UDC 621.787:539.4

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Peen-Forming - The Possibility of Technology Transfer from Aircraft Industry to the Production of High-Speed Ships

Review paper

Shot-peening is a widespread surface treatment method used to improve fatigue and stress corrosion resistance of many metals. From that technology the peen-forming method has emerged and has replaced traditional forming methods on many aircraft types, allowing wing designs to maximise strength to weight ratios. The new generation of high-speed ships and boats use similar lightweight building materials as aircraft industry, such as different aluminium alloys, which indicates that shot-peening and peen-forming methods could be introduced in shipbuilding industry. This paper describes peen-forming technology which is rarely present in shipbuilding, and shows why the peen-forming should be considered as an important ship production method that may replace more costly and complex forming technologies. The paper presents application techniques, process variables, limitations and applicable designs regarding peen-forming and concludes that peen forming will have a significant role in the future of shipbuilding of fast and high-speed vessels.

Keywords: *high-speed ship, peen-forming, shipbuilding industry, shot-peening,*

Oblikovanje kugličarenjem - mogućnost primjene tehnologije iz zrakoplovne industrije na proizvodnju vrlo brzih brodova

Pregledni rad

Kugličarenje (zrnčenje ili sačmarenje) široko je rasprostranjena metoda obrade površine uporabljivana za poboljšanje značajki umora materijala i otpornosti na koroziju zbog naprezanja mnogih kovina. Iz kugličarenja nastala je i posebna metoda nazvana *peen-forming*, koja je zamijenila tradicionalne metode oblikovanja tanjih limova kod mnogih tipova zrakoplova i pridonijela razvoju oblika krila maksimalnog odnosa čvrstoće spram težine. Brzi brodovi nove generacije upotrebljavaju, slično kao u zrakoplovnoj industriji, lagane konstrukcijske materijale kao što su različite aluminijske slitine, što ukazuje da se postupci kugličarenja i oblikovanja kugličarenjem (*peen-forming*) trebaju ozbiljno razmotriti i za primjenu u brodograđevnoj industriji, posebice u proizvodnji brzih i vrlo brzih brodova. Ovaj rad opisuje oblikovanje kugličarenjem, tj. *peen-forming* tehnologiju, koja dosad nije bila prisutna u brodograđevnoj industrijskoj praksi i pokazuje razloge zbog čega oblikovanje kugličarenjem (*peen-forming*) treba razmatrati radi njegove primjene u brodogradnji, kao važne proizvodne metode, koja uspješno može zamijeniti znatno skuplje i složenije tehnologije oblikovanja. Rad prikazuje različite načine primjene ovoga procesa, procesne parametre, ograničenja i moguća projektna rješenja pogodna za njegovu primjenu, te zaključuje da će ovaj tehnološki proces zasigurno imati važnu ulogu u budućoj primjeni u izgradnji brzih i vrlo brzih brodova.

Ključne riječi: *brodograđevna industrija, kugličarenje, oblikovanje kugličarenjem, vrlo brzi brodovi*

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Received (Primljeno): 2007-10-09
Accepted (Prihvaćeno): 2007-12-19
Open for discussion (Otvoreno za raspravu): 2009-03-31

1 Introduction

In the modern shipbuilding industry and especially in the future building of high-speed ships and other highly sophisticated vessels and vehicles, the use of unconventional shipbuilding materials and technologies will have a significant importance in materialisation of competitive products [1, 2, 3, 4]. In addition, because of complex ship designs, new structural solutions and building elements could emerge in ship production. Integral panels will certainly be among such elements [5, 6]. They can be used for the construction of shells and decks that consist of plates, longitudinals and frames made by milling in one piece, and for building thin structural components made of various aluminium alloys that have favourable strength-weight ratios, especially Al-Li alloys. Many of these structural parts are of various sizes and come curved in various shapes and forms. The production process of integral panels, as well as of other structural elements, has to be, as always, simple, economic and easily repeatable.

One solution for shaping those parts can be derived from the shot-peening technological process. It is a low-cost process used for hardening surface and improving the fatigue resistance of many different materials, including high-strength steels, titanium alloys, aluminium alloys and other engineering alloys [7, 8, 9, 10]. Shot-peening is conducted in special cabinets (large cabins or small portable machines containing small shots) through a shot-peening machine consisting of a nozzle (jet) or a wheel. The shots are spherical, usually 0.18 mm to 2.00 mm in diameter, and can be made of different materials like steel, glass, ceramic, Al-oxide etc. The shot-peening machines can be pneumatic, centrifugal and water slurry machines depending on the manner in which the shots are propelled and targeted towards the material surface.

Although the process of shot-peening has evolved and has become very technical, it still employs the old principle of pre-stressing to increase the life of materials. The shots, accelerated through a shot-peening machine, hit the material and partially penetrate its surface. Each shot creates a small dent in the surface. Kinetic energy of the shots is large enough to cause the plastic deformation under shots indentation and create the plastic zone below each dent. That zone, typically about 0.5 mm deep, is highly compressed. The tensile stresses that occur during loading can be reduced or even eliminated by creating a constant compressive surface stress in the outer layers of the structural element, which greatly improves fatigue resistance [11, 12, 13]. Moreover, during the shot-peening process, the kinetic energy of the shots causes deformation of a peened material in the direction opposite to the stream direction. Depending on the depth of the plastic deformation and the friction between shots and the treated structural element, the material stretches on the side of shots impact. This effect, if properly controlled, can be employed for shaping structural elements (Figure 1). The application of shot-peening process in shaping structural elements is known as peen-forming [14].

The aircraft industry has tried to upgrade the shot-peening process in such a way that it simultaneously improves the fatigue strength of material and forms shot-peened structural elements in a desired shape [15, 16]. The high-speed ships of the next generation [17, 18, 19] fill the gap between relatively slow sea-going vessels and aircraft. These ships offer more carrying capacities than aircraft, both for cargo and passengers, and at the same time they achieve significantly greater speed than standard ships.

These non-standard types of vessels require special attention, both in design and in the production phase of development. They have to be adequately aerodynamically shaped, with light and strong structure. All standard issues regarding strength of ships are additionally expanded with structural strength problems typical for aircraft; and the fatigue strength problem is especially emphasised [20, 21, 22, 23]. Therefore, it is necessary to introduce new shipbuilding materials and appropriate production technologies to improve structural strength and to achieve appropriate structural form. This paper explains the basic principles of peen-forming method and presents possible applications in the shipbuilding industry with emphasis on forming structural elements of high-speed ships made of lightweight materials.

