Surface mechanics design of metallic materials on mechanical surface treatments

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Abstract
In order to control the surface mechanics of a metallic material, mechanical treatment of the surface, such as by shot peening, water jet peening, cavitation peening or laser peening, is often done. In this review paper, we discuss the mechanical properties of such treated surfaces and the effect of the treatment on fatigue strength. Although there is a detrimental increase in surface roughness introduced by the various treatments, the positive effects, such as the introduction of compressive residual stress and/or work hardening, i.e., an increase in the yield stress, outweigh the negative effects, then treatments improve the fatigue strength. The compressive residual stress introduced by the various treatments is closely related to the crack closure and crack initiation. If the same peening process is used, the fatigue strength can be estimated from the residual stress distribution. However, when the mechanical surface treatments were different, the residual stress distribution of the specimen at the same fatigue strength was totally different. Namely, when different peening processes are applied to the surface, the compressive residual stress only shows a tendency to improve the fatigue strength, and the fatigue strength cannot be evaluated precisely from the residual stress distribution, Thus, a fatigue test is required to evaluate the fatigue strength. As the fatigue strength strongly depend on the crack initiation, an evaluation of the threshold level of the stress intensity factor range of a treated surface is valuable, and it can be possible by a plate bending fatigue test using a notched specimen.

Key words: Surface improvement, Surface treatment, Residual stress, Yield stress, Hardness, Strength, Fatigue, Hydrogen embrittlement, Stress corrosion cracking, Nondestructive inspection

1. Introduction

In order to create a safe and assured sustainable society, it is necessary for us to develop the technologies that will enable us to reliably extend the lifetimes of industrial plants and machinery, such as power plants, chemical plants, automobiles and airplanes. Although the bulk materials used in the components of such industrial plants and machinery have been developed specifically for particular uses, fractures and corrosion initiate mainly from the surfaces of these components. Thus, the strength and corrosion resistance of these components depend on their surface properties. Consequently, it is possible to improve the strength and corrosion resistance of these components by developing and/or controlling the surface properties. In general, the techniques to develop the surface properties are referred to as “surface improvement”, “surface treatment”, “surface enhancement” or “surface modification”. In order to distinguish a surface treatment that enhances the strength of a metallic material from chemical techniques, it is sometimes referred to as “mechanical surface treatment” (Wagner, 1999), (Zinn and Scholtes, 1999), (Nalla et al., 2003), (Turski et al., 2010), (Gill et al., 2013) or a “surface engineering treatment” (Rodopoulos et al., 2007). In this review, we examine the research area that covers the development and/or control of surface properties in order to improve the strength of metallic materials, such as controlling the fatigue fracture toughness, fretting damage, delayed fracture, stress corrosion cracking, and hydrogen embrittlement. We call this research area “surface mechanics design”.

Surface mechanics design can be widely used for machine and industrial plant components to improve the fatigue
strength, the fretting fatigue strength, the corrosion resistance and the resistance to environmental assisted cracking such as stress corrosion cracking and hydrogen embrittlement. In the past, the fatigue strength of mechanical components, such as that of spring steel (Mattson and Coleman Jr, 1954), (Farrahi et al., 1995), gears (Torres and Voorwald, 2002), (Lyu et al., 1996), (Soyama and Sekine, 2010), fastener holes (Phillips, 1973), (Yang et al., 2001), (Tan et al., 2004), (Ivetic et al., 2012), (Cuellar et al., 2012), (Cuellar et al., 2012) and bearings (Zaretsky, 2012), has been improved by mechanical treatment of the surface. Bridges have also been examined (Cheng et al., 2003). Corrosion (Jiang et al., 2006) and stress corrosion cracking have been reduced by surface treatments (Enomoto et al., 1996), (Saitou et al., 2003), (Prevey and Cammett, 2004), (Sano et al., 2006), (Mochizuki, 2007), (Hatamleh et al., 2009). Unfortunately, these treatments were optimized by trial and error and were based on a huge number of experimental results. Of course, experimental proof is required to establish the reliability of a component. However, if the effects and key factors in the treatment can be organized on the basis of surface mechanics design, the efficiency would be improved and new techniques could be easily established. In this review, main target of surface mechanics design is improvement of fatigue strength of metallic materials.

