batch size. Thus, especially for parts which belong to micro range but are placed in macro products, mass production is aspired. An economic production always suffers under inefficiencies, such as time inefficiencies but also inefficiencies in utilization of material resources. Fabrication of metallic components in high quantities under boundary conditions as

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above can be carried out by cold forming. Due to the fact that function compaction inevitably leads to miniaturization of work pieces, processes which are established in macro range have to be transferred into micro range. Parts belong to micro range, if the length of maximum 1mm is not exceeded in more than one dimension [1]. Unfortunately, knowledge gained in macro range is not, or only with restriction, applicable in micro range [2].
This effect is obvious by looking at the conventional multi stage upsetting process, which is part of many mass production chains. Material needed for each step is provided and the initial length l_0 of the work piece is reduced progressively. Depending on the basic material and the sample diameter d_0, a certain length l_0, called upset length of the workpiece can be compressed in one step. The quotient of upset length l_0 and sample diameter d_0 is called upset ratio s. The upsetting process is limited in two dimensions: the upset ratio s is the limit against buckling and the maximum natural strain φ as a limit of formability of basic material [3]. In macro range, a maximum upset ratio s=2.3 can be achieved while in micro range this value is reduced to s=1.6 for the same work piece material [4] so that the conventional upsetting process becomes more and more inefficient with increasing miniaturization as stated by Vollertsen [5]. Work hardening materials represent an exposed roll in this context, as the conventional upsetting process has to be interrupted several times for heat treatment operations further decreasing process efficiency by means of time and overall costs due to handling and needed process energy. One approach to avoid these problems is the laser based free form heading process which has been demonstrated in [6] taking advantage of the above mentioned scaling effect. Preforms generated in this process can finally be upset in open dies [7], closed dies, or calibrated by rotary swaging [8].
Previous investigations show, that the microstructure of preforms generated by laser melting is dendritic [9]. Nevertheless, a good formability is achieved even though the dendritic microstructure does not generally allow high strain ratios. Upsetting of preforms in closed dies necessitates an exact defined volume of the work piece so that defects, such as incomplete die filling [10], after massive forming operation can be eliminated. In case of conventional upsetting of rotationally symmetrical work pieces, a variation of initial diameter causes a deviation in final work piece volume if the upset length is kept constant. In this paper, this effect is investigated for the above mentioned laser free form heading process. The aspect of handling difficulties of micro parts is addressed in this paper by presenting a method to generate comb linked parts.

2. METHOD

2.1 Experimental set-up to generate preforms

The laser based free form heading process takes advantage of the shape-balance effect [11], which means that in micro range surface tension exceeds gravitational force. The laser beam energy is focused on the bottom surface of a rod and causes the end of the rod to melt. Within certain limits, the molten part of the rod sticks to the rod and automatically adopts a spherical shape due to surface tension. As soon as the weight of the spherical, molten part exceeds surface tension at the intersectional area between molten and solid rod material, the molten part releases. The process of generating material preforms by laser melting enables upset ratios $s \geq 500$ for rod diameter d_0=0.2mm. The maximum achievable upset ratio increases with decreasing rod diameter which is a greatadvantage compared to conventional upsetting process.
The experiments are carried out using rods of austenitic chromium nickel steel 1.4301 (X5CrNi18-10) as wrought material with initial diameters d_0 ranged from 0.3mm to 0.5mm. For investigations on the robustness of the accumulation process, the longitudinal axis of the rod is placed coaxially

to the laser beam. The focus layer of the laser beam is adjusted on the bottom surface of the rod so that irradiation takes place in a right angle. As soon as the molten material forms a spherical geometry, the diameter of the sphere necessarily exceeds the initial rod diameter which causes the lower end of the sphere to move upwards out of focus layer. This phenomenon is called defocussing effect [6] and decreases the total efficiency of laser based free form heading process unless feeding of rod is applied [12]. Due to the fact that the used material for specimen is susceptible for oxidation at high temperatures, Argon is used as shielding gas. The specimens are brought to the aspired length by a bite cutting process and the top and bottom surface are finally fine grinded. Fig. 1 shows a schematical view of both, the conventional upsetting process (fig. 1a) and the laser based free form upsetting process (fig. 1b). F_P demonstrates the required punch force while the associated arrow shows its direction.