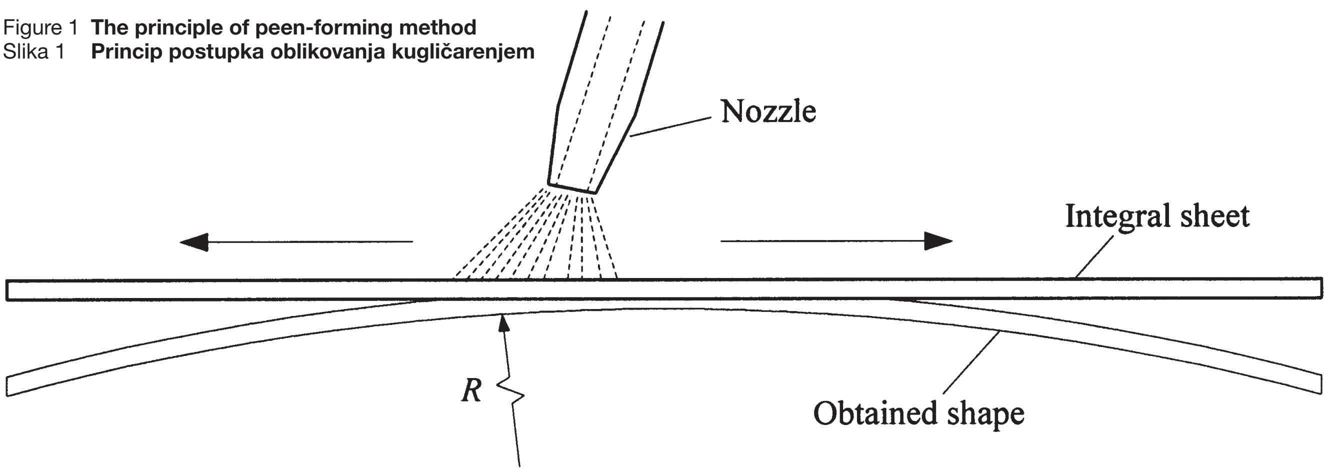
2 Short theoretical aspects of peen-forming procedure

Although the peening procedure itself is relatively low-cost and simple to perform, there are many influencing parameters that must be considered, so they can be classified in two groups: shot parameters and material parameters. The shot parameters cover size and material (hardness) of the shots, energy of the shot flow (velocity of the shot, stream angle and duration), peening intensity, saturation and coverage. Many studies on the influence of these parameters for various peened materials are available [24, 25, 26]. The second group, material parameters, covers the state of treated material that includes geometry, hardness, surface roughness and different effects of various material treatments (rolling, milling, cutting, etc.).

The knowledge about shot-peening (peen-forming) process requires an understanding of the interaction between contact mechanics and material science. No one yet has given a complete picture of the process and the practical application is primarily based on experience and 'trial and error'. In addition, part of the uncertainty has come from the difficulty in controlling and measuring a large number of intricate parameters.

Nevertheless, it is known that two mechanisms are related to forming of local plastic zones in peened materials that are responsible for the occurrence of residual stresses. The first mechanism is due to the Herzian stress field that develops when a shot piece affects the material [27]. The second mechanism is due to the compression of the surface layer under local pressure. This tends

Figure 1 **The principle of peen-forming method**
Slika 1 **Princip postupka oblikovanja kugličarenjem**



to stretch the surface layer, and therefore expand it radially, but the surrounding elastic material confines it. Stretching of the surface layer is a consequence of ‘surface hammering’ and this effect is marked with a hard shot and a soft work piece. This effect of surface stretching is the foundation for the application of peen forming. The stretching is also somewhat undesirable regarding fatigue resistance since the magnitude of the residual stress field decreases from the most stretched to the less stretched part of the material (from surface to core).

Material outstretching on the peened side, during the shot-peening process, can be explained with slip theory that involves a definition of achieved speed of material shape change in the plastic zone. Shot-peening causes different combinations of shape forms, but each of them manifests as a ‘bump’ opposite the stream angle of the shots, and in combination with the areas that are not peened, various types of curvatures may be obtained. The shot stream angle determines the curvature direction (deformation) of the material and thus it is a very significant parameter in defining the form of the treated structural element, as well as the pressure of shot stream and distance of the nozzle from the treated construction part.

The shot-peening process causes that the residual stresses in a material become distributed in a specific manner, as presented in Figure 2.

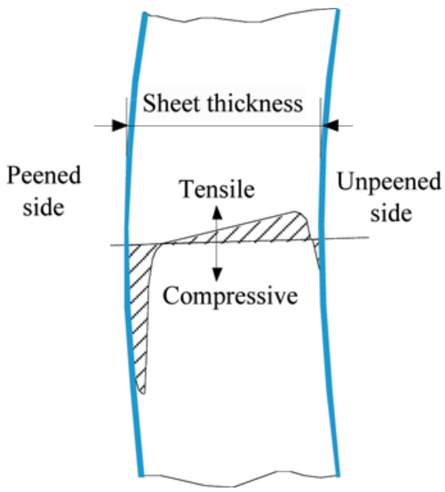


Figure 2 **Distribution of residual stresses in a peen-formed panel sheet [28]**
Slika 2 **Raspodjela preostalih naprezanja u limu oblikovanom kugličarenjem [28]**

In Figure 2, the real stress distribution at the moment of impact, and after, as well as the elastic and plastic zone due to shot impact can be seen. In that case, the maximal tensile stresses are not on the surface of the treated material, but they are at the certain distance from the surface inside the material. The maximal compressive stresses, at the peened side of the surface of the treated element, are positioned at a small distance under the peened surface.

In Figure 3, the effect of shot impact on the surface of material is shown, as well as the stress distribution. In Figure 3a the plastic and elastic zone in the material are presented at the moment of shot impact with an impact speed v_i, and equal stress distribution (compressive), and in Figure 3b after the shot impact where the shot is turned back with a return speed v_r, in some thin level under the surface of the material, the plastic zone, caused by the impact, remains in the material, which produces the different stress distribution (tensile and compressive), as it is presented in Figure 2. This impact, some kind of artificial hammering, produces the stress distribution caused by elongation on the peened side of the material and compression on the unpeened side.