Figure 1 summarizes the concept of surface mechanics design. Surface mechanics design by peening means that control of mechanical properties near subsurface by local plastic deformation induced by the solid or liquid collision or shock wave. For example, the enhancement of the fatigue strength can be roughly expressed as follows. The plastic deformation affects residual stress and microstructure such as grain size and dislocation density, which impinges on yield stress and tensile strength. The residual stress, the yield stress and the tensile strength affect fracture toughness and then they improve fatigue strength.

![Diagram of Surface Mechanics Design](image-url)
also on the residual stress (Yan et al., 2007), (Takakuwa et al., 2013). That is, the key factors used in surface mechanics design are not simple, as the parameters are interdependent. When the surface characteristics, including the characteristics of the subsurface such as the electrical resistance, are unambiguous they can be used to estimate the mechanical properties by non-destructive testing. For example, since the resistance of a metallic material is changed by the residual stress and/or the dislocation density, an eddy current method can be used to estimate the residual stress at the surface, which is one of the main factors in surface mechanics design.

In this review, the key surface properties that have an influence on surface mechanics design are discussed first, and the methods used to evaluate the mechanical properties are summarized. Then, the processes used for surface mechanics design are classified, and the effect of the process parameters discussed. Finally, some numerical simulations are introduced.

2. Influence of Surface Characteristics on Surface Mechanics Design and their Evaluation

In order to describe the surface conditions modified by manufacturing processes such as grinding, turning and machining, the term surface integrity was coined by Field and Kahles (Field and Kahles, 1964), (Kahles et al., 1969). In the machining data handbook (Machinability data center, 1980), surface integrity and surface texture were introduced to discuss the characteristics of surfaces as shown in Fig. 2. In the book, the surface texture is shown as due to exterior effects such as roughness and pits, and the surface integrity is due to interior effects such as microcracks, plastic deformation and residual stress. In this paper, in order to discuss the quantitative increases in fatigue strength obtained utilizing surface mechanics design, we consider the residual stress, yield stress, tensile strength, roughness, and hardness as factors.

As shown in Fig. 3, the fatigue strength decreases as the residual stress increases (Koster, 1974). This tendency was also shown by fatigue tests on gears (Shaw et al., 2003). As expected, the residual stress affects the crack closure (Elber, 1970), (Lados et al., 2007), and the threshold for crack initiation is also increased by compressive residual stress (John et al., 2003). Mechanical surface treatments normally change the distribution of residual stress, that is, the stress distribution perpendicular to the surface. When considering the residual stress distribution, the number of cycles to failure of a notched stainless steel specimen was found, as shown in Fig. 4, to be proportional to the area of integration under the compressive residual stress curve with respect to depth introduced by shot peening, laser peening, cavitation peening and hybrid peening, which is a combination of different peening methods (Takakuwa et al., 2013). Note that the residual stress introduced by mechanically treating the surface is an important factor in crack propagation, as is the fatigue strength of the material, as mentioned below. However, for different mechanical surface treatments, totally different residual stress distributions are found even though the fatigue strength may be the same (Odhiambo and Soyama, 2003). One reason for

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Fig. 2  Schematic diagram of surface integrity (Machining data handbook, 1980). Mechanical surface treatments affects surface integrity, i.e., interior effects and surface texture, i.e., exterior effects.
Fig. 3  Relationship between peak residual stress and fatigue strength (Koster, 1974). The fatigue strength increased with compressive residual stress.

Fig. 4  Number of cycles to failure of a notched stainless steel specimen was proportional to the area of integration under the compressive residual stress curve with respect to depth (Takakuwa, et al., 2013). In the report, the residual stress on the surface was varied from -600 MPa to -250 MPa, and the thickness of the surface modified layer was varied from 0.4 mm to 1.2 mm. The symbols mean the following peening; LP : laser peening, SP : shot peening, CPA : cavitation peening using cavitating jet in air, CPW : cavitation peening using cavitating jet in water, HP : hybrid peening (combination of different peening), HP-A : combination of CPA and CPW, HP-B : combination of CPW and SP, HP-C : combination of CPA and SP.

This might be the strain rate arising from the mechanical surface treatment, as the plastic deformation area beneath the surface was different for different treatments (Kanou et al., 2012). As the residual stress varies during operation, this variation, i.e., the residual stress relief, has also been investigated (Ochi et al., 2001), (Torres and Voorwald, 2002), (McClung, 2007).

In order to evaluate the residual stress, diffraction studies using X-rays, synchrotron radiation and neutrons have
Fig. 5  Relationship between surface roughness and fatigue strength (Bellows and Koster, 1972).