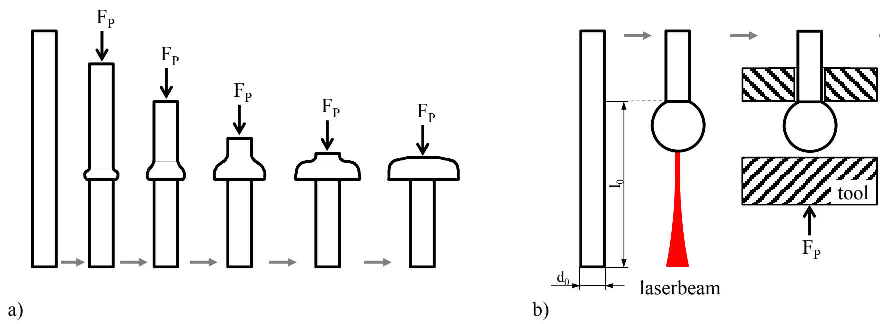


Fig.1 *- a) Conventional and upsetting. b) Laser based free form heading*

It is clearly visible, that the process chain of laser based free form heading is shorter. Table 1 represents the corresponding laser parameters.

Table 1 - *Specifications of the used laser system*

Laser type	Fibre laser, cw
Wavelength	1085nm
Focal distance	100mm
Beam radius	0.02mm
Divergence angle	40mrad
Max. power	300W

2.2 Energy balance

The required energy E_S to melt a certain amount of material being the basis for the volume $V_S$of the sphere generated by a laser based free form heading process can be estimated by an adiabatic model [6]:

$$E_S = V_S\rho\left[c_p(T_M - T_0) + H_M\right] + b = P_L t_L \alpha \tag{1}$$

with ρ as density of basic material, c_p as specific heat capacity, T_M and T_0 as melting and initial temperature, H_M as latent heat, b representing offset term such as spatter formation, P_L as laser power, t_L as irradiation timeand α as material specific absorption coefficient.
This model fits well with experimental results, but at least for larger material accumulations the model overestimates the accumulated volume. This behavior is among others based on the defocusing effect [6] as well as on heat conduction within the rod and heat radiation against ambient atmosphere. The longer the accumulation process takes place, the greater is the part of energy dissipated through the rod by heat conduction. In order to achieve comparable results despite these effects while applying the above mentioned model for different rod diameters, the effect of irradiation time has to be taken into account. The law of similarities demands the following relations [13] based on (1):

$$E = {m_l}^3 m_T \quad (2)$$

withm_l as length scale and m_T as temperature scale. Comparable results exist, if the relative quantity of heat dissipation is the same for all scaled experiments. This means:

$$m_T = 1 \quad (3)$$

Similarity in heat radiation can be described as follows:

$$m_t = m_l/{m_T}^3 \quad (4)$$

Herein, m_t is the time scale. Respecting similarity in heat conduction gives the scaling rule for irradiation time:

$$m_t = {m_l}^2 \quad (5)$$

The scaling rule for laser power P_L is the result of inserting (5) and (4) in (2)

$$m_P = {m_l}^{\frac{2}{3}} \quad (6)$$

2.3 Robustness of the laser melting process

The influence of both, a small variation of rod diameter d_f of about ±1% as well as variations of about ±25% of rod diameter d_f on the resulting volume of the spherical material accumulations are investigated.
Small variations in diameter of the rods are realized by rotary swaging. Rods with initial diameter d_i of 1.0mm - 2.0mm are reduced to d_f ~0.5mm. The initial and the final rod diameter are listed in table 2. It can be seen that the absolute value of natural strain $|\varphi_r|$ varies between 0 and 2.77 according to the initial rod diameter d_i.