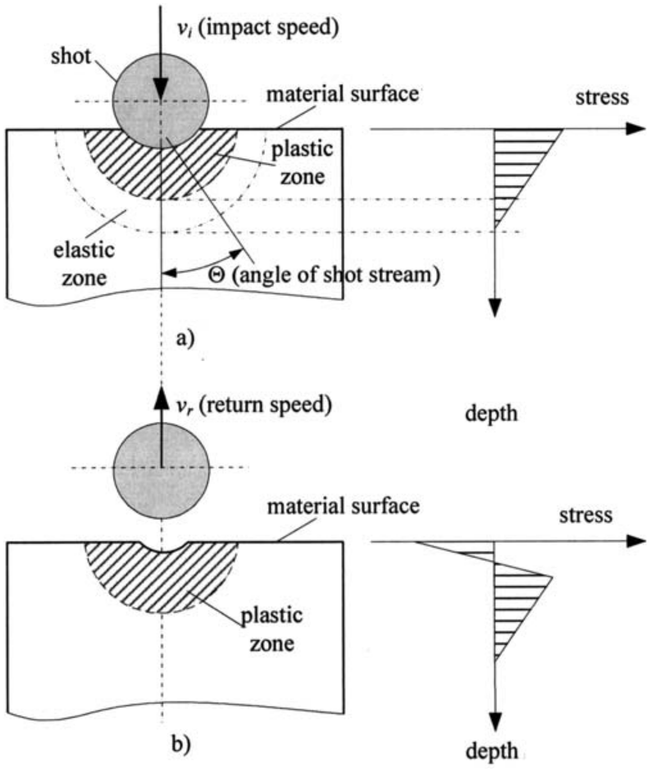
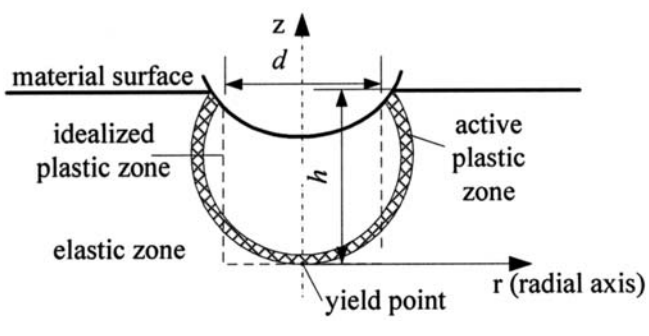


Figure 3 **The effect of shot impact on stress distribution: a) at the moment of impact; b) immediately after impact**
Slika 3 **Efekt udaranja kuglica na raspodjelu naprezanja: a) u trenutku udara; b) neposredno nakon udara**

Due to the complexity of real shot-peening effect on the material surface, some approximations are necessary to obtain values for different process parameters, as shown in Figures 4 and 5.

Figure 4 **Cylindrical approximation of shot effect in active plastic zone**
Slika 4 **Cilindrična aproksimacija utjecaja kuglica u aktivnoj zoni plastičnosti**



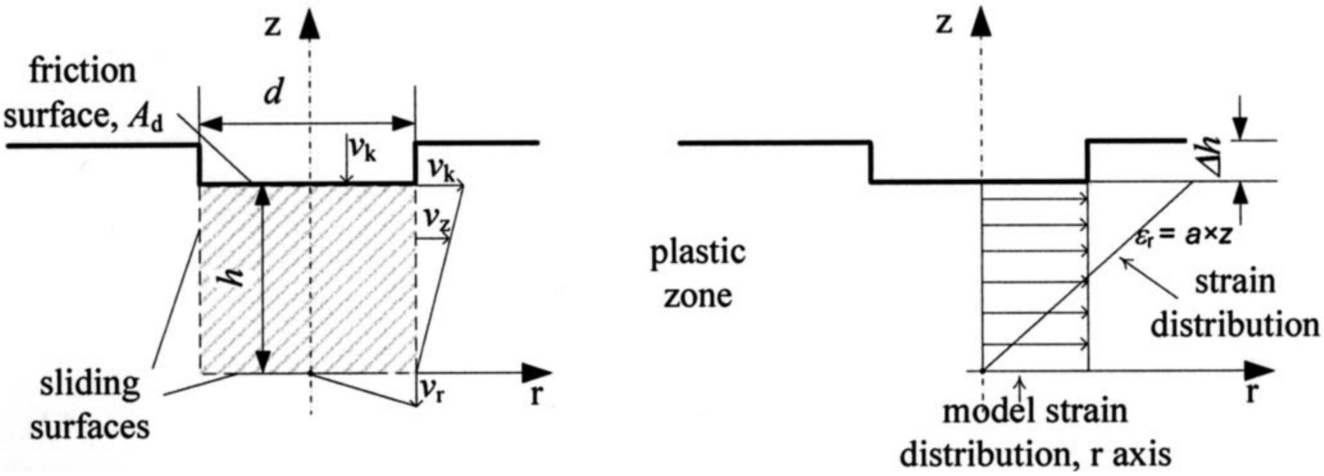


Figure 5 **Theoretical model of active plastic zone for calculation of shot-peening effect [29]**
Slika 5 **Teoretski model aktivne plastične zone za proračun utjecaja kugličarenja [29]**

For easier calculation and presentation of the stress distribution, "the real strain distribution" is of the spherical shape in the plastic zone (Figure 4) and it is transformed to a theoretical cylindrical shape (Figure 5), named "model strain distribution", where *d* is a diameter of shot penetration and *h* is the active plastic zone (according to [29] these two parameters are related with equation $d = h\sqrt{2}$) and v_k is shot speed at impact and ε_r is strain in radial direction.

For homogenous shaping, when cross-sections remain straight, the radial (v_r) and axial (v_z) components of material flow speed are calculated:

$$v_r = \frac{|v_k|}{2h} r, \quad v_z = -\frac{|v_k|}{h} z \tag{1}$$

Shot speed impact, v_k, decreases linearly to zero, while the height of active plastic zone rises from some unknown value h_0 to *h*.