The decrease of fatigue limit increased with increase of surface roughness.

been used (Withers and Bhadeshia, 2001), (Tanaka and Akiniwa, 2004). These days, the \( \sin^2 \psi \) method using X-ray diffraction is the most common method. The Society of Materials Science, Japan has introduced standard guidelines to measure the residual stress using the \( \sin^2 \psi \) method (Society of Materials Science, Japan, 2002). Note that the results would be scattered if the conditions were not for plane stress, as the \( \sin^2 \psi \) method is based on plane stress conditions. In order to measure the stress tensor, a 2D method using a two dimensional detector was proposed (He et al., 2000), (Takakuwa and Soyama, 2013). In the case of the diffraction method, the micro or lattice strain can be evaluated using the full width at half maximum and/or the diffraction profile (Stokes and Wilson, 1944), (Hall, 1949), (Williamson and Hall, 1953), (Tanaka and Akiniwa, 2004), (Soyama and Yamada, 2008). In order to measure residual stress, a hole drilling method to remove part of the material is employed, and this is an ASTM Standard (ASTM E837-13a, 2013). For a quick and simple residual stress measurement, an eddy current method can be employed (Blodgett and Nagy, 2004), (Sekine and Soyama, 2009). The eddy current method is useful for in-line measurements in the same way as a flaw detector is used in steel making plants. Since, as mentioned above, the results of indention tests depend on the residual stress an indentation with inverse analysis can be used to determine the residual stress (Suresh and Giannakopoulos, 1998), (Nishikawa and Soyama, 2011).

As is well known, hardness is proportional to the yield stress (Tabor, 1956), and the fatigue strength can be expressed as a function of hardness (Murakami et al., 1988), so that hardness, and consequently the yield stress also, is one of the factors to take into consideration in surface mechanics design. Here, yield stress means quasi-static yield stress. Although the good correlation between the cyclic yield stress and the fatigue strength was reported (Li et al., 2009), it is usually substituted by the quasi-static yield stress when the cyclic yield stress is lacking (Yip and Jen, 1996), (Jen and Wang, 2005), (Li et al., 2006). Note that the hardness as measured by an indentation test is affected by the residual stress (Kagawa and Nishimoto, 1990), (Tsui et al., 1996), (Nishikawa and Soyama, 2011). Thus, in order to not confuse matters, the yield stress rather than the residual stress should be used as the factor in surface mechanics design. In the case of bulk metals, the relationship between tensile strength and fatigue strength has been established (Nishijima, 1980). In order to evaluate the yield stress of a mechanically treated surface layer, an indentation test with inverse analysis is useful, since the yield stress of a thin layer can be obtained (Oliver and Pharr, 1992), (Ogasawara et al., 2006). It has been shown that the yield stress of stainless steel is increased by cavitation peening (Nishikawa et al., 2010).

Figure 5 shows the relationship between surface roughness and fatigue strength (Bellows and Koster, 1972). The fatigue limit decrease with increasing surface roughness as shown in Fig. 5. It was also revealed that the fatigue strength scarcely changes for surface roughness \( R_s < 1 \, \mu \text{m} \) (JSME, 1984). It has been reported that the effect of the surface roughness can be expressed by a \( \sqrt{\text{area}} \) parameter (Murakami et al., 1997) or a stress concentration factor (Masaki et al., 1999). Note that the positive effects on fatigue strength after work hardening and the introduction of a compressive residual stress outweigh the negative effect of increased surface roughness (Masaki et al., 1999).

In fracture mechanics, the crack propagation rate using a compact tension specimen has been standardized as the ASTM standard E647 (ASTM E647-13, 2013). It has been shown that the crack propagation rate can be suppressed by either shot or laser peening (Adekola et al., 2007). In order to investigate crack initiation, the threshold level of the stress
intensity factor range, $\Delta K_{th}$, should be examined. However, it is very difficult to evaluate $\Delta K_{th}$ for a surface layer modified by the standard method, as the purpose of the standard method is to evaluate bulk materials and the surface layer is only a thin part on top of the bulk material. It was shown that the suppression of crack growth rate by peening was revealed by a plate bending fatigue test with a notched specimen, as the applied tensile stress had a maximum at the surface of the specimen (Takakuwa et al., 2011). However, a conventional plate bending fatigue test machine on the market is displacement controlled machine. As the applied stress is decreased with crack growth, $\Delta K_{th}$ cannot be evaluated. Thus, a load control plate bending fatigue test machine was developed, and the crack propagation rate and $\Delta K_{th}$ of a modified surface layer has been evaluated using with the machine (Takakuwa et al., 2014). This measurement technique is very useful for the surface mechanics design of metallic materials.