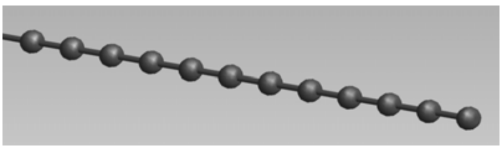
Table 2 *- Initial and final rod diameter*

d_i [mm]	$\varphi_r = ln(d_f^2/d_1^2)$	d_f [mm]
2.0	-2.77	0.501
1.5	-2.22	0.494
1.0	-1.37	0.503
0.495	0	0.495

For all final rod diameters d_f three different pulse energies E_L with constant power P_L=64W but varying irradiation times t_{P1}=500ms, t_{P2}=1500ms and t_{P3}=4000ms have been applied thus resulting in different final sphere diameters d_S of the material accumulation. Due to the fact that the differences in final rod diameters are very small, neither the laser beam power $P_L$nor the irradiation time t_P have been scaled according to the law of similarities.
In addition to small variations of rod diameters, also huge variations have been applied. Starting from rods with d_0=0.3mm and ending at d_0=0.5mm with increments Δd_0=0.1mm. Rods were irradiated with different pulse energy E_L but this time, laser power P_L and irradiation time t_P were scaled according to the law of similarities, see paragraph 2.2 so that a relationship between pulse energy E_L and volume V_S of the sphere can be determined.

3. GENERATION OF COMB LINKED PARTS

The laser melting process is a process which is enabled by size effects. Nevertheless, some size effect can be detrimental when it comes to handling of laser generated preforms. One method to improve handling of micro parts is to link the fabricated parts together so that a macro part is formed. This macro part can then be easily handled. Applying this approach to the process of generating preforms by laser melting, two different types of connecting preforms can be thought as shown in fig. 2. The preforms can either be fixed “in line” to a so-called “line linked part” (fig. 2a) or they can be fixed to a conveyor rod called “comb linked part” (fig. 2b).


a)

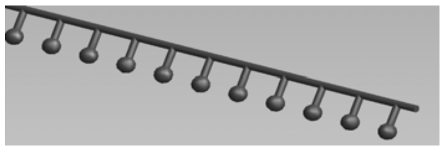

b)

Fig.2 - a) Line linked part. b) Comb linked part

A comb linked part is fabricated by the use of a “conveyor rod” and a “work piece rod”. The conveyor rod has a diameter of 1.0mm and is of the same material as the work piece rod thus allowing a welding process without flux. It is the scope to be able to produce an endless comb linked part by open-loop control.
At a first stage, the main functions of the process are determined. These are:

1. connecting work piece rod to conveyor rod,
2. cutting of work piece rod,
3. generation of preform,
4. conveying of conveyorrod,
5. conveying of work piece rod.

At a second stage the main functions are sequenced in a process chain so that an ongoing process cycle is achieved. Fig. 3 illustrates the sequence of main functions (stages 1 to 5), the orientation of work piece rod to conveyor rod and the resulting comb linked part.