The "real strain distribution" is assumed to be linear and the research showed that it is twice as large on the material surface as "model strain distribution" (Figure 5) [29]. The strain rate (speed of deformation) can be calculated as follows:

$$\dot{\varepsilon}_r = \frac{\partial v_r}{\partial r} = \frac{|v_k|}{2h}; \;\; \dot{\varepsilon}_z = \frac{\partial v_z}{\partial z} = -\frac{|v_k|}{h}; \;\; \dot{\varepsilon}_\vartheta = \frac{\partial v_r}{r} = \frac{|v_k|}{2h}, \tag{2}$$

A "model strain rate" is:

$$\dot{\varepsilon}_v = |\dot{\varepsilon}_z| = \left|\frac{v_k}{h}\right| \cong \dot{\varphi} \tag{3}$$

The referent change of shape is then calculated by:

$$\varepsilon_v = \int_t \dot{\varepsilon}_v dt = \left|\ln\frac{h}{h_0}\right| \tag{4}$$

where $\dot{\varphi}$ is a *true strain rate* given in diagram in Figure 6, depending on flow stress k_f for strain rate $\dot{\varepsilon} \cong 0.06$.

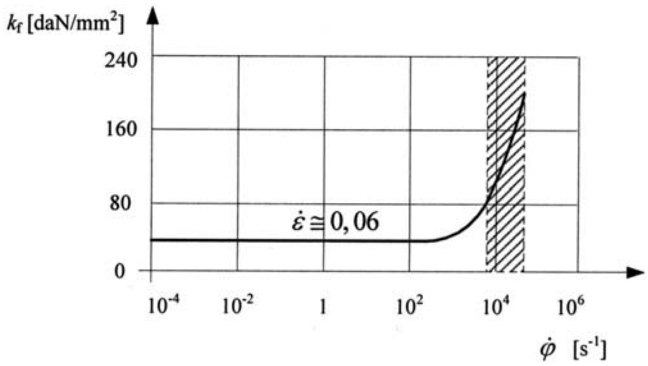


Figure 6 **Flow stress (k_f) dependence on true strain rate $\dot{\varphi}$ [29]**
Slika 6 **Ovisnost naprezanja plastičnog tečenja (k_f) o stvarnoj brzini deformacije $\dot{\varphi}$ [29]**

Hence, the peen-forming process is analysed considering a speed at which the treated material changes shape, i.e. the speed of deformation. The radial strain (change of shape) can be calculated according to V. Mises equation:

$$\varepsilon_r = \int \dot{\varepsilon}_r dt = \int_h \varepsilon_r \frac{dh}{v_k} = -\frac{1}{2}\ln\frac{h}{h_0} \tag{5}$$

where *h* is the height of the plastic deformation zone after shot-peening (active plastic zone), h_0 is certain, very small height of the plastic zone before the shot-peening.

In Figure 6 it is obvious that the flow stress at the true strain rate of $\dot{\varphi}$ =10^4 [s^{-1}] for one type of austenitic steel is k_f = 90 [daN/mm^2] and it rises to k_f = 190 [daN/mm^2] at $\dot{\varphi}$ =10^5 [s^{-1}]. Moreover, if the height (*h*) of the plasticity zone peaks at the moment of shot impact, then the lowest model strain rate $\dot{\varepsilon}_v$ occurs at the same moment. According to [29] when the shot speed at impact is $v_k = 10\,[\text{m/s}]$, the thickness of the treated element is s = 4 [mm] and the height of plasticity zone is h=1 mm then $\dot{\varepsilon}_v = 10^4$ [s^{-1}]. Also, h_0 = 0.1 [mm] at the moment of impact gives $\dot{\varepsilon}_v = 10^5\left[s^{-1}\right]$. These high values of $\dot{\varepsilon}_v$ cause that this parameter must be taken into account when calculating flow stress k_f during shot-peening process. The presented calculation model gives flow stress k_f depending on true strain rate at any point in the plasticity zone.

The radius of curvature of shot-peened structural element can be obtained according to the following calculation model:

$$\varepsilon_d = \frac{\Delta l}{l} = \frac{2\pi(R+c) - 2\pi R}{2\pi R} = \frac{c}{R} = f(\varepsilon_r) \tag{6}$$

$$R = \frac{c}{\varepsilon_d(\varepsilon_r)} \tag{7}$$

where ε_d is a strain on the surface of the treated element, which can be calculated from equilibrium conditions from a radial strain ε_r [29] and parameter c is a distance from neutral axis of the treated element to the peened surface, before peening.

A number of methods for determination of the stresses that occur due to penetration of the shots into the material surface are known. The simplest method involves a calculation of power P_t needed for deformation, which consists of three components [30]: ideal power P_i, friction power P_f, and sliding power P_s.

$$P_t = P_i + P_f + P_s \tag{8}$$

These components can be calculated as follows:

$$P_i = k_f \ v_k A_d \tag{9}$$

$$P_s = \int_A \tau v dA \tag{10}$$

$$P_f \cong 0 \tag{11}$$

where A_d is the projected impact area, $\tau = k = k_f/2$, $v = v_k/2$.

The sliding power at the beginning of the plastic zone on the edge of the treated element is:

$$P_{so} = \frac{\pi}{4} \cdot k_f \cdot v_k \cdot d \cdot h \cdot A_d \tag{12}$$

Analogously, the sliding power at the end of the plastic zone, where $v = \frac{v_r}{2} = \frac{v_k \cdot d}{8 \cdot h}$, equals to:

$$P_{sd} = \int_A \tau \cdot v \cdot dA = \frac{k_f}{2} \cdot \frac{v_k \cdot d}{8 \cdot h} \cdot \frac{\pi}{4} \cdot d^2 = \frac{1}{64} \cdot k_f \cdot \frac{d}{h} \cdot v_k \cdot A_d \tag{13}$$

Since $P_{sd} \ll P_{so}$, this component can be neglected.

At the moment when the shots penetrate the material there already exists a plastic zone with diameter d surrounded by an elastic zone, and therefore the component that involves the restraint of elastic recovery must be included in calculation. The pressure of shot impact for that component, according to [31] is:

$$p = k_f \cdot \ln \frac{D}{d} \tag{14}$$

where D is outer diameter of the elastic strain zone. If $\frac{D}{d} = 2.5$ then $p \approx 0.92 \cdot k_f$.

The total resistance to deformation can be calculated according to:

$$\frac{k_w}{k_f} = 1 + \frac{h}{d} + \ln \frac{D}{d} \tag{15}$$

Since $d = h \cdot \sqrt{2}$, the resistance to deformation is: $k_w \approx 2.6 \cdot k_f$.