3. Processes Used for Surface Mechanics Design

The key factor in surface mechanics design is local plastic deformation, which is most commonly done by shot peening. Figure 6 shows a schematic diagram illustrating three different typical peening methods; these are shot peening, cavitation peening and laser peening, in which the material treated is plastically deformed by the impact with a solid (shot), by the shock wave produced by cavitation bubbles collapsing and by the shock wave induced by laser ablation, respectively. The details of each method are discussed below. Figure 7 illustrates typical residual stress distributions in

![Fig. 6 Schematic diagram of typical peening methods to produce local plastic deformation.](image)

![Fig. 7 Typical residual stress distribution in stainless steel treated by different peening methods. The compressive residuals stress distribution in traduced by conventional shot peening had a maximum at certain depth. In the cases of cavitation peening and laser peening, the compressive residual stress had a maximum near surface. Note that the depth and the value of compressive residual stress was varied by peening conditions.](image)
Table 1 Various types of peening methods

<table>
<thead>
<tr>
<th>Name of method</th>
<th>Mechanism of impact</th>
<th>Source of impact</th>
<th>Source of impact force</th>
<th>Colloquial term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot peening</td>
<td>Solid collision</td>
<td>Shot</td>
<td>Air jet</td>
<td>Fine Particle Bombarding* (Shot diameter &lt; 200 (\mu m))</td>
</tr>
<tr>
<td>Needle peening</td>
<td>Solid collision</td>
<td>Needle</td>
<td>Ultrasonic vibration</td>
<td>Ultrasonic peening</td>
</tr>
<tr>
<td>Wet shot peening</td>
<td>Solid collision</td>
<td>Shot</td>
<td>Water jet</td>
<td>Ultrasonic peening*</td>
</tr>
<tr>
<td>Water jet peening</td>
<td>Liquid collision</td>
<td>Water droplet</td>
<td>Water jet</td>
<td>Water jet peening†</td>
</tr>
<tr>
<td>Cavitation peening</td>
<td>Shock wave</td>
<td>Cavitation collapse</td>
<td>Ultrasonic vibration</td>
<td>Pulse laser</td>
</tr>
<tr>
<td>Laser peening</td>
<td>Shock wave</td>
<td>Laser abrasion</td>
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Fig. 8 General influence of shot peening parameters on the residual stress distribution (Schiffner, et al., 1999). Note that the introduced compressive residual stress by peening is equibiaxial stress in the plane which is parallel to the surface.

Type 316L stainless steel introduced by shot peening, cavitation peening and laser peening. The introduced residual stress by peening is equibiaxial stress in the plane which is parallel to the surface. Note that the depth and the maximum value of the compressive residual stress depends on the peening methods and conditions. In the case of shot peening, the compressive residual stress reaches a maximum at some distance beneath the surface. On the other hand, the maximum compressive residual stress for cavitation peening and laser peening is near the surface. The various types of peening method are summarized in Table 1.

Several types of shot peening are used. In conventional shot peening, metal or glass shot is used to strike the surface where treatment is required. The shot, which are spherical balls or rounded cut wire, are accelerated either by a compressed air jet, a centrifugal force from a rotating blade or ultrasonic vibration. Recently, in a method called fine particle bombarding, particles as fine as 200 \(\mu m\) in diameter have been driven at the treated surface at high speed to get better fatigue strength (Kikuchi et al., 2010), (Morita et al., 2012). Kikuchi et al. (2010) investigated the combination fine particle bombarding and nitriding of austenite stainless steel as pre-treatment. Morita et al. (2012) revealed that effect of fine particle bombarding on the grain size and introduced compressive residual stress comparing with conventional shot peening using pure titanium. As shown in Fig. 8, the depth beneath the surface where the maximum compressive residual stress occurs depends on the shot diameter (Schiffner and Helling, 1999). Figure 8 also shows that the maximum compressive residual stress is larger when the shot velocity is higher. In order to get a large compressive residual stress at greater depth and large compression at the surface, large shot followed by small shot at high speed was used. This procedure is called double shot peening (Matsui et al., 2002). From the point of view of surface mechanics design, the relationship between the residual stress distribution and the fatigue strength needs to be known. In the case of shot peening, the maximum value of the compressive residual stress and the depth where this occurs is very important,
The maximum value and the depth of introduced compressive residual stress by shot peening are important parameters for the improvement of fatigue strength.