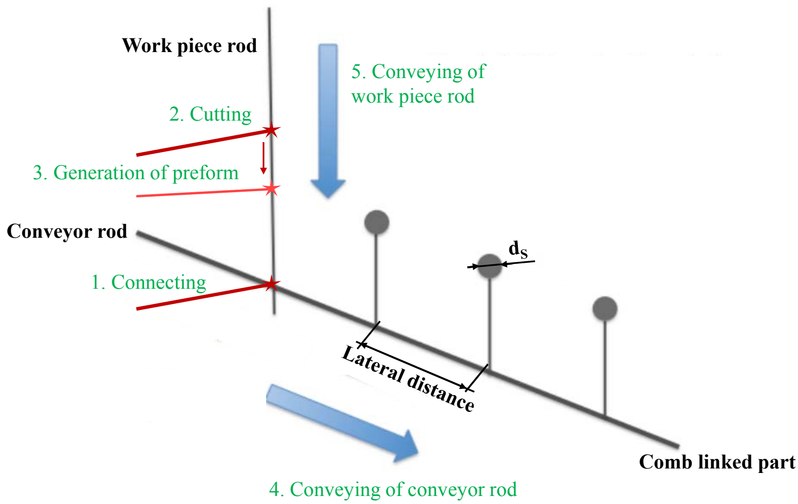


***Fig.3** - Method and main functions to generate comb linked part*

An experimental setup to generate comb linked parts by the method shown in fig.3 is realized. It is of great importance that the radial guidance of both, conveyor rod and work piece rod is very exact. In order to allow a reproducible welding operation of work piece rod to conveyor rod, a well-defined contact pressure is necessary. If both rods do not contact, the welding process cannot be carried out. If the contact pressure is too high, the heat of the welding process leads to a specified elastic and plastic deformation of the work piece rod which is detrimental for carrying out the next process step, which is “cutting of work piece rod”. In this process step, the residual stresses release and the disengaged end of the rod moves radially to a not defined location. At this stage, an optical feedback control would be necessary to continue the process. To keep the engineering part of the experimental setup as basic as possible, it is a fundamental requirement to enable the process only by using forward open-loop control. The welding process is achieved by applying two short laser pulses at the intersection between conveyor rod and work piece rod. Due to the fact that the work piece rod with a diameter of 0.2mm has a minimal greaterbacklash in the guidance, three laser pulses are applied to ensure sufficient strength of the joint. The cutting of the work piece rod is aligned with the process of generating the material accumulation. The work piece rod disengages by applying laser beam energy because radial stresses by elastic deformation are brought into the conveyor rod pulling the work piece rod incrementally backwards after welding operation. For cutting and generation of preform the laser beam is tracked parallel to the work piece rod so that the laser beam interacts perpendicular with the lateral area of the rod. The generation of the material accumulation by laser meltingis already well understood and therefore not subject of the experimental investigations. The length of the tracked line defines the amount of the molten volume of the rod and therefore the size of the material accumulation. As soon as the material accumulation is generated, the conveyor rod is pulled forward and subsequently the work piece rod is also moved ahead thus bringing the setup in initial position again so that the next fragment of the comb linked part can be produced. The described process works fully automated with open-loop control. The laser parameters for welding, cutting and accumulating in dependence of varied work piece rod diameter 0.2mm, 0.3mm and 0.5mm in correlation with a conveyor rod of 1.0mm are shown in table 3.

Table 3 - *Laser processing parameters for fabrication of comb linked parts*

		work piece rod diameter [mm]		
		0.5	0.3	0.2
welding	number of pulses	2	2	3
	laser power [W]	80	80	50
	pulse time [ms]	100	100	100
cutting and accumulating	laser power [W]	50	50	50
	tracking speed [mm/s]	4.6	6.0	6.0

The fabricated comb linked parts are contemplated through an optical laser scanning microscopy of Keyence model VHX-1000. By using an objective with a fiftyfold magnification, the uncertainty of measuring a standardized height differenceof 2µm is 14nm.

4. RESULTS

4.1. Influence of small variations of rod diameter

The volume V_S of the resulting spheres is shown in fig. 4 for small variations in rod diameter exemplarily for a laser beam energy E_L=256J. Additionally, the theoretical volume V_U of a specimen with constant upsetting length l_0 generated by a fictitious conventional upsetting process is also displayed. It can be seen that the volume V_U of thespecimen by conventional upsetting increases quadratically with increasing rod diameter. This behavior is expected because V_U can be determined by:

$$V_U = \frac{\pi}{4} {d_f}^2 l_0 \sim {d_f}^2 \quad (7)$$

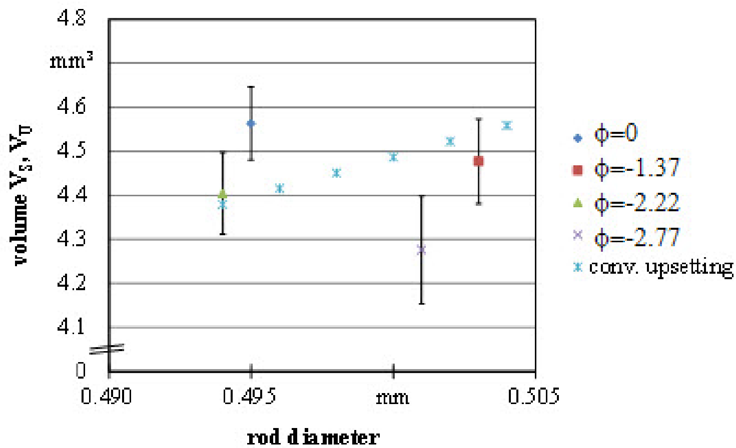


Fig.4 *- Volume V_S and V_U in dependence of rod diameter d_f for E_L=256J*

The expected behavior that volume V_S is independent of rod diameter is not proved by these results. Due to the fact, that also for smaller pulse energiesE_L the same characteristic collocation of function values is visible, the volume $V_S$of sphere is plotted in dependence of natural strain φ_r caused by rotary swaging. This relation is plotted in fig. 5 for different sphere diameters d_S.
It is obvious that there is a correlation between the volume of the spheres and natural strain of rods induced by the initial rotary swaging process. The larger the absolute value of natural strain $|\varphi_r|$, the smaller is the resulting material accumulation by constant pulse energy E_L. This behavior might be based on the fact that strain induced martensite comes into being by rotary swaging process. The martensitic microstructure, whose grain size is smaller than the initial austenitic grain size, might have a lower absorption coefficient α with the consequence, that less pulse energy E_L can be used to melt the rod and form the material accumulation.

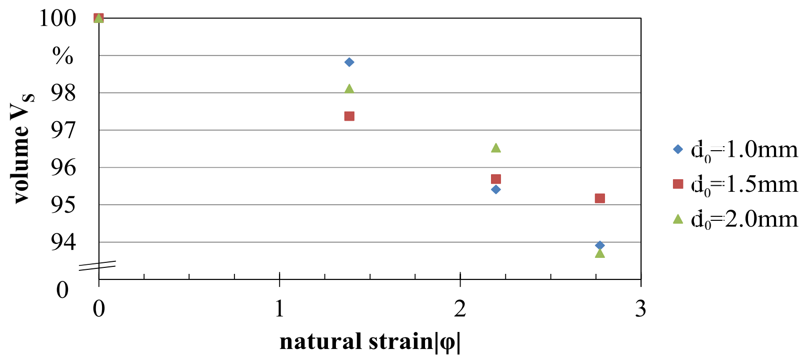


Fig.5 *- Volume V_S in dependence of natural strain $|\varphi|$ of rod induced by rotary swagi*

4.2. Influence of strong variations of rod diameter

A stronger variation of rod diameter is carried out by using rods with diameter $d_{rod}$of 0.3mm, 0.4mm and 0.5mm. The pulse energy E_L is ranged between 1.28J - 160J. Both, laser power P_L and irradiation time have been scaled for each rod diameter as shown in paragraph 2.2. The resulting sphere volumes V_S in dependence of pulse energy E_L are shown in fig. 6.
An almost linear correlation between pulse energy E_L and volume V_S of the sphere independent of rod diameter d_{rod} is detected as predicted by formula (1) for pulse energies $E_L \leq 160$J. Particularly interesting are those energy regimes where volumes V_S of different rod diameters d_{rod} overlap. For example, this is the case for 30J<E_L<40J and 50<E_L<100J. In other words: the resulting volume V_S is within certain limitations independent of rod diameter d_{rod} by given pulse energy E_L. Transferring this knowledge into possibly practical application of laser free form heading, another unique advantage compared to conventional multi stage upsetting process is obvious: the laser free form heading process is within certain limitations self-aligning. This means, that variations of rod diameters are balanced by the process and thus not negatively effecting the outcome. In contrast, the results of conventional upsetting processes are directly dependent on the accuracy of the initial rod diameter. As soon as this value is not exact, the resulting part does also not have the right volume by given upsetting lengthl_0 causing defects such as incomplete form filling.