This theoretical model is very complex, especially when the effect of multiple shots must be analysed. Numerical simulations of the shot-peening process using the finite element method show a good correlation with experiments when comparing the residual stresses. The shot-peening loading is characterised by using energy equivalence between the dynamic impact and the static indentation of a peening shot on the treated surface and the behaviour of the subjected material is supposed to be elastic plastic with damage [32]. More important regarding the peen-forming process is that the in-depth profile of the plastic deformations and the superficial damage values are in agreement with the experimental observations [28]. Thus, numerical simulation methods can be helpful in determination of peen-forming parameters.

Nevertheless, the experiments remain the most important way for determining shot-peening and peen-forming parameters. Peening intensity, covered surface, shot diameter, the distance of the jet to the surface of the treated element, the angle of the jet and the speed of the shots in the stream are the most important experimentally obtained parameters. Many comprehensive experiments have been done so far on shot-peening of various materials resulting in a large amount of data. Lightweight materials such as aluminium alloys were also studied but rarely in the context of a construction material for structural parts in high-speed ships [22, 33, 34].

3 Practical experience of the peen-forming application

In some structural elements of relatively smaller thicknesses (sheet metals, plating, integral structure, etc.), shot-peening can be used effectively for obtaining a certain space curvature in the same way as it was used for surface strengthening of elements. Integrally stiffened plating of the aircraft wing is an ideal example for the case of peen-forming shown in Figure 7.

In some cases of complex forms, there is no other possibility of forming integral structures except by peen-forming. Other methods require much more time, special auxiliary tools and they are very expensive, especially in the aircraft industry and in the shipbuilding industry for high-speed vessels of new generation. Peen-forming is done by special devices where special control and the repeating of the parameters of shot-peening during longitudinal movement of panels are executed. It is done sometimes in a free position of a panel and most times panels are tightened in tools, which have the form of the required contour (forming with prestressing).

During peen-forming in the flexible area, by introducing surface forces which create a curve contour, the interior of metal remains practically untouched, but capable to execute the

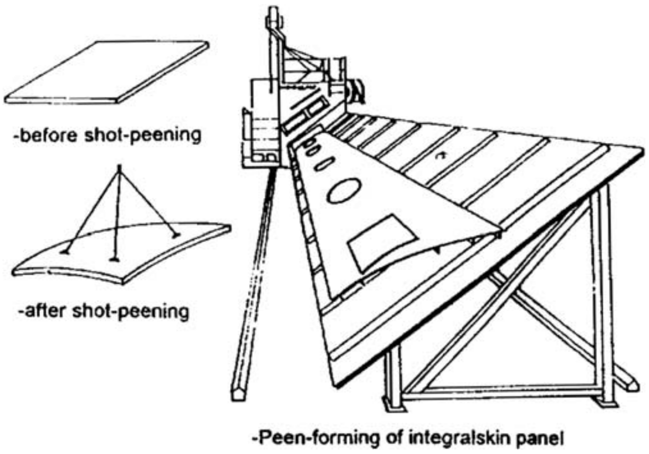
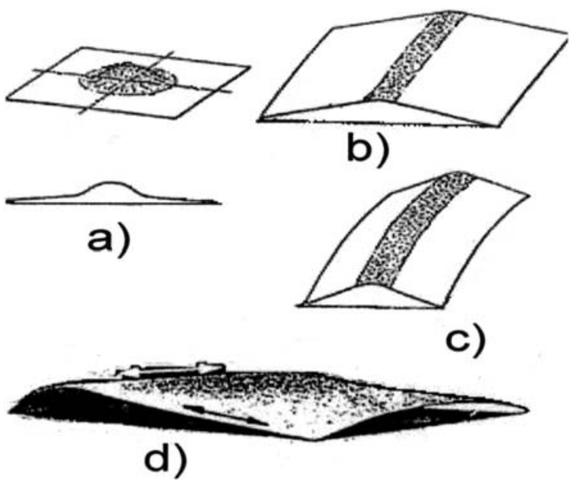


Figure 7 **Integrally stiffened aircraft wing panel in peen-forming process [28]**
Slika 7 **Integralni panel krila aviona oblikovan kugličarenjem [28]**

mechanical work. Peen-forming can be carried out even in the case when the curvature of the treated element must be realised by rolling, drawing or twisting of metal and by this process it is possible to obtain cylindrical, spherical and "sitting" forms, as in Figure 8. It does not require huge and expensive tools, while the time of the execution of the process is reduced to minimum. In such a way, the expenses of introducing and production of tools are avoided, and there is no need for extensive research as well. The process is adaptable to frequent changes in design, which are normal in the phase of introducing new constructions. It is possible, within certain limitations, to change the form of curvature by correct adjustment of air pressure, nozzles size, shots features, and the jet length.

Figure 8 **The curvatures of thin plates obtained by shot-peening: a) circular forming, b) longitudinal forming with a wide border area, c) longitudinal forming with a narrow border area, and d) biaxally bended plate**
Slika 8 **Zakrivljenosti tankih limova dobivene kugličarenjem: a) kružni oblik, b) uzdužna zakrivljenost sa širokim rubnim područjem, c) uzdužna zakrivljenost s uskim rubnim područjem, d) dvoosno zakrivljeni lim**



From the technological point of view, the curvature of structural elements is obtained:

a) if shot-peening is done on circular surface and with appropriate intensity when a protuberance occurs in the reverse direction of shot-peening,
b) if the nozzle, during shot-peening, moves along the same orbit parallel to one edge, the curvature of sheet metal appears towards edges,
c) if the intensity is stronger and the area of shot-peening bigger, the curvature occurs in both directions,
d) the direction of shot-peening defines the direction of the curvature of sheet metal according to the desired form (two-shaft bend plating), as shown in Figure 8.

By finding the relationships between individual shots, together with the relation of the depth of penetration into the surface $d = h\sqrt{2}$ the radius of the curvature for the area of one impression can be calculated. However, if the impressions of shots are multiplied, it is possible to establish the approximate middle radius of the curvature based on the expression:

$$R_m = \frac{1}{S_t}\sum_{i=1}^{n} R_i S_i \tag{16}$$

(where R_m is the middle radius of the curvature, S_t is the surface which is formed, n is the number of impressions, R_i is the radius of the curvature for one impression and S_i is the surface of one impression). This equation (16) offers the possibility to determine, in advance, the radius of the curvature for simple structural elements (single plate). The radius of the curvature for more complex elements, like the integral skin panels on shell plates and decks, can be determined so far only empirically.