Fig. 9 Relationship between residual stress distribution and fatigue strength for shot peening (Mitsubayashi et al., 1995). The maximum value and the depth of introduced compressive residual stress by shot peening are important parameters for the improvement of fatigue strength.
as shown in Fig. 9 (Mitsubayashi et al., 1995). The fatigue strength was nearly proportional to the maximum value of the compressive residual stress (see Fig. 9 (a)). For example, the fatigue strength and the maximum compressive residual stress were roughly 1500 MPa and 1400 MPa for condition ①, 1800 MPa and 1800 MPa for condition ②, and 1200 MPa and 1000 MPa for condition ③, respectively. It suggests that fatigue strength can be roughly estimated from the maximum compressive residual stress in the case of the same peening method but different conditions. When the introduced compressive residual stress distribution was changed as shown in Figs. 9 (b) and (c), the tendency of the improvement of fatigue strength by the peening can be explained by considering the maximum bending stress and the distribution of the residual stress. Thus, the effect of introduced compressive residual stress by the same peening method can be roughly estimated by a modified Goodman diagram. However, in the case of different peening methods, totally different residual stress distributions are found at the same fatigue strength as mentioned above (Odhiambo and Soyama, 2003). Namely, the fatigue test and/or the investigation of crack propagation was necessary for developing novel peening method to improve the fatigue strength. Needles, i.e., thin round bars, accelerated by ultrasonic vibration have also been applied for peening in a process called needle peening. Both shot and needle peening when the acceleration is done by ultrasonic vibration are called ultrasonic peening (Abramov et al., 1998), (Xing and Lu, 2004), (Todaka et al., 2006). Abramov et al. (1998) revealed the effect of parameters such as amplitude and frequency of ultrasonic vibration in industrial scale. Xing and Lu (2004) investigated the distribution of introduced residual stress by the ultrasonic peening. Todaka et al. (2006) revealed the formation of nanocrystalline structure produced by the ultrasonic peening. In order to avoid the dust produced by solid collisions, shot accelerated by a water jet was proposed (Ishiguro et al., 1994), (Naito et al., 2012). This process was called wet shot peening. Ishiguro et al. (1994) used the water jet to accelerate the shots to get more compressive residual stress, as the density of the water was larger than that of the air. Naito et al. (2012) developed a recirculating type shot peening system accelerated by the water jet to avoid the dust and sparks at the conventional shot peening. A peening method, called water jet peening, using glass or abrasive beads accelerated by a high speed water jet with injection pressures from 100 MPa to 220 MPa was also proposed (Yoshioka, 2002), (Sadasivam et al., 2009). Yoshioka (2002) developed water jet peening system using glass beans to get large compressive residual stress near the surface because of the hardness of glass. Sadasivam et al. (2009) revealed that an abrasive water jet cutting system using alumina particles could introduce compressive residual stress. Since the velocity of sound in water is 4.4 times larger than that in air, the speed of beads accelerated by a water jet is much higher than that of shot accelerated by an air jet. Note that the plastic deformation in this water jet peening process is induced by collision with a solid material. Another process used to modify the surface of a material is deep rolling, sometimes called roller burnishing (Juijerm et al., 2004), (Brinksmeier et al., 2008), (Tsuij et al., 2008). Juijerm et al. (2004) investigated the effect of temperature from 20 to 300 °C after deep rolling on fatigue of aluminum wrought alloy. Brinksmeier et al. (2008) revealed relation between structural change by deep rolling and hardness using high alloyed steel. Tsuij et al. (2009) investigated the effect of combined plasma-carburizing and deep rolling on notch fatigue property of titanium alloy.

Peening methods that use a high-speed water jet or oil jet without shot or beads were also proposed (Enomoto et al., 1996), (Daniewicz and Cummings, 1999), (Grinspan and Gnanamoorthy, 2006), (Chillman et al., 2007). Enomoto et al. (1996) used a submerged water jet and Daniewicz and Cummings (1999) used water jet in air. Grinspan and Gnanamoorthy (2006) applied an oil jet for the peening and Chillman et al. (2007) used a water jet at high injection pressure such as 600 MPa. These processes were called water jet peening or oil jet peening. In these processes, the local plastic deformation in the material being treated is produced by collision with the liquid droplets in the jet. In some papers cavitation impact was also used, since the water jet was submerged. However, even though the water jet was submerged, the material could still be peened by the droplets. In order to optimize the peening process, it is necessarily to distinguish between water jet peening and cavitation peening. This can be done by considering the standoff distance and the cavitation number as mentioned below.