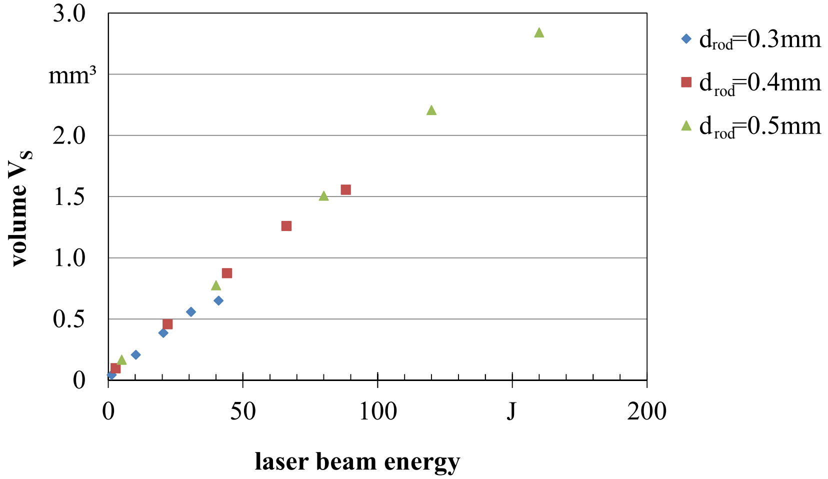


Fig.6 *- Volume V_S in dependence of pulse energy E_L for rod diameters d_{rod}=0.3mm-0.5mm*

4.3. Generation of comb linked parts

The lateral distance between the work piece rods is measured for work piece rods with diameters of 0.2mm, 0.3mm and 0.5mm. The specified value for the lateral distance is 5.00mm. As shown in fig. 7, a high reproducibility of the distance is obtained as the standard deviation is approximately 2% from the specified value. The standard deviation is independent of work piece rod diameter which leads to the conclusion that the realized precision of guidance for each rod diameter is sufficient. The measured value of the lateral distanceof the work piece rods with diameter of 0.5mm is determined to 4.97mm which is very close to the specified value of 5.00mm. The lateral distance seems to decrease with decreasing rod diameter as the measured distance for rod diameters 0.3mm is determined to 4.65mm. The reason for this shift is to be specified. Both, absolute value of lateral distance and standard deviation are calculated by a set of 50 measurements for rod diameter of 0.5mm, 40 sets for 0.3mm and 10 measurements for a work piece rod diameter of 0.2mm.
One result of the experiments is shown in fig. 8. The diameter of conveyor rod is 1.0mm and work piece rod is 0.5mm, both chromium austenitic steel 1.4301. The comb linked part is fabricated with laser pulse values of table 3.

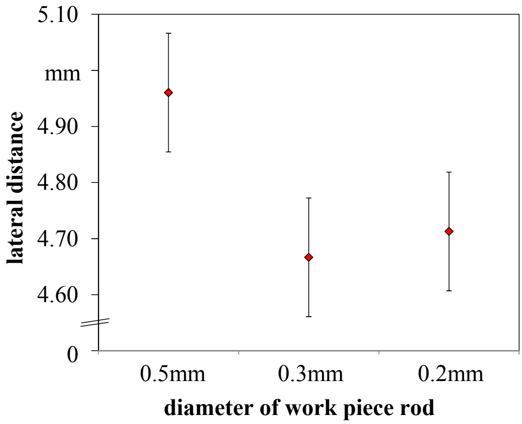


Fig.7 *- Measured absolute values and standard deviation of lateral distance between work piece rods*