Depth limits range for Al-alloys is between 1.3 mm and 50 mm and for the steel of a high flexibility limit is between 0.4 and 25 mm, in accordance with shot-peening parameters [28]. The procedure of peen forming is used for elements of a relatively large size, e.g. type of sheet metal or integrally milled panels, whose radius of the curvature is big enough and where there are no sudden changes of forms and contours. This procedure is suitable for obtaining curvatures that keep the metal in the flexible elastic area. It is sometimes also used for bringing into more severe tolerances of the correctness of curved elements which could not be obtained in another way. Elements with sharp angles of deformation and forms for deep-drawing are not suitable for this procedure. In order to obtain these shapes, special tools with a press have to be used, or, even, the combination of peen-forming and special tools with a press, step by step [5].

Peen-forming is executed from one side only, and that is usually from the smooth side so that a convex curvature is obtained without previously attaching the element to the pre-forming tool. Both sides of a material are in the compressive state of stress as a result of shot-peening (see Figure 2). These compressive stresses increase also the fatigue strength and resistance to stress corrosion. Thus, in some cases, structural elements are peened in whole before peen-forming. Also, various elements, which should be cold-formed by some other processes of forming, are peened after forming in order to obtain relaxation and a harmonious distribution of tensile stresses, which were disrupted by bending or some other way of processing.

All large producers, both of civil and fighter aircraft use this procedure for the mentioned purposes, as, for example, *Grumman*

(A6A, EA 6B), *Lockheed* (53A, C-130; L1011), *Boeing* (727, 737, 747, 757, 767), *McDonnell* (DC-9; DC-10; F-15), *Airbus* (310, 320), *Canadair* (Cl-600), *De Havilland* (Dash 27), etc. If necessary, after peen-forming the integral skin panels have to be trimmed to finish perimeter dimensions.

In the control phase of production of large sized plates slight corrections in form can be executed with control tools by means of shot-peening.

Judging from the experience of aircraft industry it can be stated, with great certainty, that peen-forming process will have an important role in production of high-speed ships. Along high strength steels, titanium alloys and composites, the new generation of high-speed ships will utilise different types of Al-alloys for building most of high-speed ships' hull construction elements, particularly for large structural parts that have gentle curvatures like decks or superstructures (Figure 9). High-speed ships like the *Gliding Wing* and the FAROP [35] also involve many uncommon structural parts such as integral skin panels that could be made from Al-Li alloys and formed in shapes with significant curvatures. Numerous parts of these ships will benefit from the use of peen forming and shot-peening procedures, such as: spoilers and submarines (skis), vertical supporters, top skin, rudders and pillars frontal borders, skins of stabilisers, supports of air-propulsors, etc. [36].

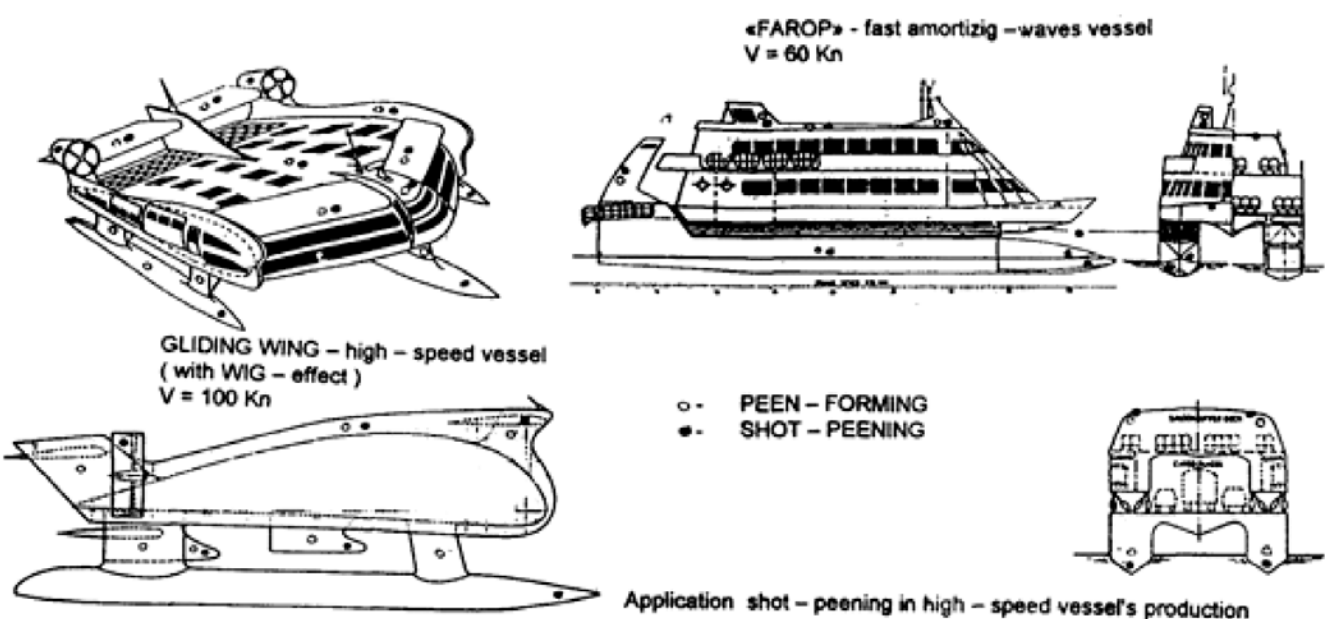


Figure 10 **Peen formed integral panel of high-speed ship *Gliding Wing***
Slika 10 **Integralna oplata brzog broda *Gliding Wing* oblikovana kugličarenjem**

Figure 9 **Proposed application of shot-peening and peen-forming in production of high-speed ships [36]**
Slika 9 **Primjena kugličarenja i oblikovanja kugličarenjem u proizvodnji brzih brodova [36]**