A submerged water jet has also been used for peening (Soyama et al., 1995), (Hirano et al., 1996), (Soyama et al., 2002), (Saitou et al., 2003), (Odhiambo and Soyama, 2003), (Qin et al., 2006). Soyama et al. (1995) and then Hirano et al. (1996) proposed practical use of a cavitating jet to produce compressive residual stress, and Qin et al. (2006) investigated the effect of incidence angle of the cavitating jet on the introduction of compressive residual stress. Saitou et al. (2003) reported that the introduction of compressive residual stress into reactor internal components of nuclear power plant to prevent stress corrosion cracking by a submerged high speed water jet. Soyama et al. (2002) revealed the improvement of fatigue strength of aluminum casting alloy by the cavitating jet. Odhiambo and Soyama (2003)
Fig. 10 Typical residual stress distribution in stainless steel introduced by cavitating jets in air and water. The cavitating jet in air introduced large compressive residual surface near subsurface and the cavitating jet in water introduced the compressive residual stress in deeper region.

demonstrated that the fatigue strength of carbonized chrome-molybdenum alloy steel treated by the cavitating jet was better than that of shot peening. When a high-speed water jet is injected into a water-filled chamber, cavitation bubbles are generated around the jet, and the impact generated when the cavitation bubbles collapse is utilized for the peening. Peening using cavitation impact is called cavitation peening (Takakuwa et al., 2011), (Seki et al., 2012), (Takakuwa and Soyama, 2012) or cavitation shotless peening, as shot are not required (Soyama et al., 2002), (Odhambo and Soyama, 2003). Takakuwa et al. (2011) revealed the improvement of the yield stress of the electrical steel sheet used for IPM motors by cavitation peening. Seki et al. (2012) demonstrated that the improvement of rolling contact fatigue life of steel rollers. Takakuwa and Soyama (2012) revealed the suppression of the hydrogen embrittlement of the stainless steel by cavitation peening. By optimizing the nozzle geometry the aggressive intensity of a cavitating jet can be enhanced by the nozzle outlet geometry (Soyama, 2011) and the guide pipe around the nozzle outlet (Soyama, 2014a) then the enhanced jet was applied to improve the fatigue strength of fastener holes (2014b), since the aggressive intensity strongly depends on the outlet geometry of the nozzle (Soyama, 2013). In cavitation peening, a high-speed water jet with low injection pressure and a large nozzle throat is more effective compared with a jet with high injection pressure and a small nozzle (Soyama and Takakuwa, 2011). Note that the aggressive intensity decreases as the injection pressure increases too higher levels (Soyama et al., 2012). As mentioned above, a normal cavitating jet is submerged. However, Soyama developed a cavitating jet in air by injecting a high-speed water jet into a low-speed water jet using a concentric nozzle (Soyama, 2004), and the hydrodynamic mechanism at optimum condition was revealed (Soyama, 2005). As a cavitating jet in air can be applied to industrial plants and machine components which cannot be put into water chambers, the applications of cavitation peening have expanded. As shown in Fig. 10, an optimized cavitating jet in air can introduce larger compressive residual stress into a surface compared with a cavitating jet in water. The introduced compressive residual stress by the cavitating jets in air and water was equibiaxial stress in the plane which was parallel to the surface as same as shot peening (Soyama et al., 2000), (Soyama, 2004). The distribution of the residual stress introduced by a cavitating jet in air corresponds to that of shot peening using small shot at high speed, and that of cavitation jet in water corresponds to that of shot peening using large shot at low speed.

When the peening process mainly uses cavitation impact, “cavitation peening” rather than “water jet peening” is the recommended name in order that the key factors are not misunderstood. Cavitation peening is now discussed in the SAE International, Surface Enhancement Committee (SEC) and Aerospace Metals and Engineering Committee, Surface
(a) Weight loss, i.e., the aggressive intensity of the jet, as a function of standoff distance changing with cavitation number at constant injection pressure (Momma and Lichtarowicz, 1995). The standoff distance of the far side from the nozzle, i.e., the second peak, was changing with cavitation number and the weight loss at the second peak was also changed by cavitation number.

(b) Inverse of radius of curvature, i.e., the aggressive intensity of the jet at the equivalent jet power, as a function of standoff distance at constant downstream pressure $p_2 = 0.1$ MPa. The aggressive intensity of the jet of 2nd peak at $p_1 = 30$ MPa was much larger than that of 1st and 2nd peak at $p_1 = 300$ MPa.