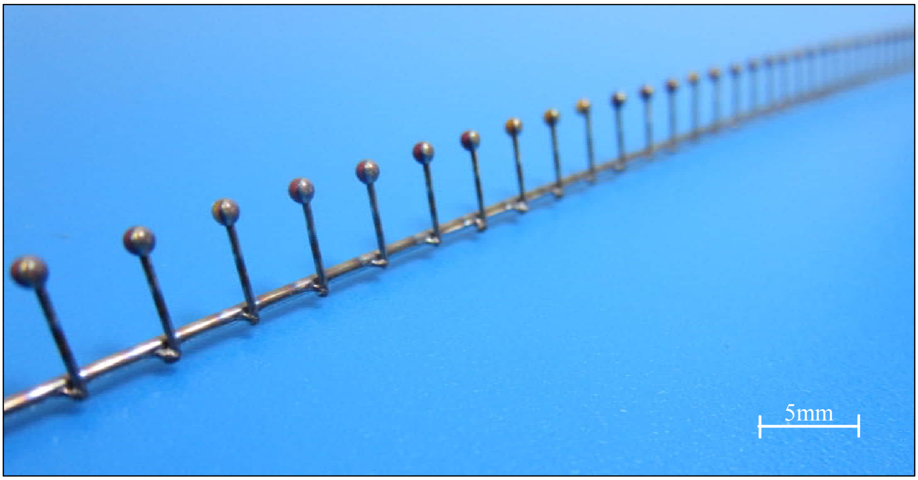


Fig.8 *- Comb linked part of 1.4301. Conveyor rod 1.0mm, work piece rod 0.5mm*

5. SUMMARY

The self-aligning capability of the laser based free form heading process is investigated. Within the experiments which have been carried out, small variations of rod diameter of ±1% as well as huge variations of rod diameter of ±25% have been evaluated. A relation between natural strain φ_r of rods and the absorption coefficient α of laser beam energy E_L is detected which is assumed to be based on the lower absorption coefficient α of martensite compared to austenite. The investigations on self-aligning capability of laser free form heading process come to the conclusion, that a variation of rod diameter within certain limits does not affect the resulting sphere volume V_S. This

makes the presented process more than a good alternative in micro range for conventional upsetting. The quality of goods manufactured by a conventional upsetting process is directly dependent of the geometric accuracy of initial wrought material. For example a slight variation in initial diameter of axially symmetric parts is amplified by the power of two regarding the final volume of the part.
Furthermore, it is shown that it is possible to weld the material accumulations with its shafts on a conveyor rod called “comb linked part”. This method enables much easier handling of the micro parts. Experiments prove that fabrication of comb linked parts is possible for work piece rods with diameters of 0.5mm, 0.3mm down to 0.2mm. In combination with the self-aligning capability, laser based free form heading recommends itself as a trend-setting process for mass production in micro range.

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PRELIMINARNA ISTRAŽIVANJA U IZRADI ČEŠLJASTIH MIKRO STRUKTURA POMOĆU TEHNOLOGIJE LASERSKOG TOPLJENJA

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REZIME

Mikro obrade su one pri kojima su dve ili tri dimenzije radnog komada manje od 1mm. Nažalost, znanje usvojeno u makro oblasti je samo delimično primenljivo u mikro oblasti. U oblasti mikro obrade, balans između gravitacionih sila i sila koje dejstvuju na površinu radnog komada je obrnut u odnosu na makro obradu. Smanjivanje geometrije radnog komada dovodi do bržeg smanjivanja gravitacionih sila u odnosu na smanjenje površinskih sila. U određenom trenutku, efekat površinskog naprezanja prevazilazi gravitacionu silu. Pogodnosti ove pojave su iskorišćene u ovom istraživanju prilikom topljenja laserom vrha svakog grebena češljaste strukture. Dobijena sfera ostaje spojena sa grebenom i može biti deformisana posle hlađenja u sledećoj operaciji. U ovom radu vršeno je ispitivanje robustnosti ovog procesa i prikazane je metod dobijanja češljaste mikro strukture. Ispitivani materijal je austenitni hrom-nikl čelik oznake X5CrNi18-10.
Ključne reči: *Formiranje slobodnih površina laserom, topljenje laserom, uticaj veličine, mikro deformisanje*