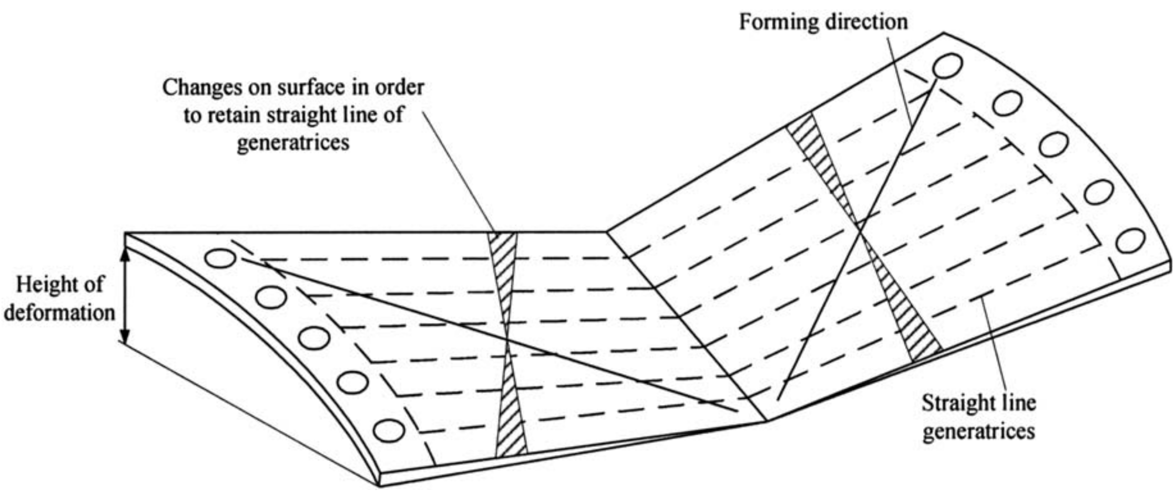


Figure 10 shows a complex geometrical shape of integral skin panel, which is considered as a part of the *Gliding Wing's* hull. It is expected that integral skin panels, i.e. the shell plate structure which incorporates shell plates and longitudinals (stringers) by milling from one depth plate of material, will be used in the production of high-speed vehicles as the shell plate and decks. Depending on the panel's length, the height of deformation ranges from about 5 cm to 25 cm, which can certainly be obtained by shot-peening process [28].

4 Conclusion

Shot-peening and peen-forming originate from the aircraft industry and that experience has shown usefulness and efficiency of those procedures. This paper shows that the application of modern aircraft industrial technologies can be successfully adapted for production of structural parts of ships, particularly high-speed and super-high-speed ships, which utilise lightweight materials similar to those in aircraft. A peen-forming procedure may be introduced in shaping plates and integral panels made of Al-Li alloys, which are expected to be used in the production of the latest high-speed ships generation. The procedure is low-cost, reliable and easily repeatable and can be used not only for shaping structural elements but also for increasing material properties like fatigue strength and corrosion resistance.

It is pointed out here that defining proper process parameters is of vital importance for the application of peen-forming. The wrong choice of process parameters can lead to over-peening, which causes deterioration of material mechanical properties. It is concluded that theoretical and numerical methods that describe peening process are very complex and practically very little utilizable, thus the experiments remain the major way of determining adequate process parameters.

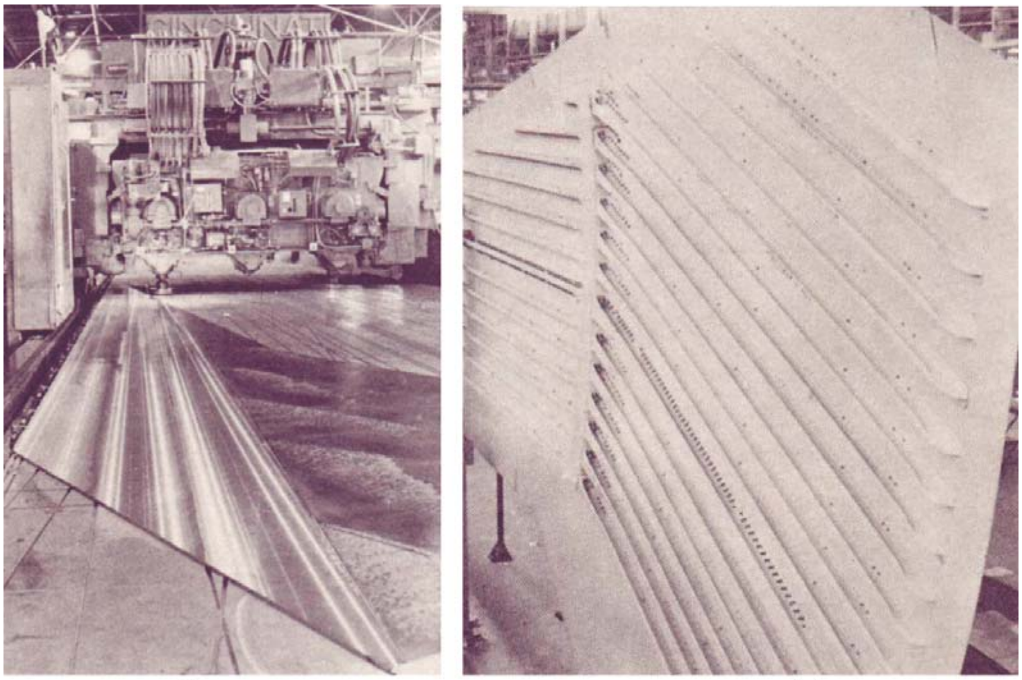
Peen-forming cannot form all conceivable shapes. The design of any structural part must be compatible to peen-forming. The method is capable of producing gentle curvatures with accurate control.

In any case, the benefit of this procedure is manifold and this paper has shown that it could play a significant role in the future production of high-speed ships and boats, which cannot be conducted without application of modern aircraft industrial technologies.

References

1. YU, Z.W.: "The Application of the Superconducting Materials in the High Property Ship", Proceeding of China International Boat Show & High Performance Marine Vehicles, March 25-26, 2004. Shanghai, China.
2. BABCOCK, W.G., CZYRYCYA, E.J: "The Role of Materials in Ship Design and Operation", The AMPTIAC Quarterly, Volume 7, No.3, 2003.
3. DAXIONG, Z., MINGFA, C., WEI, X., LANG, G.: "A New Explore-High Speed Fiberglass Hydrofoil Passenger Craft", 3rd International Conference for High Performance Marine Vehicles, April 19-23, 2000., China.
4. BROWN, S.: "Feasibility of Replacing Structural Steel with Aluminum Alloys in the Shipbuilding Industry", University of Wisconsin, 1-15, 1999.