Enhancement Subcommittee (AMEC-SE), each of which is standardizing peening methods including shot peening and laser peening. If impact with a liquid is used, water jet peening is an acceptable name for the peening method. The impact mechanism, which depends on the distance between the nozzle and the target surface, i.e., the standoff distance, falls into two regions, a cutting region and a peening region, with a peak in each region (Yamauchi et al., 1995). The first peak is suitable for cutting and/or water jet peening using the impact with the droplets, while the second peak is suitable for peening using cavitation impact. The standoff distance at which the second peak occurs varies with cavitation number (Momma and Lichtarowicz, 1995), as shown in Fig. 11 (a). The standoff distance where the weight loss, i.e., the aggressive intensity had a maximum, was named as optimum standoff distance. The cavitation number $\sigma$ is defined...
Fig. 12 Classification map for cavitation peening and water jet peening, considering the optimum standoff distance $s_{\text{opt}}$, where the aggressive intensity of the jet had a maximum, as a function of cavitation number $\sigma$.

In terms of the injection pressure of the jet $p_1$, the pressure downstream from the nozzle $p_2$ and the vapor pressure of the liquid $p_v$ as follows.

$$\sigma = \frac{p_1 - p_v}{p_1 - p_2} \geq \frac{p_2}{p_1}$$

where the absolute pressure should be used for both $p_1$ and $p_2$. The cavitation number can be simplified as in Eq. (1), because usually $p_1 \gg p_2 \gg p_v$. The weight loss as a function of standoff distance is illustrated in Fig. 11 (a), where it is assumed that the weight loss corresponds with the aggressive intensity of the jet. In Fig. 11 (b), the inverse of the radius of curvature of peened spring steel is used to show the aggressive intensity of the jet at constant downstream pressure $p_2 = 0.1$ MPa, as the arc height of Almen strip was used to measure the peening intensity. The effect of the injection pressure, $p_1$, and nozzle size, $d$, on the peening intensity is shown by the results for $p_1 = 30$ MPa ($\sigma = 0.0033$) with $d = 2$ mm and $p_1 = 300$ MPa ($\sigma = 0.00033$) with $d = 0.4$ mm. In each case both peaks are shown. The jet power, which depends on the flow rate and the injection pressure, were nearly equal. However, it is clear that the second peak with $p_1 = 30$ MPa is much larger than that with $p_1 = 300$ MPa, even though the first peak with $p_1 = 300$ MPa is larger than that with $p_1 = 30$ MPa. Thus, a cavitating jet with a low injection pressure and a large nozzle is better than that with high injection pressure larger and a small nozzle (Soyama, 2011), (Soyama et al., 2012). This is one of the reasons why a cavitating jet for which the injection pressure is too high cannot introduce large compressive residual stress (Demma and Frederick, 2006).

In order to distinguish between cavitation peening and water jet peening, Fig. 12 illustrates the optimum standoff distance $s_{\text{opt}}$, where the aggressive intensity of the jet had a maximum, as a function of cavitation number $\sigma$. As shown in Fig. 11 (b), the aggressive intensity at the first peak, i.e., water jet peening, is increasing with the injection pressure. However, the aggressive intensity at the second peak, i.e., cavitation peening, at too high injection pressure is decreasing with the injection pressure, as the cavitation number is too low. Then, it is necessarily to discriminate cavitation peening from water jet peening to understand the peening mechanism and to get better peening effects. The data in Fig. 12 were obtained from the literature, which are shown by abbreviations for the name of the journal, and the volume and number. The data for the second peak are plotted on the upper right, while those for first peak are plotted on the lower left. The line dividing these two can be expressed by the following equation.

$$\frac{s_{\text{opt}}}{d} = 1.8 \sigma^{-0.6}$$
This line is very useful for distinguishing between cavitation peening and water jet peening. As is well known, ultrasonic vibration generates cavitation bubbles, which is known as ultrasonic cavitation. A machining process using ultrasonic cavitation was attempted (Yamaguchi et al., 2002); however, the process is difficult to control, as considerable changes in the cavitation intensity with the distance between the vibration horn and the treated surface occur (Kikuchi et al., 1991). Thus, hydrodynamic cavitation, such as a cavitating jet, is better for the mechanical treatment of a surface. A pulsed laser produces similar bubbles to cavitation bubbles, which generates a shock wave (Vogel et al., 1996), (Tiberi et al., 2013). Thus, cavitation peening using a pulsed laser might be possible. Note that laser ablation induced by a pulsed laser is used in laser peening.

Another peening method using shock waves is laser peening (Peyre et al., 1996), (Sano et al., 2006), (Hatemleh et al., 2007), (Luong and Hill, 2008), (Gill et al., 2013). Peyre et al., 1996 revealed the comparisons between shock wave profiles and in-depth residual stress fields. Hatemleh et al. (2007) investigated the fatigue crack growth in friction stir welded joint treated by laser peening comparing with shot peened one. Luong and Hill (2008) reported on the high-cycle fatigue performance of aluminum alloy treated with combinations of laser peening and anodization. Gill et al. (2013) investigated the introduction of the compressive residual stresses into a Ni-Base superalloy by laser peening comparing with cavitation peening and ultrasonic nano structure modification. The history of the development of laser peening is described in a review paper (Montross et al., 2002). In conventional laser peening, the pulsed laser is focused on a tape or coating on the target, and the shock wave induced by ablation is blocked by a film of water on the surface, so that the pressure wave propagates into the target, as shown in Fig. 6 (c). In order to apply laser peening for shrouds in the pressure vessels of nuclear power plants, laser peening without a coating was developed (Sano et al., 2006), and has been successfully applied in power plants.

4. Numerical Simulations

Numerical simulations have been used to simulate the residual stress distribution introduced by shot peening, (Alobaid, 1990), (Alobaid, 1995). Since shot peening is a dynamic process, three dimensional dynamic simulation has also been carried out (Meguid et al., 1999). Simulation, taking account of the material properties and shot peening conditions, such as the speed and diameter of the shot, has also been done (Schiffrin and Helling, 1999). The effect of multi impacts (Majzoobi et al., 2005), damage to the surface (Frija et al., 2006) and rebound of the shot (Hong et al., 2008) have also been considered.

As mentioned above, the compressive residual stress distribution introduced by shot peening can be simulated by finite element analysis, as the pressure distribution at impact can be assumed to be governed by Hertzian contact theory. Unfortunately, the pressure distribution in cavitation peening cannot be simulated. As is well known, the cavitating region can be simulated numerically. Although numerical simulations of cavitation bubbles collapsing have been tried (Zhang et al., 1993), (Matsumoto and Takemura, 1994), (Prosperetti, 1997), (Brujan et al., 2002), (Futakawa et al., 2005), the pressure wave induced by the collapse is still a big problem, since cavitation is a phase change phenomenon at high Reynolds number. In this case it is very difficult to numerically simulate the distribution of the residual stress. The progress of the numerical simulation about cavitation bubble collapse would be expected in the near future to enhance cavitation peening.

In the case of laser peening, the shock wave from the plasma generated by the pulsed laser can be simulated (Fabbro et al., 1990), (Berthe et al., 1997), as can the distribution of the compressive residual stress introduced by laser peening (Peyre et al., 2003), (Peyre et al., 2007).

5. Concluding Remarks

In order to improve the fatigue strength of metallic materials by mechanical surface treatments such as shot peening, water jet peening, cavitation peening and laser peening, the concept of surface mechanics design was discussed. The important properties of the surface mechanics design are the residual stress, yield stress, hardness, roughness, crack propagation rate and the range of the threshold level of the stress intensity factor. Although the surface roughness increases after mechanical treatment, the positive effects, such as the introduction of a compressive residual stress and...
an increase in yield stress, i.e., work hardening, outweigh the negative effects. One of important factors on the improvement of the fatigue strength is the compressive residual stress, as the crack initiation and the crack propagation rate are affected by the compressive residual stress distribution. When similar peening treatments are applied, the fatigue strength can be estimated from the compressive residual stress distribution. However, the compressive residual stress distribution needed to improve the fatigue strength is totally different for different peening methods. Namely, fatigue tests are required at the development of mechanical surface treatments. The investigation of the crack initiation and the crack growth of surface modified layer by mechanical surface treatments are very helpful to improve the peening effect, as the fatigue strength closely depends on the crack initiation and the crack growth. A load controlled fatigue strength test using a notched specimen is an effective method, as the threshold level of the stress intensity factor range, i.e., crack initiation of surface modified layer, can be obtained by the test. In order to understand the impact mechanism and to improve the peening effects, a classification map to distinguish between cavitation peening and water jet peening was also discussed.

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