Figure 11 **Production of integral skin panels: a) CNC milling before peen-forming, b) in the assembly phase-incorporated shell plate and stringers [28]**
Slika 11 **Proizvodnja integralnih panela: a) CNC glodanje prije oblikovanja, b) u fazi montaže - u jednom komadu oplata i uzdužnjaci [28]**



a)   b)

5. MARKOVINA ,R.: "Osnove procesa oblikovanja integralnih oplata" (The Principles of Integral Skins Forming Process), Metalopreradivačka industrija, SOKO, Mostar, 1977.
6. MARKOVINA, R.: "The main principles of using integral panels (skins) in modern shipbuilding industry"//AMST '02 - Advanced Manufacturing Systems and Technology
7. WAGNER, L.: "Mechanical surface treatments on titanium, aluminum and magnesium alloys", Materials Science & Engineering A, A263, (1999), p. 210-216.
8. MARKOVINA, R.: "Influence of shot peening process parameters on the carrying properties of aluminum thin plates", Journal for Technology of Plasticity, no. 1-2, nov.1991., p. 39-54.
9. CURTIS, S., RIOS, de los, E.R., RODOPOULOS, C.A., LEVERS, A. : "Analysis of the effects of controlled shot peening on fatigue damage of high strength aluminium alloys", Int. Journal of Fatigue 25, 2003, p. 59–66.
10. GUPTA, R.K., et al: "Development and characterization of Al–Li alloys", Materials Science and Engineering A, 420 (1-2), March 2006, pp. 228-234.
11. ALMEN, J., BLACK, J.P.H.: "Residual Stresses and Fatigue in Metals", McGraw-Hill, Toronto, 1963.
12. FATHALLAH, R., et al.: "High cycle fatigue behaviour prediction of shot-peened parts", Int. Journal of Fatigue, 26 (10), October 2004, p. 1053-1067.
13. GUECHICHI, H., CASTEX, L.: "Fatigue limits prediction of surface treated materials", Journal of Materials Processing Technology, 172, (2006), p. 381–387.
14. MOORE, D.: "The application of shot-peen forming technology to commercial aircraft wing skins", Mac Donnell Douglas – Canada, 1985.
15. FELD, P.G., JOHNSON, D.E.: "Advanced Concepts of the Process Shot Peening for Advanced Aerospace Design" SP-528, Society of Automotive Engineers, 1982, p. 19–22.
16. ZHANG, X., et al: "Prediction of Shot Peen Forming Parameters of Integral Aircraft Wing Panels", Materials Science Forum, Vol. 532-533, 2006., p 937-940, Trans Tech Publications, Switzerland.
17. MARKOVINA, R.: "The preliminary investigations and the main principles of super-high-speed vessel Gliding Wing", International Shipbuilding Progress, 49 (2), June 2002.
18. BAL, S.: "High-speed submerged and surface piercing cavitating hydrofoils, including tandem case", Ocean Engineering, Volume 34, Issues 14-15, October 2007, p. 1935-1946.
19. COPPOLA, T. MANDARINO, M.: "The Design of Trimaran Ships: General Review and Practical Structural Analysis", Practical design of ships and other floating structures 2001, p. 127-134.
20. WANG, S., et al.: "Fatigue limits of shot peened metals", Journal of Materials Processing Technology, 73, 1998, p. 57-63.
21. RALPH, I.S., et al.: "Metal Fatigue in Engineering", 2nd edition, Wiley Int., 2001.
22. MARKOVINA, R., BLAGOJEVIĆ, B., BAN, D.: "Technologically improved strength of critical structural elements of high-speed ships", 11th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology", TMT 2007. Hammamet, Tunisia, 5-9 September 2007, p. 935-938.
23. BLAGOJEVIĆ, B., ŽIHA, K., DOMAZET, Ž.: "Productional, operational and theoretical sensitivities of fatigue damage assessment in shipbuilding", SNAME, Journal of Ship Production, Vol. 18, No.4, November 2002, p. 185-195.
24. GEORGE, P.M., PILLAI, N., SHAH, N.: "Optimization of shot - peening parameters using Taguchi technique", Journal of Materials Processing Technology, Volumes 153-154, 10 November 2004, p. 925-930.
25. FAIR, G.H., NOBLE, B., WATERHOUSE, R.B.: "The effect of shot-peening on the fatigue and fretting fatigue behavior of 8090 and 7010 aluminum alloys", International Conference on shot-peening, ICSP-3, (p.431-438), Garmisch-Partenkirchen (Germany), September 1987.
26. BENEDETTI, M., BORTOLAMEDI, T., FONTANARI, V., FRENDO, F.: "Bending fatigue behavior of differently shot-peened Al 6082 T5 alloy", Int. Journal of Fatigue, 26 (2004), p. 889-897.
27. WOHLFAHRT, H.: "The influence of peening conditions on the resulting distribution of the residual stresses", 2nd International Conference on Shot Peening, p. 316-331, Chicago, Illinois,1984.
28. MARKOVINA, R.: "Research of elements surface strengthening influence on their carrying capacity properties", Doctoral Thesis, University of Mostar 1991.
29. KOPP, R., HORNAUER, K.P.: "Kugelstrahl–Umformen, ein flexibles Umformverfahren", Institut für Bildsame Formgebung, RWTH Aachen, 1974.
30. LEE, C. H.; MASAKI, S.; KOBAYASHI, S.-International Journal of Mechanical Sciences, 1972, p. 417-426.
31. JOHNSON, W., SOWERBY, R., HADDOWJ. B.:-Edward Arnold (publ.)LTD, 1970, p. 57-60.
32. KONDO, K., TSUZUKI, S., KATO, A.: "Investigations on peen-forming", Pergamon Press, 1981.
33. MARKOVINA, R.: "Application of modern materials and technologies in production of super high speed vessels", XIV Symposium SORTA, Plitvice, Croatia, 2000, p. 111-122.
34. MARKOVINA, R., BLAGOJEVIĆ, B., VLAK, F.: "Bending fatigue behavior of shot - peened Al-Li 8090T3 thin plates", unpublished (under review in Strojniški Vestnik, Journal of Mechanical Engineering).
35. MARKOVINA, R.: "The survey of the preliminary solutions of super–high speed vessels of the new generation FAROP and GLIDING WING", Proc. of IMAM, Naples, 2000.
36. MARKOVINA, R.: "Oberflachenfestigung durch Kugelstrahlen (Praktishe Anwendung im Shiffbau)", Zeitschrift für Wirtschaftliche Fertigung und Automatisierung (ZWF)-München/Berlin, 96 (2001.)1-2, p. 65-67.